Order Number 8814217

Validating hierarchical sequences in the design copying domain using latent trait models

Burch, Melissa Price, Ph.D.

The University of Arizona, 1988

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

VALIDATING HIERARCHICAL SEQUENCES IN THE DESIGN COPYING DOMAIN USING LATENT TRAIT MODELS

by

MELISSA PRICE BURCH

A Dissertation Submitted to the Faculty of the

DIVISION OF EDUCATIONAL FOUNDATIONS AND ADMINISTRATION

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY
WITH A MAJOR IN EDUCATIONAL PSYCHOLOGY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 8

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Melissa Price Burch

entitled Validating Hierarchical Sequences in the Design Copying Domain Using Latent Trait Models

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

John R. Bergan — Date 3/11/88

Shitala P. Mishra — Date 3/11/88

John E. Obrzut — Date 3/11/88

Date

Date

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director John R. Bergan — Date 3/11/88

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Melissa P. Busch

ACKNOWLEDGMENTS

I would like to express my appreciation to Dr. John Bergan, my major advisor and director of this work, for his expertise and guidance on this project and through my doctoral studies. I would also like to express gratitude to Dr. Shitala Mishra and Dr. John Obrzut for their assistance with this project. Appreciation also goes to Dr. Glen Nicholson and Dr. Rosemary Rosser for their support and assistance throughout my graduate studies.

A very special thank you goes to my husband, Rick, for the patience, support, encouragement, and love he has provided me.

TABLE OF CONTENTS

Page

LIST OF TABLES.. 7

ABSTRACT.. 10

1. INTRODUCTION....................................... 12

2. REVIEW OF LITERATURE............................... 19

Graphic Copying Skills................................ 19
Age-Related Changes in Graphic Copying Skills......... 20
Spatial Orientation and Graphic Copying Skills........ 23
Graphic Copying Skills as Rule-Governed Behavior...... 32
Learning Hierarchies.................................. 38
Validating Learning Hierarchies....................... 39
Latent Trait Theory................................... 44
Hypothesized Design Copying Hierarchy................. 49
Rules... 50
Task Representation................................... 53
Stimulus Properties................................... 59

3. METHOD... 66

Subjects.. 66
Performance Measure................................... 66
Scoring Criteria...................................... 67
Procedures.. 67
Data Analysis... 68

4. RESULTS.. 69

Hierarchy 1 Model Comparison Results.................. 69
Hierarchy 2 Model Comparison Results.................. 75
Hierarchy 2A Model Comparisons........................ 75
Hierarchy 2B Model Comparisons........................ 81
Hierarchy 3 Model Comparison Results.................. 87
Hierarchy 3A Model Comparisons........................ 87

TABLE OF CONTENTS--*Continued*

Page

Hierarchy 3B Model Comparisons............. 93
Hierarchy 4 Model Comparison Results........... 98
Hierarchy 4A Model Comparisons............. 98
Hierarchy 4B Model Comparisons............. 103
Hierarchy 4C Model Comparisons............. 109
Hierarchy 5 Model Comparison Results........... 114

5. DISCUSSION...................................... 119

APPENDIX A: DESIGN COPYING TEST.................... 128

APPENDIX B: SCORING CRITERIA....................... 136

APPENDIX C: DIRECTIONS............................. 141

APPENDIX D: OBSERVED AND EXPECTED FREQUENCY TABLES................................. 142

APPENDIX E: STATISTICAL FORMULAS.................. 161

LIST OF REFERENCES................................. 162

LIST OF TABLES

Table Page

1. Task Descriptions for Hierarchy 1 Based on Starting and Progression Rules for Standard Figures.. 52

2. Rule Components, Rule Conflicts, and Rule Replacements for Starting Rules by Standard Design.. 54

3. Rule Components, Rule Conflicts, and Rule Replacements for Progression Rules by Standard Design.............................. 55

4. Task Descriptions for Hierarchy 2 Based on Task Representation.............................. 58

5. Task Descriptions and Related Rule Conflicts for Hierarchy 3 Based on Spatial Orientation..... 61

6. Task Descriptions for Hierarchy 4 Based on Presence of Angles.......................... 63

7. Task Descriptions for Hierarchy 5 Based on Stimulus Complexity......................... 65

8. Hierarchy 1 Models and Estimated Parameters...... 70

9. Hierarchy 1 Model Comparisons................... 71

10. Hierarchy 2A Models and Estimated Parameters..... 76

11. Hierarchy 2A Model Comparisons.................. 77

12. Hierarchy 2B Models and Estimated Parameters..... 82

13. Hierarchy 2B Model Comparisons.................. 83

14. Hierarchy 3A Models and Estmiated Parameters..... 88

15. Hierarchy 3A Model Comparisons.................. 89

LIST OF TABLES--CONTINUED

Table Page

16. Hierarchy 3B Models and Estimated Parameters..... 94

17. Hierarchy 3B Model Comparisons.................. 95

18. Hierarchy 4A Models and Estimated Parameters..... 99

19. Hierarchy 4A Model Comparisons.................. 100

20. Hierarchy 4B Models and Estimated Parameters..... 104

21. Hierarchy 4B Model Comparisons.................. 105

22. Hierarchy 4C Models and Estimated Parameters..... 110

23. Hierarchy 4C Model Comparisons.................. 115

24. Hierarchy 5 Models and Estimated Parameters...... 116

25. Hierarchy 5 Model Comparisons................... 117

26. Hierarchy 1 Expected and Observed Cell Frequencies for Models M1, M2, and M3........ 143

27. Hierarchy 1 Expected and Observed Cell Frequencies for Models M4, M5, and M6........ 144

28. Hierarchy 2A Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4.... 145

29. Hierarchy 2A Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8.... 146

30. Hierarchy 2B Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4.... 147

31. Hierarchy 2B Expected and Observed Cell Frequencies for Models M5, M6, and M7........ 148

32. Hierarchy 3A Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4.... 149

33. Hierarchy 3A Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8.... 150

LIST OF TABLES--CONTINUED

Table Page

34. Hierarchy 3B Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4.... 151

35. Hierarchy 3B Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8.... 152

36. Hierarchy 4A Expected and Observed Cell Frequencies for Models M1, M2, and M3........ 153

37. Hierarchy 4A Expected and Observed Cell Frequencies for Models M4, M5, and M6........ 154

38. Hierarchy 4B Expected and Observed Cell Frequencies for Models M1, M2, and M3........ 155

39. Hierarchy 4B Expected and Observed Cell Frequencies for Models M4, M5, M6, and M7.... 156

40. Hierarchy 4C Expected and Observed Cell Frequencies for Models M1, M2, and M3........ 157

41. Hierarchy 4C Expected and Observed Cell Frequencies for Models M4, M5, M6, and M7.... 158

42. Hierarchy 5 Expected and Observed Cell Frequencies for Models M1, M2, and M3........ 159

43. Hierarchy 5 Expected and Observed Cell Frequencies for Models M4, M5, and M6........ 160

ABSTRACT

The present study was a systematic investigation of hierarchical skill sequences in the design copying domain. The factors associated with possible variations in task difficulty were delineated. Five hierarchies were developed to reflect variations in rule usage, the structuring of responses, presence of angles, spatial orientations, and stimulus complexity.

Three-hundred thirty four subjects aged five through ten years were administered a 25 item design copying test. The data were analyzed using probabilistic models. Latent trait models were developed to test the hypothesized skill sequences. Each latent trait model was statistically compared to alternate models to arrive at a preferred model that would adequately represent the data.

Results suggested that items with predictable difficulty levels can be developed in this domain based on an analysis of stimulus dimensions and the use of rules for task completion. The inclusion of visual cues to guide design copying assists accurate task completion.

Implications of the current findings for facilitating the construction of tests which accurately provide

information about children's skill levels were discussed. The presence of hierarchical skill sequences in a variety of ability domains was supported.

CHAPTER 1

INTRODUCTION

The development of visual-motor control represents an integral part of the overall motor development of the young child. The skillful performance of visual-motor behaviors is essential for young children to effectively function in home and school environments. Visual-motor control has been defined as the ability to coordinate the eyes and hands in efficient and precise movement patterns (Laszlo & Bairstow, 1985; Williams, 1983). These movement patterns are displayed in a variety of forms including writing, drawing, cutting, and manipulating small objects.

Measures of visual-motor control are often included in screening batteries for Kindergarten and first grade students. Children who have difficulty with school tasks that require a particular level of eye-hand coordination (e.g., writing alphabet letters or numbers) may be identified as being in need of special assistance. Remedial strategies which will assist in the mastery of instructional materials can then be developed for these children.

The most prevalent method used by schools to assess visual-motor control involves the grapho-motor task of design copying (Lepkin & Pryzwansky, 1983). Many commonly used developmental tests such as the Denver Developmental Screening Test (Frankenburg & Dodds, 1973),the Developmental Indicators for the Assessment of Learning, or DIAL, (Mardell & Goldenberg, 1975), and the Bruininks-Oseretsky Test of Motor Proficiency (Bruininks, 1978), as well as general ability tests such as the Wechsler Preschool and Primary Scale of Intelligence (Wechsler, 1967) and the Stanford-Binet Intelligence Scale (Thorndike, Hagen, & Sattler, 1986), include a design copying section. Typically, items are chosen through a factor analytic approach whereby potential items are identified through an analysis of theoretical and empirical data.

Several instruments have been developed for the specific purpose of assessing graphic copying skills, most notably the Bender Motor Gestalt Test (Bender, 1938) and the Developmental Test of Visual-Motor Integration (Beery, 1982). The Bender is a form copying test derived from Gestalt principles of perceptual organization. The Test of Visual-Motor Integration, commonly referred to as the VMI, was designed to assess all shapes and angles required to write letters and numbers.

The majority of instruments that are currently in use for the assessment of graphic design copying skills describe a child's skills in terms of age norms. In general, a child's performance level is based on the number of successes or failures that differentiate the performance of average children along a chronological continuum. The child's skills are then described in terms of the age norms associated with the number of test items he/she passed or failed. Two basic criteria, age-progression and the contribution of an item to the test's internal consistency, are often used in item selection. Such an approach, which describes a child's skill level in comparison to his/her age mates, may prove to be of limited value in delineating tasks that the child can and cannot perform.

An alternative method by which changes in graphic copying skill performance might be represented is through the analysis of a hierarchical sequencing of skills. Researchers in the area of cognitive development have proposed that learning and development may involve hierarchically sequenced changes in capability that reflect successively higher levels of functioning (e.g., Gagne, 1962). Gagne (1977) suggested that a hierarchy of skills is composed of tasks that may be equivalent in difficulty or that may be ordered in a manner such that subordinate tasks are prerequisite to superordinate tasks.

Historically, such hierarchical sequences were presumed to be based on the development of complex skills from simpler component skills. More recently, it has been suggested that hierarchical ordering may occur in a variety of ways. For example, a change in knowledge structures comprising a learning hierarchy may occur when a simple rule applied to a task is replaced by a more complex rule (Bergan, Stone, & Feld, 1984).

Validated learning hierarchies can serve a number of useful functions. Assessment devices based on validated hierarchies can be useful in the development of individual instructional sequences for students (Glaser & Nitko, 1971; Nitko, 1980). In addition, validated hierarchies can provide a rationale for diagnostic testing aimed at identifying skills that are necessary for achieving a variety of instructional goals (Bergan, 1980b). Thus, hierarchies can provide a basis for the sequencing of learning tasks in an educational curriculum. Finally, hierarchically derived assessment tools can be used at the completion of an instructional sequence to evaluate progress and to identify skills that should be taught next (Bergan, 1980b).

A number of investigations into the validity of learning hierarchies have supported the view that hierarchies represent patterns of prerequisite intellectual skills leading to terminal skill development (White & Gagne, 1974). To date, however, only a small number of learning hierarchy validation studies have been reported. The majority of these investigations have focused on skills that might comprise a math or science curriculum (Bergan, Towstopiat, Cancelli, & Karp, 1982; Macready, 1975; Resnick, Wang, & Kaplan, 1973). Because learning hierarchies appear to be a promising instructional tool, it seems useful to discover how widely they exist across subject areas, including the area of motor skill development.

Two general approaches for the empirical validation of learning hierarchies have been suggested. Many investigators have used the experimental method of hierarchy validation described by White (1973) and White and Gagne (1974). An alternative approach utilizing psychometric procedures also has been proposed. Until recently, however, no viable psychometric technology for empirically validating hierarchical skill sequences had been developed. A variety of latent trait models have now been developed that offer a psychometric method for validating skill sequences (Macready, 1982). An application of one such model provides a hypothesis testing approach for investigating developmental skill sequences that is useful in validating learning hierarchies. The present study examined the hierarchical structure of skills in the graphic copying skill area utilizing a hypothesis testing approach.

In addition to validation problems, research concerning the development of learning hierarchies has been hindered by difficulties related to imprecise specification of component elements in postulated hierarchies (White, 1973). Interestingly, recent discussions of traditional test item development have included similar criticisms. Embretson (1985) suggested that task characteristics associated with task difficulty must be addressed in item development so that cognitive processes underlying performance can be determined. Within this framework, task demands that impose various requirements on cognitive processes are identified (Newell & Simon, 1972). Stimulus features of items that control the cognitive demands that are necessary for successful task completion can then be identified. Once stimulus properties are identified, those properties that are likely to cause performance to vary can be included in item selection (Nitko, 1980). The difficulty of items can then be traced back to the cognitive operations that are required for skilled performance of the task.

A similar item specification approach can be used in developing items within a hierarchy. In the present study, specific stimulus attributes associated with copying were identified and used in hierarchy construction to systematically investigate the skills and processes required in graphic copying. Skill sequences within the graphic copying domain were identified and validated using a probabilistic statistical model. In this context, the processes involved in visual-motor skill performance were treated as cognitive processes rather than as uniquely "motor" behaviors.

CHAPTER 2

REVIEW OF LITERATURE

This chapter provides a review of the literature in the graphic copying skill area. A general overview of learning hierarchies and the statistical models used to validate hierarchical skill sequences is also presented. Particular consideration is given to the use of latent trait models in the validation of learning hierarchies. Finally, the application of latent trait technology to the validation of a proposed graphic copying skills hierarchy is described.

Graphic Copying Skills

A number of investigations have been conducted to analyze the nature and development of graphic copying skills. Several approaches appear to dominate this area of inquiry. Traditionally, researchers have focused on the age-related nature of the task by establishing norms related to developmental changes in the accuracy of copying standard geometric forms. There also has been considerable speculation as to why some geometric forms are more difficult to copy than others. This has led to analyses of the nature of specific difficulties that are inherent in certain copying tasks, e.g., drawing the diagonal. Finally, recent studies have described the acquisition of graphic copying skills as a problem-solving, rule-governed activity.

Age-Related Changes in Graphic Copying Skills

In 1926, Goodenough (cited in Williams, 1983) identified the following stages through which children progress while beginning to draw two-dimensional forms: (a) non-goal directed scribbling at age one, (b) scribbling with inclusions of loops at age two, (c) copying in the form of loops with some attention to a visual model at age three, (d) copying with rudimentary angles and more attention to a visual model at age four, and (e) copying with more organization and a closer relationship to the model at age five or six. Generally, the ability to copy a circle begins to emerge at age three, a square at age four, a triangle at age five, and a diamond at age seven (Cratty, 1979; Laszlo & Bairstow, 1985). Accurate performance does not emerge for several more years, however.

Data provided by Ayres (1978) from her study of the growth of perceptual-motor skills suggested that the period of major growth in design copying skills is from age five to age nine. These years coincide with the elementary school grades when graphic copying skills are emphasized. By age eight there is a gradual deceleration in the rate of change in copying skills. Though the range of skills varies from age to age for both sexes, there are no differences between boys and girls at any age (Williams, 1983).

A comprehensive investigation of age changes and the nature of inaccuracies in design copying was conducted by Birch and Lefford (1967). These investigators suggested that errors in copying geometric shapes might not be solely related to motor inadequacies. Rather, they hypothesized that such copying errors might be related to the inability of young children to use visual stimuli to control and direct motoric action. To test this hypothesis, subjects aged five through eleven were asked to draw an upright isosceles triangle, an equilateral diamond, and an elongated diamond. The geometric designs were drawn with the aid of visual models and the following levels of stimulus support:

1. Tracing: The subjects placed their response sheets over the models to be copied and traced the shapes.

2. Connecting dots: Dots were included on the models at points where the design lines intersected or ended; dots were printed on the response sheet in the same

positions. The subjects were instructed to copy the models using the dots as a guide.

3. Dot grid: Models were superimposed on a grid of dots. The response sheets contained only the dot grids. The subjects were instructed to copy the models on the grids.

4. Line grid: Models were superimposed on a grid composed of straight intersecting lines. The response sheets contained only the line grids. The subjects were instructed to copy the models on the grids.

5. No visual support: Models were presented on a blank page. Subjects were instructed to draw freehand copies of the models on their response sheets.

Based on an analysis of the mean number of errors obtained at each age level, results provided by Birch and Lefford's study indicated that copying performance under all conditions improved with age. As might be expected, variability of performance decreased with age. The most rapid rate of development in the ability to copy designs was observed between age five and seven.

As expected, Birch and Lefford observed a definite differential in performance with respect to the conditions of available visual information. In general, drawings made by tracing and by connecting dots were executed with ease. Drawings made on line and dot grids were executed at an intermediate level. Finally, the freehand drawings and drawings from a model with dots emphasizing line intersections and line endings were executed most poorly. Tracing abilities for all three forms were usually mastered by age six; line grid and freehand drawings were not mastered until age nine. In general, freehand drawings improved through nine years of age for the triangle forms and through eleven years of age for the diamond shape.

There is considerable agreement, then, that the ability to copy basic geometric figures is acquired in an age-related order (Ayers, 1978; Birch & Lefford, 1967; Rand, 1973; Williams, 1983). It has been established that children can copy certain geometric forms before others. A steady improvement in these skills from approximately age five through age ten is apparent. The accuracy of children's responses can be improved by the inclusion of visual cues on both the stimulus and response sheets.

Spatial Orientation and Graphic Copying Skills

An important aspect of the development of graphic copying skills involves the child's ability to recognize and identify the position or orientation of objects in space. Space is highly structured; there are various axes along which visual stimuli may be oriented. Stimuli may be placed along the horizontal or vertical, up or down, or high or low. Until children begin to develop an awareness of these spatial opposites, they are apt to reverse, rotate, or invert visual models when copying.

The ability to construct a straight line that can bisect space in various directions is a key element in the development of spatial comprehension. Piaget has proposed that there are two links between space and drawing, (a) a link between the child's conception of space and his/her conception of accurate representations of stimuli, and (b) the division of mental development into two stages which determine both spatial and graphic ability (Piaget & Inhelder, 1969). From this perspective, it has been suggested that young children make graphic reproduction errors because they lack a proper spatial appreciation of the external frame of reference of the drawing.

Though Piaget's work has led to a large amount of research on spatial abilities in children, it has failed to produce significant work related to graphic reproduction performance. Fortunately, a number of researchers have investigated the relationship between spatial orientation and graphic copying skills within a less theoretical framework.

Children appear to master visual awareness of spatial directions in a more-or-less orderly sequence (Williams, Temple & Bateman, 1978). By age six, most children can discriminate between horizontal and oblique lines (- /). However, they continue to have difficulty with vertical-oblique discriminations (\ /) and oblique-oblique (\ /) discriminations for at least several more years (Freeman, 1980; Jeffrey, 1966). The vertical-oblique and oblique-oblique discriminations are usually mastered by age nine. Because they make discrimination errors, young children have more difficulty making left-right discriminations when copying figures that are adjacent ([ ]) than when they are one above the other (□).

It appears that the ability to perceive the spatial orientation of objects to be copied is not fully developed until sometime after age eight (Williams, Temple, & Bateman, 1978). Consequently, children would be presumed to have difficulty accurately copying geometric forms containing lines drawn on a variety of spatial axes.

Vertical and Horizontal Orientation Errors. It has been observed that when children draw geometric shapes, they tend to begin with vertical, downward strokes rather than horizontal strokes. In addition, when drawing horizontally, children tend to draw from left to right rather than from right to left (Gesell & Ames, 1946; Ilg & Ames, 1964). As a consequence of these propensities, young children make frequent orientation errors along the vertical and horizontal axes.

Vertical and horizontal orientation errors have been specified in several ways. Goodnow and Levine (1973) reported a differential frequency of left-right reversals for shapes presented in different orientations. More reversals were observed when a vertical line was to the right of the figure (as in the letter "d") than when it was to the left of the figure (as in the letter "b"). The authors considered the source of this effect to lie in the child's tendency to start drawing with a vertical line and to progress towards the right.

Several investigators, however, have specified an alternate explanation for vertical-horizontal orientation errors. For example, Serpell (1971) suggested that these orientation errors occur in design copying when an abstract shape, regarded by a child as "right side up" in one orientation and "upside down" in another, is presented in the upside-down orientation. In this situation, the copying error may originate from the figure being perceived and copied in terms of its right-side-up orientation as opposed to its correct orientation. For this explanation to be tenable, such errors should occur most often when shapes are presented in positions regarded by children as upside down.

A study reported by Eldred (1973) supported the notion that children's inherent perceptions of right and wrong orientation effected their copying. In this study, children's orientation preferences for a variety of figures were obtained. The same figures were then presented to and copied by young subjects. Eldred reported a lower incidence of inversion errors for shapes that were presented in the preferred orientations. Eldred also observed that the frequency of these inversion errors declined after age six. It was not clear whether this reflects a change in the child's notion of what looks right or, perhaps, an increase in the child's ability to monitor his/her performance in terms of accuracy.

In a cross-cultural study, Goodnow, Young, and Kvan (1976) presented 4-year-old subjects with shapes that might lead to vertical or horizontal orientation errors. Consistent with Eldred's results, they observed inversion errors related to shapes regarded by children as having a right-side-up and wrong-side-up orientation. These inversion errors often contained left-right reversals of shapes that were inconsistent with the usual sequence of strokes found in young children's drawings.

The Perpendicular Bias. A number of investigators have observed that children have difficulty drawing lines that are not perpendicular (Birch & Lefford, 1967; Freeman & Hayton, 1980; Olson, 1970). Figures containing right angles are correctly drawn at an earlier age than are figures containing oblique angles. When meaningful material is presented, children younger than seven do not correctly draw as horizontal the level of liquid in a tilted glass (Thomas & Jamison, 1975). Children also have difficulty drawing trees which stand on a sloping hill as vertical to the slope rather than as perpendicular to the slope (Mackay, Brazendale, & Wilson, 1972). However, when the object to be drawn is perpendicular to the baseline, and the baseline itself is horizontal or vertical, the children do not make mistakes. Piaget (Piaget and Inhelder, 1967) suggested that young children demonstrate errors when producing non-perpendicular angles because they lack a proper spatial appreciation of an external frame of reference for use in accurate drawing. From Piaget's perspective, young children lack an understanding of Euclidean geometry that is needed for accurate representations of visual models. In contrast, other authors have proposed that the child's copying ability is affected by a performance bias toward making acute and oblique angles perpendicular i.e., a perpendicular bias (Berman, Cunningham & Harkulich, 1974; Ibbotson & Bryant, 1976). Consequently, diagonal lines and nonperpendicular angles are more difficult to draw than vertical lines, horizontal lines, and right angles.

Ibbotson and Bryant (1976) designed an experiment to demonstrate that children's tendencies to draw angles as more perpendicular than they actually are is a general one. Subjects aged 5-0 to 6-6 copied figures comprised of a long baseline (six inches). A shorter line (four inches) extended from the middle of the baseline, comprising a  or a . The figures to be copied differed in two ways. First, the orientation of the baseline was varied; the baseline was presented either on a vertical-horizontal axis or at a left-right 45^{o} angle. Second, the angle made by the two lines was either 90^{o} of 45^{o}. The baseline was provided on the subject's response sheet.

Results obtained by Ibbotson and Bryant indicated that the subjects were significantly more accurate at copying 90^{o} angles than 45^{o} angles irrespective of the orientation of the baseline. This occurred whether the line to be copied was oblique or on the horizontal or vertical, although the perpendicular tendency was reduced slightly when the figure's baseline was vertical. These results suggest that the error relates to reproduction of nonperpendicular angles rather than to reproduction of lines in a particular orientation.

Several authors have shared Ibbotson and Bryant's proposition that a perpendicular bias exists in children's figural copies (e.g., Freeman, 1980). However, it has been proposed that this bias is related to a general tendency in children to produce symmetry or simplicity in their drawings. Bremner and Taylor (1982) had 5-year-old subjects reproduce a variety of bisected lines. In this study, the subjects reproduced the bisected figures accurately but distorted nonbisected figures toward bisection (although they contained right angles). However, the bisection effect only occurred for figures with oblique baselines. When the baselines were horizontal or vertical, the subjects may have viewed the nonbisected figures as asymmetrical about the vertical and horizontal axes and, thus, resisted the temptation to distort the representation toward symmetry.

The Role of Framework. An alternative approach suggests that children's ability to construct a line of any particular orientation is primarily determined by the shape of the immediate surround. Specifically, the surround provides a frame of reference for reproducing accurate figures. Children have difficulty copying oblique lines because they tend to center on the horizontal and vertical cues provided by the rectangular framework. Younger children may be more influenced by the framework than older children.

Berman, Cunningham, and Harkulich (1974) designed a study to assess children's ability to draw horizontal, vertical, and oblique lines in the absence of a rectangular framework. Children aged 3-10 to 5-3 reproduced lines of varying orientation by drawing on a circular framework from immediate memory. The investigators observed that the vertical orientation was more accurately reproduced than either the horizontal or oblique. This is congruent with the tendency toward verticalization noted by Ibbotson and Bryant (1976). Although the horizontal and oblique lines were equally difficult for the preschool subjects, it may be that older children reconstruct the horizontal more easily than the oblique even without the aide of the horizontal and vertical referents in the immediate surround. However, the age range in this study was too narrow to test this hypothesis across ages. Based on these results, the authors concluded that children's difficulty with the oblique is due to their tendency to center on the horizontal and vertical cues in the immediate surround.

In a follow-up study, Berman (1976) had preschool children draw a series of vertical, horizontal, and oblique lines from immediate memory on square backgrounds to further analyze the types of errors children make. In contrast to the earlier results in which essentially random errors were observed on a circular background, a systematic pattern of errors was expected when a square framework was provided. Errors were hypothesized to be related to the child's categorization of orientations as either parallel or not parallel to the frame. Oblique lines were expected to be confused with opposite oblique line lines; horizontal and vertical lines were expected to be confused with each other. Analyses of the subjects' responses were supportive of these expectations. Consistent with these results, Naeli and Harris (1976) have reported that young children copy or place diamond and square shapes in alignment with the surrounding frame.

Graphic Copying Skills as Rule-Governed Behavior

There are two predominant views concerning the nature of sensorimotor development. The first describes sensorimotor skills in terms of the habitual nature of motor learning. Development is seen as a fixing-in of motor patterns through extensive practice. In contrast, the processes involved in motor learning have been related to similar processes that underlie cognitive behavior in general. From this perspective, the line between sensorimotor and cognitive behaviors may be more apparent than real.

Bruner (1970, 1973) described the acquisition of motor skills as a problem-solving, rule-governed activity. During the course of development, what is learned is not a motor pattern but a set of rules that specify a range of behaviors that can be performed. The set of rules allows for the transfer of skills to novel, but related, tasks. Based on this premise, the paths children use when copying figures can be described in terms of a limited set of principles or rules that specify the procedures necessary for accurate performance.

There are several advantages to demonstrating that rules and patterns apply to graphic copying skills. First, tasks using similar rules can be substituted for other tasks. In addition, general theories of behavior that are not tied to specific contexts such as "motor behavior" can be developed. These advantages have often been realized in work that relates perceptual and cognitive behaviors. However, they are virtually ignored in analyses of sensorimotor behavior. This may result from a tendency to regard motor behavior as less complex than cognitive behavior and, consequently, not as worthy of study. Additionally, it may be difficult to specify variables that are common to motor and cognitive behavior.

Rules and Directionality. There is some evidence that children do use rules when displaying graphic copying skills. A study of directionality in children's drawings conducted by Gesell and Ames (1946) provided early support for the concept that design copying is a rule-governed behavior. The investigators analyzed the drawing of children aged 18 months to 84 months on the basis of page placement, line length, line continuity, and order of strokes. Figures to be copied included vertical and horizontal lines, and a circle, cross, square, diamond, triangle, and rectangle. Results indicated that at all ages, children tend to draw a vertical line downward and a horizontal line from left to right.

More recent results consistent with Gesell and Ames' findings have been provided by a number of researchers. Goodnow and Levine (1973) and Bernbaum, Goodnow, and Lehman (1974) analyzed children's copying of rectilinear forms in terms of rules that specify the choice of starting point and the direction of strokes. Their research suggested that a small number of rules describe strategies used by children when copying various geometric designs. Children start at the top of the figure more often than at the bottom, they start at the left of the figure more often than at the right, and they start with vertical strokes more often than horizontal. Furthermore, the rules were observed to stabilize with age. Goodnow and Levine (1973) suggested that these rules form "the grammar of action" according to which progression of strokes in design copying can be viewed as a sequence of choices made at various points in the copying process.

<u>The Effects of Rule-Based Training</u>. Children's ability to utilize drawing rules may determine how recognizable their drawings are. Olson (1970) found that teaching children drawing construction rules resulted in significant improvement in their ability to copy figures containing diagonal lines. Rand (1973) compared the effects of visual analysis training and rule training on copying accuracy in 3-year-old to 5-year-old subjects. In the drawing rule training group, subjects were taught to plan their drawings by making small dots where the corners of the figure would appear and then to connect the dots. In the visual analysis training group, subjects pointed at and counted sides and corners of a square, triangle, and diamond. Before training, the subjects did not have the skill to plan their copying; they did not know where to start, which direction to move, or when to stop and change direction. Subsequent to training, children taught drawing rules showed marked improvement in their copying skills, but none in their visual discrimination performance. Subjects receiving visual analysis training improved their discrimination performance but did not produce more accurate copies.

Rand concluded that drawing rule training taught the subjects how to plan their drawings. Training, however, did not change the children's ability to organize space without the use of dots; they were unable to draw recognizable figures without the assistance of these cues. Rand suggested that the subjects' primary deficit was an inability to reconstruct segment-whole relationships rather than an inability to analyze the model. Based on these results, the author concluded that drawing is a sequential, rule-related process.

Kirk (1981) evaluated the effect of rule-based instruction and rule observance on copying performance. She examined three methods of teaching rules: demonstration, verbal, and a combination of demonstration-verbal instruction. The usefulness of these methods was compared with copying without instruction. Results supported the view of rule-governed acquisition of copying skills. Flexibility and ability to select alternative routes characterized skillful performance. Departures from rules were lawful and were generally related to the complexity of the stimulus. Subjects displayed the same starting point and progression rules as had been observed in earlier studies.

Summary. Considerable attention has been given to the analysis of children's performance on graphic copying tasks. The results are quite consistent in demonstrating that age-related differences exist on these tasks. In addition, the order of difficulty of standard geometric designs is generally consistent across studies. Based on this consistent ordering, inferences can be drawn as to the specific aspects of the designs which might be related to difficulty. However, such inferences require confirmation and a more precise delineation of the relevant stimulus properties and dimensions of the designs that contribute to their difficulty. The possible differential effects of various stimulus dimensions need to be explored.

Much of the available evidence was obtained from samples of very young children (below age six). The quality and accuracy of their responses were often liberally defined to ensure that data would not be lost through the necessity of discarding inaccurate responses. For example, a child's copy of a square might be included in the analysis although it did not contain four sides. Consequently, conclusions were frequently based on responses that were minimally scoreable, and, therefore, difficult to analyze. Any analysis of dimensions that may affect the differential difficulty of various designs must include a wide age range to provide subjects who are minimally proficient as well as those who have mastered all aspects of the designs. Designs must be strictly scored to ensure the validity of the analysis.

Several authors (Kirk, 1981; Williams, 1983) have supported the need for further investigation into the stimulus dimensions that contribute to differences in performance of graphic copying tasks. The present study attempted to more precisely specify these component elements through an analysis of the hierarchical foundations of graphic copying skills.

Learning Hierarchies

In a seminal article, Glaser and Nitko (1971) discussed the lack of psychometric techniques that might be useful in the analysis and assessment of specific classes of behavior. Glaser and Nitko called for the development of techniques for analyzing performance and deriving assessment procedures for specific domains of behavior. From this perspective, research should focus on delineating the structure of the subject matter comprising a particular performance domain. Through an analysis of the nature of the underlying structure of subject matter areas, useful information for making decisions regarding the improvement and implementation of instructional sequences might be generated (Macready, 1975). The analysis of a set of interrelated items might provide a basis for sequencing tasks in instruction and developing special teaching strategies for students with performance difficulties (Resnick, 1973).

At the time Glaser and Nitko's article was published, there were few techniques available for the analysis of learning tasks and their structure. One procedure that appeared to be promising was the learning hierarchy approach that developed out of the work of Gagne (1962, 1968).

In a learning hierarchy, the structure of knowledge refers to the order of acquisition of specific intellectual capabilities (Macready, 1975). The term learning hierarchy refers to a set of component tasks that lead to a particular instructional objective (Glaser & Nitko, 1971; Cotton, Gallagher, & Marshall, 1977). It is suggested that the component tasks have an ordered relationship to each other. In developing a learning hierarchy, a terminal objective of instruction is delineated and an attempt is made to analyze the objective into component tasks or skills. Any high level skill within the domain is presumed to have one or more immediate descendants which are referred to as subskills of that task (White & Gagne, 1974). The attainment of subskills provides positive transfer, facilitating task performance and increasing the probability of successful completion of the higher level skills.

Validating Learning Hierarchies

There has been considerable interest in the use of hierarchy theory in the analysis of hypothesized sequences of cognitive development since Gagne initially used the term learning hierarchy. Two general approaches have been used in the validation of learning hierarchies. The majority of investigations of hierarchical structures have used the experimental methodology described by Gagne (1962, 1968) to evaluate hierarchical relations among skills. An alternative method, using psychometric procedures, has recently evolved into a viable alternative to the experimental approach for hierarchy validation.

The Experimental Approach. Experimental analyses of the sequencing of skills began with a preliminary study of the learning hierarchy model conducted by Gagne (1962). In this study, Gagne attempted to teach seven children how to find formulas for sums of terms in several number series. Gagne delineated a number of prerequisite skills that he believed must be acquired prior to successful performance of the final goal of finding the formula for the series. The prerequisite skills were identified by answering the question "What would the individual have to be able to do in order that he can attain successful performance on this task provided he is given only instructions" (Gagne, 1962, p. 358). One or more subordinate tasks were specified in response to this question. The question was then applied to the subordinate tasks themselves down through the hierarchy. Through this method, Gagne developed an ordered set of skills which he called a learning hierarchy.

Gagne taught the skills in the hypothesized hierarchy to the subjects in his study. He hypothesized that no individual would perform the final task unless he/she could perform the skills subordinate to that task. In addition, any superordinate task could be performed by any individual provided with instruction if relevant subordinate knowledge could be recalled. Subsequently, he observed that none of the children acquired a skill without having acquired all of the skills that were hypothesized to be subordinate to it in the hierarchy. Gagne used a measure called the proportion of positive transfer to validate his hypothesized hierarchy; the usefulness of this technique has been questioned. It has been suggested that the proportion of positive transfer measure may merely assess the correlation between subskills rather than their hierarchical nature (White, 1973).

The experimental validation of learning hierarchies has also been approached through the study of the controlled transfer of learning. In this context, the training of an immediate prerequisite skill is presumed to result in positive transfer to the superordinate skill. White (1973) and White and Gagne (1974) suggested that the most definitive investigations of hierarchical orderings involve the experimental validation approach with transfer included. This methodology is useful only for hierarchies with few elements because it is quite time consuming.

Summarizing hierarchy validation research to 1973, White and Gagne (1974) stated that studies had provided tentative support for Gagne's conceptualization of learning hierarchies. However, the number of studies validating hierarchies was small and the available studies were marred by methodological flaws. Most studies were limited by small sample size, imprecise specification of component skills, omission of instruction for testing transfer, and the lack of a meaningful quantitative analysis (Resnick, 1973; White, 1973).

White (1973) called for the use of a more rigorous hierarchy validation model which he described in the following manner. Let Roman numerals I and II stand for the subskills in the learning hierarchy. Suppose the hypothesized hierarchy suggests that possession of subskill I is essential for learning subskill II. The hypothesis might be tested in this manner:

1. Test for possession of subskills I and II.

2. Discard subjects who have subskill II; divide the remaining subjects into two groups.

3. Teach group one subskill II, then teach the same group subskill I; teach group two subskill I only.

4. Test both groups for possession of subskills I and II. If the hypothesized hierarchical ordering is correct, and no incidental learning has occurred, only group one will have members with subskill II.

A number of authors (e.g., Capie & Jones, 1971; Uprichard, 1970) have investigated learning hierarchies in the math and science areas utilizing an experimental approach similar to that described by White. Despite the application of White's proposals, significant problems in the analysis of hierarchical relationships remained. For example, the more rigorous validation approach is quite time consuming. Consequently, it may not be applicable to wide-scale efforts to validate hierarchies (Bergan, 1980b). More importantly, the experimental approach does not provide a mathematical description of the relationships among the variables in the model that can be tested statistically (Bergan, 1980b).

Psychometric Approaches. Various attempts have been made to test Gagne's learning hierarchy concepts statistically. The psychometric approach provides a more efficient method for hierarchy validation in terms of time and outcome. In general, a psychometric approach involves the use of a test battery that samples various behaviors in a hypothesized hierarchy. The relationships among items are examined for dependency relations, i.e., the extent to which passing one item precedes passing another item. A variety of statistical tests for analyzing relations among items have been proposed.

Many psychometric procedures that were used in the validation of learning hierarchies were deterministic in nature. Such procedures did not involve inferential statistical criteria in testing hypothesized orderings of subskills (Dayton & Macready, 1976). Moreover, Hambleton and Swaminathan (1983) indicated that deterministic models might not fit most data sets adequately. Dayton and Macready (1976) proposed that probabilistic models might provide a more useful validation technique for evaluating the fit of a hypothesized hierarchy to the data.

Latent Trait Theory

A probabilistic approach to testing hypothesized learning hierarchies involves the use of latent structure analysis. Latent structure analysis was introduced by Lazarsfeld (Lazarsfeld & Henry, 1968). A variety of latent trait models (also referred to as item response models) have been developed from Lazarfeld's work (Lord, 1980). Latent trait models specify the relationship between observable examinee test performance and the unobservable traits or abilities that are assumed to underlie performance on the test (Hambleton & Cook, 1977; Hambleton & Swaminathan, 1983).

The relationship between examinee item performance and the traits assumed to be influencing performance is described by the item characteristic curve. The ICC represents a mathematical function that provides the probability of answering an item correctly for examinees at different points on the ability scale. In this context, an individual's ability is measured on the same scale as task difficulty. Thus, latent ability is linked directly to an examinee's position in a skill sequence, described as theta, and provides a measure of the examinee's developmental level. The probability that an examinee will be able to perform tasks of varying difficulty is specified by the developmental level.

The Two-Parameter Logistic Model. A variety of latent trait models which can be distinguished by the mathematical form of their item characteristic curves have been developed. Of particular interest to the present study is the two-parameter logistic model developed by Birnbaum (1968). In this model, the item characteristic curve takes the form of a two-parameter logistic function including a discrimination index and a difficulty index. The item discrimination index, a_j, represents the steepness of the item characteristic curve at its inflection point and indicates how quickly the probability of a correct response changes as theta (ability) increases. The discrimination index also reflects the degree to which an item relates to the underlying latent trait. The parameter b_j, referred to as the index of difficulty, represents the point on the ability scale at which an examinee has a 50 percent probability of correctly answering an item.

Model Fitting. Because ability is directly linked to task difficulty, latent trait models are useful for testing hypotheses regarding the ordering of cognitive skills in a developmental sequence (Bergan & Stone, 1985; Macready, 1982). Latent trait models provide a statistical method for choosing between several models representing different hypotheses about the ordering of skills. The models provide a probabilistic method for linking examinee responses to theoretical constructs (Bergan, 1980a).

Model fitting has generally involved choosing between a one-parameter model (based on item difficulty), a two-parameter model (based on item discrimination and item difficulty), and the three-parameter model (based on item difficulty, item discrimination, and guessing). More recently, Bergan and Stone (1985) described a method for comparing a set of hierarchically related latent trait models that places restrictions on the item discrimination and item difficulty parameters. These restricted models can be used to test hypotheses about difficulty ordering and item discrimination uniformity for a set of items that represents a hypothesized skill sequence.

Consider an example in which two items in a skill sequence are hypothesized to be ordered by difficulty. The hypothesis could be tested by developing two models. The first model might restrict the estimated difficulty of the two items to be equal. The alternative model would allow the estimated item difficulty to vary. Because only one item difficulty value would be estimated for the item pair in the first model, the restricted model contains fewer estimated item parameters than the unrestricted model. Therefore, the restricted model would be considered more parsimonious than the unrestricted model. The two models are considered to be hierarchical in the sense that the unrestricted model contains all the estimated parameters in the restricted model plus additional estimated parameters. The two models can be compared statistically because they are hierarchical. In this example, the restricted model is more parsimonious and would be the preferred model. However, if the unrestricted model provided a significant improvement in fit over the restricted model, it would be the preferred model.

The goal of testing hierarchically-related models is the selection of a preferred model that provides an adequate fit for the data and that might improve on the fit afforded by a more parsimonious model. Models that restrict item discrimination may also be developed to determine if the discriminating power is the same for all items being considered. When item discrimination values are equal, it can be assumed that all items are related to the underlying latent trait to the same degree. This state of affairs occurs when the restricted model, which restricts estimates of discrimination values to be equal, is preferred over the unrestricted model, which allows discrimination values to be free to vary.

Statistical Analysis. The likelihood ratio chi-square statistic can be used to determine which hypothesized latent trait model provides a better fit for the data. The statistic partitions exactly, facilitating hierarchical statistical comparisons between hypothesized models (Bishop, Feinberg, & Holland, 1975; Macready & Dayton, 1980). Two models are hierarchical when one model contains all the parameters of the other plus one or more additional parameters which must be estimated. The model with fewer estimated parameters is considered to be the more parsimonious model. In this case, the likelihood ratio statistic for the model with the smaller number of degrees of freedom would be subtracted from the model with more degrees of freedom. The resulting statistic can be analyzed to determine if it provides a better fit to the data.

The marginal maximum likelihood procedure developed by Bock and Aitken (1981) provides accurate estimates of item parameters for model fitting. In restricted models, maximum likelihood estimates for the item parameters are produced by imposing restrictions on the values of the discrimination and difficulty parameters. Parameters may be restricted by estimating one parameter for an item set rather than separately estimating a parameter for each item.

Hypothesized Design Copying Hierarchy

In order to precisely delineate the hierarchical structure of the domain, a model for design copying should include consideration of rule usage, the total design, the spatial relations it depicts, and different methods for structuring responses. Three sources of variation in hierarchical structuring that focus on these considerations were used in this study. The first source involved the application of, and changes in, rule usage across designs. A second source of hierarchical variation involved the differential structuring of responses through the provision of alternative task representations. Such variations in task representation may affect task difficulty and lead to alterations in rule usage. A final source of hierarchical variation included an analysis of stimulus dimensions that may account for variations in task performance.

Rules

Recent investigations into the hierarchical sequencing of academic skills, particularly in the mathematics area, have focused on the acquisition of rules that govern increasingly complex performance (Bergan, Stone, & Feld, 1984; Bergan, Towstopiat, Cancelli, & Karp, 1982). Hierarchies composed of rule learning tasks involve equivalence relations between tasks. Rules can form an ordered relation in which one rule is considered to be a component of another rule. In this way, component skills can combine together to produce more complex skills.

Generally, children's copying of rectilinear forms has been analyzed in terms of a limited number of component rules that specify the choice of starting points and direction of strokes (Goodnow & Levine, 1973; Kirk, 1981). Several investigators (Kirk, 1981; Ninio & Lieblich, 1976) have demonstrated that although there are some rules of linear order, older children often make systematic departures from these rules. Flexibility, i.e., the ability to select alternative rules, is more characteristic of skilled action than is consistency of rule observance (Bruner, 1973). In the case of design copying, invariant use of rules may actually be counterproductive. For example, overuse of rules can lead to figural reversals and/or inaccurate reproductions. Thus, older or more skillful children may replace simple rules governing design copying with more complex rules. This is consistent with the observation of Bergan et al. (1982) in the mathematics area that rules may form an ordered relation through the replacement of simple rules by more complex rules.

Rule replacement suggests a qualitative change in a child's performance. This is in contrast to the component rule hypothesis which asserts that new skills are constructed from individual components (Bergan et al., 1982). The component rule and rule replacement concepts were used to develop hypotheses concerning equivalence and ordered relationships in the design copying domain.

Hierarchy 1 Based on Rules. The hierarchy based on rules was composed of standard figures that are often included in tests of design copying. The tasks included in this hierarchy in order of difficulty are depicted in Table 1. The hypothesized order of difficulty was based on an analysis of component starting and progression rules.

Task difficulty was associated with the number of component rules needed for task completion as well as conflicts in rule application. More difficult items were hypothesized to be those in which a conflict between starting and/or progression rules was observed. When this

Table 1

Task Descriptions for Hierarchy 1 Based on Starting and Progression Rules for Standard Figures

Item Number and Description	
7.	Copy a vertical line
8.	Copy a horizontal line
9.	Copy a cross
10.	Copy a square
11.	Copy a triangle

occurs, standard rule application must be replaced by alternative rules to ensure accurate reproduction. The more skilled individual will be able to shift from standard rule usage to ensure accurate design reproduction.

The starting and progression rules associated with standard designs are depicted in Table 2 and Table 3, respectively. Component and replacement rules associated with each design are delineated in Table 2 and Table 3. Rules were taken from Goodnow and Levine (1973) with additional rules developed where necessary.

Task Representation

Hierarchy 2 Based on Task Representation. Three variants of task representation appeared to be particularly important in the analysis of hierarchical sequences in design copying. Variations in task representation involved the amount of visual information provided on the child's response sheet. The three task representation variants in this study included tracing over figural outlines, copying with provision of visual cues on the response sheet, and free-hand copying with no visual cues provided. It was suggested that the use of component and replacement rules might differ depending on the amount of cues provided. The copying of a shape on a blank space versus copying on a space containing visual clues may involve the use of different strategies for task completion, for example,

Table 2

Rule Components, Rule Conflicts, and Rule Replacements for Starting Rules by Standard Design

Design	Starting Rule Associated with Rule Components	Conflicts	Replacements
Vertical Line	2,3	None	None
Horizontal Line	1,2	None	None
Square	1,2	None	None
Cross	1,2	1,2	3
Triangle	1,2,3	1,2	4

Starting Rules:

1. Start at point farthest to the left.
2. Start at topmost point.
3. Start with a vertical line at a 45° or 90° angle to the page base.
4. Given an apex, start at the top and come down the left oblique.

Table 3

Rule Components, Rule Conflicts, and Rule Replacements for Progression Rules by Standard Design

Design	Progression Rule Associated with Rule Components	Conflicts	Replacements
Vertical Line	5	None	None
Horizontal Line	6	None	None
Square	5,6,7	6,7	8
Cross	5,6	5,6,7	10
Triangle	6,7,8	7,8	9

Progression Rules:

5. Draw all vertical lines from top to bottom.
6. Draw all horizontal lines from left to right.
7. Thread (draw with a continuous line).
8. Given an apex, draw down one side and then draw down the other from the vertex.
9. Return to the starting point rather than thread.
10. Given a design composed of intersecting lines, follow the sequence of vertical to horizontal.

although a child may attempt to internally represent the three vertices of a triangle as being on the page, it is more likely that the representation of the problem would be to draw three lines, converging in an angle.

The selection of tracing as a source of response variation was based on the frequent use of tracing as a technique for improving performance in copying and writing despite a paucity of experimental data to support the technique (Hirsch & Niedermeyer, 1973). The lack of experimental verification for classroom practice suggested that the tracing strategy needed further analysis.

Tracing was hypothesized to be the easiest skill in the task representation hierarchy. When copying designs, children must first develop a plan of action and they must then carry out the plan. The provision of a figural outline on the response sheet simplifies this planning process by specifying a plan of action in advance. The child is thus able to focus attention on coordinating movements required to execute the plan. When tracing, the child must only connect the outline, regardless of rule application. Research has shown that there is some difference in compliance to starting and progression rules across age levels (Goodnow & Levine, 1974). When visual cues are not provided, these inconsistencies might lead to inaccurate reproductions. In the case of tracing, such rule following is unnecessary for accurate reproductions.

The use of visual cues is a strategy that is frequently employed in the training of copying skills (Kirk, 1982; Rand, 1973). The differential effects of visual cues were analyzed through the second task representation variant, the provision of partial visual cues on the subject's response sheet. Dots which emphasized line intersections (angle vertices) and line endings were provided. In this manner, starting and stopping points were provided and did not need to be determined by the child. However, the child had to be capable of applying appropriate progression rules or replacing them when necessary to accurately reproduce the figures.

The final and most difficult variant in the task representation hierarchy involved free hand copying with no provision of visual cues. The child needed to develop a plan of action for copying the model and carry out the plan with no assistance provided. Items selected for inclusion in the task representation hierarchy are depicted in Table 4. Items are presented in order of hypothesized difficulty. The models to be copied were standard geometric shapes that are often included in visual-motor

Table 4

Task Descriptions for Hierarchy 2 Based on Task Representation

Item Number and Description	
1.	Trace square
2.	Trace triangle
3.	Trace diamond
4.	Copy square with visual cues provided
5.	Copy triangle with visual cues provided
6.	Copy triangle with visual cues provided
10.	Freehand copy square
11.	Freehand copy triangle
12.	Freehand copy diamond

tests and instructional sequences. The hypothesized order of difficulty was based on these sources.

Stimulus Properties

Delineating the properties of shapes, i.e., the dimensions on which they may differ from one another, is a recurring problem in studies of graphic copying behavior. Three dimensions that appeared to be related to task difficulty were analyzed. The stimulus dimensions included presence of non-perpendicular angles, spatial orientation, and figural complexity. Standard geometric figures and various combinations of their parts were analyzed. The interactions between stimulus dimensions were not included in the present analysis.

Hierarchy 3 Based on Spatial Orientation. Young children have been observed to make frequent orientation errors when copying rectilinear designs (Eldred, 1973) These errors may stem from over-application of component starting and progression rules. It was hypothesized that tasks using standard starting and progression rules would be copied with more accuracy than would tasks in which a conflict is present. When a conflict was present, skillful performers were expected to demonstrate flexibility in rule application in order to copy figures accurately.

Tasks included in the spatial orientation hierarchy are depicted in Table 5. Possible rule conflicts associated with the tasks are also presented. Items are presented in order of hypothesized difficulty.

Hierarchy 4 Based on the Presence of Angles. The inclusion of an acute angle in a rectilinear design transforms a vertical-perpendicular drawing system into an oblique system. The hierarchy based on angles was included to analyze relationships between these two systems. Studies have consistently demonstrated that 45^{o} angles are more difficult to reproduce than 90^{o} angles. The effect of varying baselines is not completely understood, however. Ibbotson and Bryant (1976) have suggested that this relationship holds regardless of baseline orientation; other investigators have disputed this contention (e.g., Berman, Cunningham, & Harkulich, 1974; Bremner & Taylor, 1981).

Within the context of this study, it was hypothesized that the orientation of the baseline would effect accurate angle reproduction. Children tend to organize their responses around the vertical (Berman, Cunningham, & Harkulich, 1974). They may also tend to solve design reproduction problems around this feature. It was therefore hypothesized that designs with a vertical baseline would be easier than designs with horizontal or oblique baselines whether they contained an

Table 5

Task Descriptions and Related Rule Conflicts for Hierarchy 3 Based on Spatial Orientation

Item Number and Description	Rule conflict
13. L shape	None
14. Vertical baseline with perpendicular bisector to right	None
15. Rectilinear U shape	None
16. V shape	None
17. Inverted L	Left vs. vertical start
18. Vertical baseline with perpendicular bisector to left	Left vs. vertical start
19. Inverted rectilinear U shape	Left vs. vertical start
20. Inverted V shape	Left vs. vertical start

oblique system or not. Based on established progression rules, designs containing a horizontal baseline were expected to be completed more accurately than designs containing an oblique baseline. For each baseline type, designs with a right angle were expected to be easier to reproduce than designs with an oblique angle. Items included in the hierarchy based on the presence of angels are presented in Table 6.

Hierarchy 5 Based on Stimulus Complexity. The development of the hierarchy based on stimulus complexity was predicated on the hypothesis that stimulus complexity, defined here as a change in direction or line discontinuity, may contribute to design difficulty. By this definition, an L-shaped design is a two-part figure containing a vertical line with a change in direction to a horizontal line. The sharpness in the change of direction may also contribute to its difficulty. For this reason, a V-shaped figure would be considered more complex than a U-shaped figure. Similarly, a figure containing two acute angles would be more difficult than a figure containing three right angles. It is possible to reproduce an acute angle by joining two lines, thus reducing complexity. However, young children usually attempt to reproduce angles with a continuous line that changes directions; this tends to lead to significant distortions (Gesell & Ames, 1946).

Table 6

Task Descriptions for Hierarchy 4 Based on Presence of Angles

Item Number and Description
14. Vertical baseline with perpendicular bisector to right
21. Vertical baseline with 45° angle bisector up and to the right
22. Horizontal baseline with perpendicular bisector
23. Horizontal baseline with 45° angle bisector up and to the right
24. 45° baseline to right with right angle bisector to right
25. 45° baseline to right with 45° angle bisector to right

Table 7 presents the items that were included in the complexity hierarchy.

Table 7

Task Descriptions for Hierarchy 5 Based on Stimulus Complexity

Item Number and Description
13. L shape
15. Rectilinear U shape
20. Inverted V shape
10. Square
11. Triangle

CHAPTER 3

METHOD

Subjects

A total of 334 children, 158 boys and 176 girls, from elementary schools in Tucson, Arizona participated in the study. Every effort was made to include subjects who were representative of the school-age population in Tucson. There were 221 Anglo children, 106 Hispanic children, and 7 black children. The subjects ranged from five to ten years of age. The age range was chosen to encompass the time period corresponding to the development of design copying skills. The age span was necessary to demonstrate the progression of skills from nonmastery to mastery.

Performance Measure

The assessment instrument that was used in this study was developed according to the model described in the previous chapter. The instrument was comprised of 25 items that were presented in a test booklet. The items included standard geometric shapes as well as a variety of rectilinear forms. The assessment instrument is provided in Appendix A.

Scoring Criteria

Scoring criteria were developed based on an analysis of criteria used in a number of similar instruments. The instruments that were analyzed included the VMI (Beery, 1982), the Stanford-Binet (Thorndike, Hagen, & Sattler, 1986), and the Wechsler Preschool and Primary Scale of Intelligence (1967). Scoring criteria are presented in Appendix B.

Procedures

Testing was completed in groups in the subjects' classrooms. The participants were told that the purpose of the study was to determine how children copy designs. After the test booklets were distributed, the examiner explained how the children were to complete the tasks. Following the explanation, the children were instructed to begin the test. During the course of the testing, the examiner monitored the children's performance to ensure that the task was understood. The directions were re-explained when necessary. The test booklets were examined at the end of the session to determine that all items were attempted by the students. Directions for examiners are provided in Appendix C.

Data Analysis

Thissen's (1986) MULTILOG computer program was used to calculate the a_j (discrimination) and b_j (difficulty) parameters that were needed for validating the hierarchical sequences in the study. MULTILOG produces marginal maximum likelihood parameter estimates. In addition, the program produces estimates of the difficulty and discrimination item parameters with restrictions that can be used in comparing hierarchical models. Statistical formulas for parameter estimation are provided in Appendix E.

A variety of hypothesized latent trait models and possible alternative models were examined for each hierarchy. As described earlier, models may be hypothesized which allow all difficulty and discrimination parameters to be free to vary. Such a model might be compared to a model which restricts all discrimination parameters to be equal and which allows all difficulty parameters to be free to vary. The hypothesized hierarchies were analyzed by allowing the parameters of various latent trait models to be free to vary or constraining them to be equal. The hypothesized latent trait models were evaluated and compared statistically using the likelihood ratio chi-square statistic as described in Chapter 2. The formula for the chi-square statistic is provided in Appendix E.

CHAPTER 4

RESULTS

The results of the hierarchical model comparisons for the skill sequences are presented in Tables 8 through 25. The estimated item difficulty (b_j) and discrimination (a_j) parameters with corresponding degrees of freedom (df) for each model are shown. In addition, the difference L^2 and corresponding df for each model comparison are shown. The degrees of freedom for each model were obtained by subtracting the number of model parameters plus one from the number of score patterns with observed counts greater than zero (Bock & Aitken, 1981). Score patterns represent all possible pass-fail combinations for the items in each hierarchy with 1 representing failure and 2 representing passing. Score patterns and their respective observed and expected cell frequencies are presented in Table 26 through Table 43 in Appendix D.

Hierarchy 1 Model Comparison Results

The item parameter estimates and results of the model comparisons for Hierarchy 1, the standard design hierarchy, are shown in Table 8 and Table 9, respectively.

Table 8

Hierarchy 1 Models and Estimated Parameters

Model	a1	a2	a3	a4	a5	b1	b2	b3	b4	b5	df
M1	2.19	6.86	1.84	3.54	3.42	-1.65	-1.29	-.66	.92	1.21	5
M2	2.39	2.39	2.39	3.32	3.32	-1.62	-1.46	-.60	.93	1.21	8
M3	2.74	2.74	2.74	2.74	2.74	-1.55	-1.39	-.58	.97	1.27	9
M4	2.73	2.73	2.73	2.73	2.73	-1.48	-1.48	-.59	.98	1.27	10
M5	2.19	2.19	2.19	2.19	2.19	-1.18	-1.18	-1.18	2.19	2.19	12
M6	.44	.44	.44	.44	.44	-.61	-.61	-.61	-.61	-.61	13

Table 9

Hierarchy 1 Model Comparisons

		Difference	
Models	df	L^2	*p*
M1,M2	3	7.8	>.05
M2,M3	1	2.1	>.10
M3,M4	1	1.7	>.10
M4,M5	2	26.4	<.001
M4,M6	3	36.2	<.001

Score patterns and their respective observed and expected cell frequencies are presented in Table 26 and 27 in Appendix D. Hierarchy 1 included items 7, 8, 9, 10, and 11. The first model (M1) to be examined was the unrestricted two parameter model. Ten parameters (five a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was sixteen. Therefore, there were 16-(10+1)=5 df in the analysis.

The second model (M2) imposed constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The discrimination parameters for items 7, 8, and 9 were restricted to be equal. In addition, the discrimination parameters for items 10 and 11 were restricted to be equal. Seven parameters (five b_j and two a_j) were estimated in the model. There were 16-(7+1)=8 df in the analysis. M1 and M2 were hierarchically related because M1 contained all of the parameters included in M2 plus additional parameters. Because the models were hierarchically related, they could be compared statistically. The difference L^2 for the comparison of M1 and M2 was 7.8 with 3 df ($p>.05$). M1 did not significantly improve on the fit afforded by M2. Because M2 was more parsimonious than M1 and M1 did not offer a significant improvement in fit, M2 was chosen over M1.

The third model (M3), the hypothesized model, constrained the discrimination parameters for all five items to be equal and allowed the difficulty parameters to be free to vary. Six parameters (one a_j and five b_j) were estimated in the model. There were 16-(6+1)=9 df in the model. Models M3 and M2 were hierarchically related and could be statistically compared. The difference L^2 for the comparison of M3 and M2 was 2.1 with 1 df ($p>.10$). M2 did not significantly improve on the fit afforded by M3. Because M3 was more parsimonious than M2 and M2 did not offer a significant improvement in fit, M3 was the chosen model.

Models 4, 5, and 6 included restrictions on the difficulty parameters and were developed to test hypotheses about the ordering of items according to their difficulty. In addition, each model restricted the discrimination parameters for the five items to be equal. M4 constrained the b_j parameters for items 7 and 8 to be equal. There were five parameters (one a_j and four b_j) estimated in the model. There were 16-(5+1)=10 df in the model. M4 was hierarchically related to M3 and the two models could be compared statistically. The difference L^2 for the comparison of M4 and M3 was 1.7 with 1 df ($p>.10$). This indicated that M3, the hypothesized model, did not improve significantly on the fit offered by M4. Because M4 was more parsimonious than M3 and M3 did not offer a significant improvement in fit, M4 was preferred over M3.

Model 5 constrained the b_j parameters for items 7, 8, and 9 to be equal. In addition, the b_j parameters of items 10 and 11 were restricted to be equal. There were three parameters (one a_j and two b_j) estimated in the model. There were 16-(3+1)=12 df in the model. M5 and M4 were hierarchically related. The difference L^2 for the comparison of M5 and M4 was 26.4 with 2 df (p<.01). M4 improved significantly on the fit offered by M5.

Model 6 constrained the b_j and a_j parameters for the five items to be equal. There were two parameters (one a_j and one b_j) estimated in the model. Therefore, there were 16-(2+1)=13 df in the model. Model 6 and Model 4 were hierarchically related. The difference L^2 for the comparison of M6 and M4 was 36.2 with 3 df (p<.01). Model 4 improved significantly on the fit offered by M6.

In this set of model comparisons, M4 was the preferred model, supporting the assumption that the five items in the standard design hierarchy related to the same degree to the underlying ability of design copying. Items 7 and 8 were the easiest items and were of equal difficulty. Items 9, 10, and 11 increased in difficulty in the hypothesized order. These results suggested that copying a vertical line was as difficult as copying a horizontal line for the age groups included in the study. Copying a cross and a square were of intermediate difficulty. Copying a triangle was the most difficult task.

Hierarchy 2 Model Comparison Results

In order to facilitate efficient data analysis, Hierarchy 2, the task representation hierarchy, was divided into two parts, Hierarchy 2A and 2B, for model comparison. The results are presented in Tables 10 through 13.

Hierarchy 2A Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 2A, the task representation hierarchy, are presented in Table 10 and 11, respectively. Score patterns and their respective observed and expected frequency counts are shown in Tables 28 and 29 in Appendix D. Hierarchy 2A included items 1, 2, 3, 4, and 5. The first model (M1) to be examined was the unrestricted two parameter model. Ten parameters (five a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was

Table 10

Hierarchy 2A Models and Estimated Parameters

Model	a1	a2	a3	a4	a5	b1	b2	b3	b4	b5	df
M1	3.03	3.55	7.06	3.54	4.89	-.65	-.23	.34	.45	.71	8
M2	3.33	3.89	5.28	3.33	3.89	-.67	-.28	.26	.42	.72	10
M3	4.02	4.02	4.02	3.64	3.64	-.68	-.32	.18	.37	.67	11
M4	3.85	3.85	3.85	3.85	3.85	-.67	-.31	.19	.39	.71	12
M5	3.89	3.89	3.89	3.89	3.89	-.64	-.31	.24	.75	.75	13
M6	3.82	3.82	3.82	3.82	3.82	-.66	-.29	.32	.32	.72	13
M7	3.78	3.78	3.78	3.78	3.78	-.49	-.49	.17	.37	.69	13
M8	2.37	2.37	2.37	2.37	2.37	.01	.01	.01	.01	.01	16

Table 11

Hierarchy 2A Model Comparisons

Models	df	Difference L^2	*p*
M1,M2	2	2.1	>.10
M2,M4	1	2.6	>.10
M3,M4	1	.2	>.10
M4,M5	1	6.9	<.01
M4,M6	1	7.7	<.01
M4,M7	1	27.9	<.001
M4,M8	3	373.4	<.001

nineteen. Therefore, there were 19-(10+1)=8 df in the model.

Models 2, 3, and 4 imposed various equality constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2) set the discrimination parameters for items 1 and 4 to be equal. In addition, the discrimination values for items 2 and 5 were set to be equal. Eight parameters (three a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was nineteen. Therefore, there were 19-(8+1)=10 df in the model. Because M1 contained all of the parameters of M2 plus additional parameters, the two models were compared statistically. The difference L^2 for the comparison of M2 and M1 was 2.1 with 2 df ($p>.10$). M1 did not significantly improve on the fit afforded by M2.

Model 4 (M4) constrained the discrimination parameters for all items to be equal. The difficulty parameters were free to vary. Six parameters (one a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was nineteen. Therefore, there were 19-(6+1)=12 df in the model. M2 and M4 were hierarchically related. The difference L^2 for the comparison of M2 and M4 was 2.6 with 1 df ($p>.10$). M2 did not significantly improve on the fit afforded by M4.

Model 3 (M3), the hypothesized model, constrained the discrimination parameters for items 1, 2, and 3 to be equal. In addition, the discrimination parameters for items 4 and 5 were constrained to be equal. The difficulty parameters were free to vary. Seven parameters (two a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was nineteen. Therefore, there were 19-(7+1)=11 df in the model. M3 and M4 were hierarchically related. The difference L^2 for the comparison of M3 and M4 was .2 with 1 df ($p>.10$). M3 did not improve significantly on the fit afforded by M4. Because M4 is more parsimonious than M3 and M3, the hypothesized model, did not offer a significant improvement in fit, M4 was chosen over M3.

Models 5, 6, 7, and 8 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the five items to be equal. Model 5 (M5) constrained the b_j parameters of items 4 and 5 to be equal. Five parameters (one a_j and four b_j) with

19-(5+1)=13 df were estimated in the model. M5 was hierarchically related to M4. The difference L^2 for the comparison of M4 and M5 was 6.9 with 1 df ($p<.01$). M4 improved significantly on the fit of M5.

Model 6 (M6) constrained the difficulty parameters of items 3 and 4 to be equal. The discrimination parameters were allowed to vary. Five parameters (one a_j and four b_j) with 19-(5+1)=13 df were estimated in the model. M6 was hierarchically related to M4. The difference L^2 for the comparison of M6 and M4 was 7.7 with 1 df ($p<.01$). M4 significantly improved on the fit of M6.

Model 7 (M7) constrained the difficulty parameters of items 1 and 2 to be equal. Five parameters (one a_j and four b_j) with 19-(5+1)=13 df were estimated in the model. M7 was hierarchically related to M4. The difference L^2 for the comparison of M7 and M4 was 27.9 with 1 df ($p<.01$). M4 significantly improved on the fit of M7.

Model 8 (M8) constrained the difficulty and discrimination parameters for the five items to be equal. Two parameters (one a_j and one b_j) with 19-(2+1)=16 df were estimated for the model. M8 and M4 were hierarchically related. The difference L^2 for the comparison of M8 and M4 was 373.4 with 3 df ($p<.01$). M4 significantly improved on the fit M8.

In this set of model comparisons, the hypothesized model, M3, was not the preferred model. Rather, M4 was the preferred model, supporting the hypothesis that the five items 1, 2, 3, 4, and 5 in Hierarchy 2A, the task representation hierarchy, were ordered by difficulty. For all designs, tracing was found to be easier than partial tracing. Squares were easier to trace than triangles which were easier to trace than diamonds. Partially tracing squares was the next most difficult task. Partially tracing triangles was the most difficult task.

This set of model comparisons did not support the hypothesis that the skills of tracing and partial tracing belonged in separate ability domains. Rather, the preferred model, M4, indicated that both skills relate to the same degree to the underlying ability of design copying.

Hierarchy 2B Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 2B, the task representation hierarchy, are shown in Tables 12 and 13, respectively. Score patterns and their respective observed and expected frequency counts are presented in Tables 30 and 31 in Appendix D. Hierarchy 2B included items 5, 6, 10, 11, and 12. The first model (M1) to be examined was the unrestricted two parameter model. Ten parameters (five a_j

Table 12

Hierarchy 2B Models and Estimated Parameters

Model	a1	a2	a3	a4	a5	b1	b2	b3	b4	b5	df
M1	4.22	7.22	3.90	3.84	2.64	.45	.53	.74	1.02	1.56	12
M2	3.76	3.29	4.11	3.76	3.29	.49	.64	.77	1.08	1.51	14
M3	5.29	5.29	3.10	3.10	3.10	.45	.55	.80	1.10	1.50	15
M4	3.49	3.49	3.49	3.49	3.49	.51	.65	.83	1.12	1.52	16
M5	3.55	3.55	3.55	3.55	3.55	.57	.57	.81	1.11	1.49	17
M6	3.33	3.33	3.33	3.33	3.33	.53	.67	.86	1.35	1.35	17
M7	2.59	2.59	2.59	2.59	2.59	1.01	1.01	1.01	1.01	1.01	20

Table 13

Hierarchy 2B Model Comparisons

Models	df	Difference L^2	*p*
M1,M2	2	3.4	>.10
M2,M4	2	2.4	>.10
M3,M4	1	.4	>.10
M4,M5	1	6.6	<.01
M4,M6	1	12.3	<.001
M4,M7	3	136.2	<.001

and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was 23. Therefore, there were 23-(10+1)=12 df in the model.

Models 2, 3, and 4 imposed various constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2) set the discrimination parameters for items 5 and 11 to be equal and the discrimination parameters for items 6 and 12 to be equal. Eight parameters (three a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was 23. Therefore, there were 23-(8+1)=14 df in the model. M2 and M1 were hierarchically related. The difference L^2 for the comparison of M1 and M2 was 3.4 with 2 df (p>.10). M1 did not significantly improve on the fit offered by M2. Because M2 is more parsimonious than M1 and M1 did not offer a significant improvement in fit, M2 was chosen over M1.

Model 4 (M4) constrained all discrimination parameters for the five items to be equal and allowed the difficulty parameters to be free to vary. Six parameters (one a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was 23. Therefore, there were 23-(6+1)=16 df in the model. M4 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M4 was 2.4 with 2 df (p>.10). M2 did not improve significantly on the fit afforded by M4.

Model 3 (M3), the hypothesized model, constrained the discrimination parameters for items 5 and 6 to be equal and constrained the discrimination parameters of items 10, 11, and 12 to be equal. The difficulty parameters were allowed to vary. Seven parameters (two a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was 23. Therefore, there were 23-(7+1)=15 df in the model. Models M4 and M3 were hierarchically related. The difference L^2 for the comparisons of M3 and M4 was .4 with 1 df (p>.10). M3 did not offer a significant improvement in fit over M4.

Models 5, 6, and 7 included restrictions on the difficulty parameters designed to test hypotheses about the ordering of items according to their difficulty levels. In addition, these models restricted the discrimination parameters for the five items to be equal. Model 5 (M5) constrained the difficulty parameters for items 5 and 6 to be equal. Five parameters (one a_j and four b_j) with 23-(5+1)=17 df were estimated for M5. Models M5 and M4 were hierarchically related. The difference L^2 for the comparison of M5 and M4 was 6.6 with 1 df ($p<.01$). M4 offered a significant improvement in fit over M5.

Model 6 (M6) constrained the difficulty parameters for items 10 and 11 to be equal. Five parameters (one a_j and four b_j) with 23-(5+1)=17 df were estimated for the model. Models M6 and M4 were hierarchically related. The difference L^2 for the comparison of M4 and M6 was 12.3 with 1 df ($p<.01$). M4 offered a significant improvement in fit over M6.

Model 7 constrained the difficulty and discrimination parameters for the five items to be equal. Two parameters (one a_j and one b_j) with 23-(2+1)=20 df were estimated in the model. M7 and M4 were hierarchically related. The difference L^2 for the comparison of M4 and M7 was 136.2 with 3 df ($p<.01$). Model 4 significantly improved on the fit offered by M8.

In this set of model comparisons, M4 was the preferred model, supporting the hypothesis that items 5, 6, 10, 11, and 12 in Hierarchy 2B, the task representation hierarchy, were ordered by difficulty in the order presented. Partial tracing was found to be easier than free-hand copying. Triangles were easier to partially trace than were diamonds. The item next in difficulty, copying a square, was easier than copying a triangle. Copying a triangle was easier than copying a diamond.

This set of model comparisons did not support the hypothesis that the skills of partially tracing and copying belong in different domains. Rather, the preferred model, M4, indicated that both skills relate to the same degree to the underlying ability of design copying.

Hierarchy 3 Model Comparison Results

In order to facilitate efficient data analysis, Hierarchy 3, the spatial orientation hierarchy, was divided into two parts, Hierarchy 3A and 3B, for model comparison. The results are presented in Tables 14 through 17.

Hierarchy 3A Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 3A, the spatial orientation hierarchy, are presented in Tables 14 and 15, respectively. Score patterns and their respective observed and expected frequency counts are presented in Tables 32 and 33 in Appendix D. Hierarchy 3A included items 13, 14, 17, and 18. The first model (M1) to be examined was the unrestricted two parameter model. Eight parameters (four a_j and four b_j) were estimated in the model. There were sixteen possible score patterns in the analysis.

Table 14

Hierarchy 3A Models and Estimated Parameters

Model	a1	a2	a3	a4	b1	b2	b3	b4	df
M1	1.76	1.75	3.42	2.23	-.84	-.44	-.31	-.24	7
M2	1.76	1.76	2.63	2.63	-.85	-.44	-.32	-.23	9
M3	2.38	2.01	2.38	2.01	-.75	-.42	-.32	-.25	9
M4	2.16	2.16	2.16	2.16	-.78	-.41	-.33	-.24	10
M5	2.12	2.12	2.12	2.12	-.59	-.59	-.24	-.33	11
M6	2.16	2.16	2.16	2.16	-.41	-.78	-.29	-.29	11
M7	2.07	2.07	2.07	2.07	-.41	-.51	-.51	-.33	11
M8	2.05	2.05	2.05	2.05	-.44	-.44	-.44	-.44	13

Table 15

Hierarchy 3A Model Comparisons

Models	df	Difference L^2	p
M1,M2	2	1.8	>.10
M2,M4	1	3.1	>.05
M3,M4	1	.9	>.10
M4,M5	1	13.7	<.001
M4,M6	1	20.8	<.001
M4,M7	1	29.3	<.001
M4,M8	3	33.5	<.001

The number of score patterns with observed counts greater than zero was also sixteen. Therefore, 16-(8+1)=7 df were in the model.

Models 2, 3, and 4 imposed various equality constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2) set the discrimination parameters for items 13 and 14 to be equal. In addition, the discrimination values for items 17 and 18 were set to be equal. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. Because M1 contained all of the parameters of M2 plus additional parameters, the two models were compared statistically. The difference L^2 for the comparison of M2 and M1 was 1.8 with 2 df ($p > .10$). M1 did not significantly improve on the fit afforded by M2.

Model 4 (M4), the hypothesized model, constrained the discrimination parameters for all items to be equal. The difficulty parameters were free to vary. Five parameters (one a_j and four b_j) with 16-(5+1)=10 df were estimated in the model. M2 and M4 were hierarchically related. The difference L^2 for the comparison of M2 and M4 was 3.1 with 1 df ($p > .10$). M2 did not significantly improve on the fit afforded by M4.

Model 3 (M3), constrained the discrimination parameters for items 13 and 17 to be equal. In addition, the discrimination parameters for items 14 and 18 were constrained to be equal. The difficulty parameters were free to vary. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. M3 and M4 were hierarchically related. The difference L^2 for the comparison of M3 and M4 was .9 with 1 df ($p > .10$). M3 did not significantly improve on the fit afforded by M4.

Models 5, 6, 7, and 8 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the four items to be equal. Model 5 (M5) constrained the b_j parameters of items 13 and 14 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M5 was hierarchically related to M4. The difference L^2 for the comparison of M4 and M5 was 13.7 with 1 df ($p < .01$). M4 improved significantly on the fit of M5.

Model 6 (M6) constrained the difficulty parameters of items 17 and 18 to be equal. The discrimination parameters were allowed to vary. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M6 was hierarchically related to M4. The difference L^2 for the comparison of M6 and M4 was 20.8 with

1 df ($p<.01$). M4 significantly improved on the fit offered by M6.

Model 7 (M7) constrained the difficulty parameters of items 14 and 17 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M7 was hierarchically related to M4. The difference L^2 for the comparison of M7 and M4 was 29.3 with 1 df ($p<.01$). M4 significantly improved on the fit of M7.

Model 8 (M8) constrained the difficulty and discrimination parameters for the four items to be equal. Two parameters (one a_j and one b_j) with 16-(2+1)=13 df were estimated for the model. M8 and M4 were hierarchically related. The difference L^2 for the comparison of M8 and M4 was 33.5 with 3 df ($p<.01$). M4 significantly improved on the fit afforded by M8.

In this set of model comparisons, M4 was the preferred model, supporting the hypothesis that the four items 13, 14, 17, and 18 in Hierarchy 3A, the spatial orientation hierarchy, were ordered by difficulty in the hypothesized sequence. Items in the "correct" orientation were easier to copy than those in the "incorrect" orientation. The preferred model, M4, also supported the hypothesis that the skills related to the same degree to the underlying ability of design copying.

Hierarchy 3B Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 3B, the spatial orientation hierarchy, are presented in Tables 16 and 17, respectively. Score patterns and their respective observed and expected frequency counts are presented in Tables 34 and 35 in Appendix D. Hierarchy 3B included items 15, 16, 19, and 20. The first model (M1) to be examined was the unrestricted two parameter model. Eight parameters (four a_j and four b_j) were estimated in the model. There were sixteen possible score patterns in this analysis. The number of score patterns with observed counts greater than zero was also sixteen. Therefore, 16-(8+1)=7 df were in the model.

Models 2, 3, and 4 imposed various equality constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2) set the discrimination parameters for items 15 and 16 to be equal. In addition, the discrimination values for items 19 and 20 were set to be equal. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. Because M1 contained all of the parameters of M2 plus additional parameters, the two models were compared statistically. The difference L^2 for the comparison of M2

Table 16

Hierarchy 3B Models and Estimated Parameters

Model	a1	a2	a3	a4	b1	b2	b3	b4	df
M1	2.78	2.53	2.72	2.76	.39	.17	.44	.47	7
M2	2.64	2.64	2.73	2.73	.39	.16	.43	.47	9
M3	2.74	2.62	2.74	2.62	.39	.16	.43	.48	9
M4	2.68	2.68	2.68	2.68	.38	.16	.43	.47	10
M5	2.68	2.68	2.68	2.68	.39	.16	.45	.45	11
M6	2.65	2.65	2.65	2.65	.28	.28	.44	.48	11
M7	2.63	2.63	2.63	2.63	.39	.30	.30	.47	11
M8	2.61	2.61	2.61	2.61	.37	.37	.37	.37	13

Table 17

Hierarchy 3B Model Comparisons

Models	df	Difference L^2	*p*
M1,M2	2	.1	>.10
M2,M4	1	.1	>.10
M3,M4	1	.1	>.10
M4,M5	1	7.1	<.01
M4,M6	1	7.2	<.01
M4,M7	1	10.5	<.01
M4,M8	3	16.3	<.001

and M1 was .1 with 2 df ($\underline{p}$>.10). M1 did not significantly improve on the fit afforded by M2.

Model 4 (M4), the hypothesized model, constrained the discrimination parameters for all items to be equal. The difficulty parameters were free to vary. Five parameters (one a_j and four b_j) with 16-(5+1)=10 df were estimated in the model. M2 and M4 were hierarchically related. The difference L^2 for the comparison of M2 and M4 was .1 with 1 df ($\underline{p}$>.10). M2 did not significantly improve on the fit afforded by M4.

Model 3 (M3), constrained the discrimination parameters for items 15 and 19 to be equal. In addition, the discrimination parameters for items 16 and 20 were constrained to be equal. The difficulty parameters were free to vary. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. M3 and M4 were hierarchically related. The difference L^2 for the comparison of M3 and M4 was .1 with 1 df ($\underline{p}$>.10). M3 did not significantly improve on the fit afforded by M4.

Models 5, 6, 7, and 8 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the four items to be equal. Model 5 (M5) constrained the b_j parameters of items 19 and

20 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M5 was hierarchically related to M4. The difference L^2 for the comparison of M4 and M5 was 7.1 with 1 df ($p<.01$). M4 improved significantly on the fit of M5.

Model 6 (M6) constrained the difficulty parameters of items 15 and 16 to be equal. The discrimination parameters were allowed to vary. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M6 was hierarchically related to M4. The difference L^2 for the comparison of M6 and M4 was 7.2 with 1 df ($p<.01$). M4 significantly improved on the fit of M6.

Model 7 (M7) constrained the difficulty parameters of items 16 and 19 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M7 was hierarchically related to M4. The difference L^2 for the comparison of M7 and M4 was 10.5 with 1 df ($p<.01$). M4 significantly improved on the fit offered by M7.

Model 8 (M8) constrained the difficulty and discrimination parameters for the four items to be equal. Two parameters (one a_j and one b_j) with 16-(2+1)=13 df were estimated for the model. M8 and M4 were hierarchically related. The difference L^2 for the comparison of M8 and M4 was 16.3 with 3 df ($p<.01$). M4 significantly improved on the fit of M8.

In this set of model comparisons, M4 was the preferred model, supporting the hypothesis that the four items 15, 16, 19, and 20 in Hierarchy 3B, the spatial orientation hierarchy, were ordered by difficulty in the hypothesized sequence. Items in the "correct" orientation were easier to copy than those in the "incorrect" orientation. The preferred model, M4, also supported the hypothesis that the skills related to the same degree to the underlying ability of design copying.

Hierarchy 4 Model Comparison Results

In order to facilitate efficient data analysis, Hierarchy 4, the angles hierarchy, was divided into three parts, Hierarchy 4A, 4B, and 4C, for model comparison. The results are presented in Tables 18 through 22.

Hierarchy 4A Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 4A, the angles hierarchy, are presented in Tables 18 and 19, respectively. Score patterns and their respective observed and expected frequency counts are shown in Tables 36 and 37 in Appendix D. Hierarchy 4A included items 14, 21, 22, and 23.

Table 18

Hierarchy 4A Models and Estimated Parameters

Model	a1	a2	a3	a4	b1	b2	b3	b4	df
M1	1.35	3.13	4.54	2.27	-.95	-.26	-.27	.13	7
M2	1.35	3.15	4.32	2.27	-.95	-.26	-.27	.13	8
M3	2.22	2.68	2.22	2.68	-.73	-.24	-.26	.13	8
M4	2.08	2.08	2.92	2.92	-.76	-.26	-.26	.13	9
M5	2.49	2.49	2.49	2.49	-.70	-.24	-.25	.13	10
M6	2.17	2.17	2.17	2.17	-.28	-.28	-.28	-.28	13

Table 19

Hierarchy 4A Model Comparisons

Models	df	Difference L^2	p
M1,M2	1	.2	>.10
M2,M4	1	20.0	<.001
M3,M4	1	.5	>.10
M2,M5	2	23.8	<.001
M2,M6	5	109.4	<.001

The first model (M1) to be examined was the unrestricted two parameter model. Eight parameters (four a_j and four b_j) were estimated in the model. There were sixteen possible score patterns in this analysis. The number of score patterns with observed counts greater than zero was also sixteen. Therefore, there were 16-(8+1)=7 df in the model.

Models 2 and 3 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to difficulty. The second model (M2) set the difficulty parameters of items 21 and 22 to be equal. The discrimination parameters were allowed to vary. Seven parameters (4a_j and 3 b_j) with 16-(7+1)=8 df were estimated in the model. M2 and M1 were hierarchically related. The difference L^2 for the comparison of M1 and M2 was .2 with 1 df ($\underline{p}>.10$). M1 did not significantly improve on the fit afforded by M2.

Model 4 (M4), the hypothesized model, constrained the discrimination parameters for items 14 and 22 to be equal. In addition, the discrimination parameters for items 21 and 23 were constrained to be equal. The difficulty parameters were free to vary. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. M4 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M4 was 20.0 with

1 df ($p<.01$). M2 significantly improved on the fit afforded by M4.

Model 3 (M3) constrained the b_j parameters of items 14 and 21 to be equal. The discrimination parameters were free to vary. Seven parameters (four a_j and three b_j) with 16-(7+1)=8 df were estimated in the model. M3 was hierarchically related to M4. The difference L^2 for the comparison of M31 and M4 was .5 with 1 df ($p>.10$). M3 did not improve significantly on the fit of M4. Because M2 was chosen over M4 in the last model comparison, M2 will be preferred over M4.

Model 5 (M5) constrained the discrimination parameters for all items to be equal. The difficulty parameters were free to vary. Five parameters (one a_j and four b_j) with 16-(5+1)=10 df were estimated in the model. M5 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M5 was 23.8 with 2 df ($p<.01$). M2 significantly improved on the fit afforded by M5.

Model 6 (M6) constrained the difficulty and discrimination parameters for the four items to be equal. Two parameters (one a_j and one b_j) with 16-(2+1)=13 df were estimated for the model. M6 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M6 was 109.4 with 5 df ($p<.01$). M2 significantly improved on the fit offered by M6.

In this set of model comparisons the hypothesized model, M4 was not the preferred model. Rather, the preferred model was M2. The hypothesis that items 14, 21, 22, and 23 in the angles hierarchy were ordered by difficulty in the hypothesized sequence was partially supported. Item 14, the vertical baseline with a perpendicular bisector, was the least difficult item. Drawing a vertical baseline with an oblique bisector and drawing a horizontal baseline with a perpendicular bisector were of equal difficulty. The horizontal baseline with an oblique bisector was most difficult. The hypothesis that items 14 and 21, both of which contained vertical baselines, belonged to the same domain was not supported. Similarly, the hypothesis that designs 22 and 23, both of which contained horizontal baselines, belonged to the same domain was not supported.

Hierarchy 4B Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 4B, the angle hierarchy, are presented in Tables 20 and 21, respectively. Score patterns and their respective observed and expected frequency counts are shown in Tables 38 and 39 in Appendix D. Hierarchy 4B included items 14, 21, 24, and 25. The first model (M1) to be examined was the unrestricted two parameter model. Eight parameters (four a_j and four b_j)

Table 20

Hierarchy 4B Models and Estimated Parameters

Model	a1	a2	a3	a4	b1	b2	b3	b4	df
M1	1.30	2.36	2.56	2.72	-1.01	-.30	.30	.59	7
M2	1.74	1.74	2.70	2.70	-.88	-.33	.29	.58	9
M3	2.18	2.18	2.18	2.18	-.80	-.32	.30	.62	10
M4	2.11	2.11	2.11	2.11	-.56	-.56	.30	.62	11
M5	2.12	2.12	2.12	2.12	-.82	-.31	.46	.46	11
M6	2.02	2.02	2.02	2.02	-.82	-.01	-.01	.64	11
M7	1.54	1.54	1.54	1.54	-.04	-.04	-.04	-.04	13

Table 21

Hierarchy 4B Model Comparisons

Models	df	Difference L^2	p
M1,M2	2	5.9	>.05
M2,M3	1	3.7	>.05
M3,M4	1	24.4	<.001
M3,M5	1	10.2	<.01
M3,M6	1	41.1	<.001
M3,M7	3	22.8	<.001

were estimated in the model. There were sixteen possible score patterns in this analysis. The number of score patterns with observed counts greater than zero was also sixteen. Therefore, there were 16-(8+1)=7 df in the model.

Models 2 and 3 imposed various equality constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2), the hypothesized model, set the discrimination parameters for items 14 and 21 to be equal. In addition, the discrimination values for items 24 and 25 were set to be equal. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. Because M1 contained all of the parameters of M2 plus additional parameters, the two models were compared statistically. The difference L^2 for the comparison of M2 and M1 was 5.9 with 2 df (p>.05). M1 did not significantly improve on the fit afforded by M2.

Model 3 (M3), constrained the discrimination parameters for the four items to be equal. The difficulty parameters were free to vary. Five parameters (one a_j and four b_j) with 16-(5+1)=10 df were estimated in the model. M3 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M3 was 3.7 with 1 df (p>.05). M2 did not significantly improve on the fit afforded by M3.

Models 4, 5, 6, and 7 included restrictions on the Models 5, 6, 7, and 8 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the four items to be equal. Model 4 (M4) constrained the b_j parameters of items 14 and 21 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M4 was hierarchically related to M3. The difference L^2 for the comparison of M3 and M4 was 24.4 with 1 df ($p<.01$). M3 improved significantly on the fit of M4.

Model 5 (M5) constrained the difficulty parameters of items 24 and 25 to be equal. The discrimination parameters were allowed to vary. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M5 was hierarchically related to M3. The difference L^2 for the comparison of M5 and M3 was 10.2 with 1 df ($p<.01$). M3 significantly improved on the fit of M5.

Model 6 (M6) constrained the difficulty parameters of items 21 and 24 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M6 was hierarchically related to M3. The difference L^2 for the comparison of M6 and M3 was 41.1 with 1 df ($p<.01$). M3 significantly improved on the fit offered by M6.

Model 7 (M7) constrained the difficulty and discrimination parameters for the four items to be equal. Two parameters (one a_j and one b_j) with 16-(2+1)=13 df were estimated for the model. M7 and M3 were hierarchically related. The difference L^2 for the comparison of M7 and M3 was 22.8 with 3 df ($p<.01$). M3 significantly improved on the fit offered by M7.

In this set of model comparisons, M3 was the preferred model, supporting the hypothesis that the four items 14, 21, 24, and 25 in Hierarchy 4B, the angle hierarchy, were ordered by difficulty in the hypothesized sequence. Item 14, the vertical baseline with a perpendicular bisector, was the easiest item. Item 21, the vertical baseline with an oblique bisector was more difficult than item 14. Item 24, the oblique baseline with a perpendicular bisector was the next most difficult item. Finally, the oblique baseline with an oblique bisector was the most difficult to copy.

The preferred model, M3, did not support the hypothesis that designs with vertical and oblique baselines were in different domains. All items were found to relate to the same degree to the underlying design copying ability.

Hierarchy 4C Model Comparisons

The item parameter estimates and results of the model comparisons for Hierarchy 4C, the angle hierarchy, are presented in Tables 22 and 23, respectively. Score patterns and their observed and expected frequency counts are shown in Tables 40 and 41 in Appendix D. Hierarchy 4C included items 22, 23, 24, and 25. The first model (M1) to be examined was the unrestricted two parameter model. Eight parameters (four a_j and four b_j) were estimated in the model. There were 16 possible score patterns in this analysis. The number of score patterns with observed counts greater than zero was also sixteen. Therefore, there were 16-(8+1)=7 df in the model.

Models 2 and 3 imposed various equality constraints on the discrimination parameters and allowed the difficulty parameters to be free to vary. The second model (M2), the hypothesized model, set the discrimination parameters for items 22 and 23 to be equal. In addition, the discrimination values for items 24 and 25 were set to be equal. Six parameters (two a_j and four b_j) with 16-(6+1)=9 df were estimated in the model. Because M1 contained all of the parameters of M2 plus additional parameters, the two models were compared statistically. The difference L^2 for the comparison of M2 and M1 was 2.9 with 2 df ($p > .10$). M1 did not significantly improve on the fit afforded by M2.

Table 22

Hierarchy 4C Models and Estimated Parameters

Model	a1	a2	a3	a4	b1	b2	b3	b4	df
M1	2.02	4.18	2.46	2.63	-.30	.07	.40	.68	7
M2	2.72	2.72	2.58	2.58	-.30	.07	.38	.67	9
M3	2.65	2.65	2.65	2.65	-.29	.08	.38	.67	10
M4	2.56	2.56	2.56	2.56	-.13	-.13	.37	.67	11
M5	2.62	2.62	2.62	2.62	-.29	.08	.52	.52	11
M6	2.63	2.63	2.63	2.63	-.30	.29	.29	.64	11
M7	2.17	2.17	2.17	2.17	.19	.19	.19	.19	13

Table 23

Hierarchy 4C Model Comparisons

Models	df	Difference L^2	*p*
M1,M2	2	2.9	>.10
M2,M3	1	.1	>.02
M3,M4	1	19.6	<.001
M3,M5	1	10.9	<.001
M3,M6	1	16.9	<.001
M3,M7	3	131.0	<.001

Model 3 (M3), constrained the discrimination parameters for the four items to be equal. The difficulty parameters were free to vary. Five parameters (one a_j and four b_j) with 16-(5+1)=10 df were estimated in the model. M3 and M2 were hierarchically related. The difference L^2 for the comparison of M2 and M3 was .1 with 1 df ($p > .10$). M2 did not significantly improve on the fit afforded by M3.

Models 4, 5, 6, and 7 placed restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the four items to be equal. Model 4 (M4) constrained the b_j parameters of items 22 and 23 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M4 was hierarchically related to M3. The difference L^2 for the comparison of M3 and M4 was 19.6 with 1 df ($p < .01$). M3 improved significantly on the fit of M4.

Model 5 (M5) constrained the difficulty parameters of items 24 and 25 to be equal. The discrimination parameters were allowed to vary. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M5 was hierarchically related to M3. The difference L^2 for the comparison of M5 and M3 was 10.9 with 1 df ($p < .01$). M3 significantly improved on the fit of M5.

Model 6 (M6) constrained the difficulty parameters of items 23 and 24 to be equal. Four parameters (one a_j and three b_j) with 16-(4+1)=11 df were estimated in the model. M6 was hierarchically related to M3. The difference L^2 for the comparison of M6 and M3 was 16.9 with 1 df ($p<.01$). M3 significantly improved on the fit of M6.

Model 7 (M7) constrained the difficulty and discrimination parameters for the four items to be equal. Two parameters (one a_j and one b_j) with 16-(2+1)=13 df were estimated for the model. M7 and M3 were hierarchically related. The difference L^2 for the comparison of M7 and M3 was 131 with 3 df ($p<.01$). M3 significantly improved on the fit afforded by M7.

In this set of model comparisons, M3 was the preferred model, supporting the hypothesis that the four items 22, 23, 24, and 25 in Hierarchy 4B, the angle hierarchy, were ordered by difficulty in the hypothesized sequence. Item 22, the horizontal baseline with a perpendicular bisector, was the easiest item. Item 23, the horizontal baseline with an oblique bisector was more difficult than item 22. Item 24, the oblique baseline with a perpendicular bisector was the next most difficult item. Finally, the oblique baseline with an oblique bisector was the most difficult to copy.

The preferred model, M3, did not support the hypothesis that designs with horizontal and oblique baselines were in different domains. All items were found to relate to the same degree to the underlying design copying ability.

Hierarchy 5 Model Comparison Results

The item parameter estimates and results of the model comparisons for Hierarchy 5, the stimulus complexity hierarchy, are presented in Table 24 and 25, respectively. Score patterns and their observed and expected frequency counts are shown in Tables 42 and 43 in Appendix D. Hierarchy 5 included items 13, 15, 20, 10, and 11. The first model (M1) to be examined was the unrestricted two parameter model. Ten parameters (five a_j and five b_j) were estimated in the model. There were 32 possible score patterns in this analysis. However, the number of score patterns with observed counts greater than zero was 26. Therefore, there were 26-(10+1)=15 df in the model.

Model 2 (M2), the hypothesized model, constrained the discrimination parameters for all items to be equal. The difficulty parameters were free to vary. Six parameters (one a_j and five b_j) with 26-(6+1)=19 df were estimated in the model. M2 and M1 were hierarchically related. The difference L^2 for the comparison of M2 and M1

Table 24

<u>Hierarchy 5 Models and Estimated Parameters</u>

Model	a1	a2	a3	a4	a5	b1	b2	b3	b4	b5	df
M1	1.55	1.87	3.89	2.18	3.12	-.46	.37	.47	.84	1.18	15
M2	2.12	2.12	2.12	2.12	2.12	-.42	.34	.47	1.06	1.38	19
M3	2.10	2.10	2.10	2.10	2.10	-.41	.41	.47	1.07	1.39	20
M4	2.10	2.10	2.10	2.10	2.10	-.42	.34	.47	1.21	1.21	20
M5	2.12	2.12	2.12	2.12	2.12	-.42	.40	.40	1.06	1.38	20
M6	1.42	1.42	1.42	1.42	1.42	.63	.63	.63	.63	.63	23

Table 25

Hierarchy 5 Model Comparisons

Models	df	Difference L^2	p
M1,M2	4	5.7	>.10
M2,M3	1	57.6	<.01
M2,M4	1	6.7	<.01
M2,M5	1	1.8	>.10
M5,M6	3	316.1	<.01

was 5.7 with 4 df ($p > .10$). M1 did not significantly improve on the fit afforded by M2.

Models 3, 4, 5, and 6 included restrictions on the difficulty parameters and were included to test hypotheses about the ordering of items according to their difficulty values. In addition, each model restricted the discrimination parameters for the five items to be equal. Model 3 (M3) constrained the b_j parameters of items 13 and 15 to be equal. Five parameters (one a_j and four b_j) with 26-(5+1)=20 df were estimated in the model. M3 was hierarchically related to M2. The difference L^2 for the comparison of M2 and M3 was 57.6 with 1 df ($p < .01$). M2 significantly improved on the fit offered by M3 in this comparison.

Model 4 (M4) constrained the difficulty parameters of items 10 and 11 to be equal. The discrimination parameters were allowed to vary. Five parameters (one a_j and four b_j) with 26-(5+1)=20 df were estimated in the model. M2 was hierarchically related to M4. The difference L^2 for the comparison of M2 and M4 was 6.7 with 1 df ($p < .01$). M2 significantly improved on the fit of M4.

Model 5 (M5) constrained the difficulty parameters of items 15 and 20 to be equal. Five parameters (one a_j and four b_j) with 26-(5+1)=20 df were estimated in the model. M5 was hierarchically related to M2. The difference L^2 for the comparison of M5 and M2 was 1.8 with 1 df ($p>.10$). M2 did not improve significantly on the fit offered by M5.

Model 6 (M6) constrained the difficulty and discrimination parameters for the five items to be equal. Two parameters (one a_j and one b_j) with 26-(2+1)=23 df were estimated for the model. M6 and M5 were hierarchically related. The difference L^2 for the comparison of M6 and M5 was 316.1 with 3 df ($p<.01$). M5 significantly improved on the fit M6.

In this set of model comparisons, the hypothesized model, M2, was not the preferred model. Rather, M5 was the preferred model, partially supporting the hypothesis that the five items in Hierarchy 5, the stimulus complexity hierarchy, were ordered by difficulty in the hypothesized sequence. Item 13, the L-shaped design, was the easiest design. Items 15 and 20, the rectilinear U-shape and V-shape, were of equal difficulty, contrary to the hypothesized order. Item 10, the square, was more difficult. Finally, Item 11, the triangle, was the most difficult. Consistent with predictions, the preferred model, M2, indicated that all skills related to the same degree to the underlying ability of design copying.

CHAPTER 5

DISCUSSION

The present study was an attempt to establish hierarchical skill sequences in the design copying area. Based on age-related norms, previous research in the design copying domain has suggested the possible presence of a general hierarchical skill sequence in the domain (Laszlo & Bairstow, 1985). However, the sources of variation that might lead to differential design difficulty have not been systematically explored.

The current investigation focused on three sources of variation in hierarchical structuring in order to more precisely delineate the design copying domain. The first source of variation involved an exploration of the application of starting and progression rules across a variety of designs. A second source of hierarchical variation focused on the structuring of responses through the provision of visual clues. The third source of variation in hierarchical structuring involved the delineation of several stimulus dimensions that might lead to differential performance across designs. Five hierarchies with items based on these sources of variation in hierarchical structuring were developed.

The hypothesized skill orderings within each hierarchy were validated through the use of probabilistic models (i.e., latent trait models). It has been suggested that latent trait models are suitable for validating cognitive skill sequences (Bergan & Stone, 1985). In the present study, the visual-motor task of design copying was conceptualized as a problem-solving, rule-governed activity that might be analyzed in a similar manner. Hypothesized latent trait models were statistically compared to alternative models that placed various restrictions on the difficulty and discrimination parameters of each item within the hierarchy. A preferred model was then determined for each of the hierarchical skill sequences. Hypotheses about skill orderings were analyzed in this manner.

Hierarchy 1 was developed to explore the concept of design copying as rule-governed behavior. From this perspective, the paths children use when copying designs were described in terms of a limited set of rules that specified the procedures necessary for accurate performance. Starting and progression rules for standard geometric shapes were delineated based on rule-following behaviors that were observed by previous researchers (Rand, 1973; Goodnow & Levine, 1974). The hypothesized model assumed that designs in which standard starting and progression rules could be followed would be the easiest items. More complex designs (i.e., designs that inherently included conflicts between starting and progression rules) would be of intermediate difficulty. The most difficult designs were expected to be those in which accurate copying necessitated replacing standard rules with more flexible rule application.

In the set of model comparisons based on this hierarchy, the preferred model provided general support for the hypotheses regarding rule usage. Obtained results suggested that the items involving the free-hand copying of vertical lines and horizontal lines were equivalent items. These designs followed standard starting rules. Interestingly, the notion that young children have a tendency to "verticalize" horizontal lines was not supported. It might be argued that the inclusion of a wide age range in this study may have masked the verticalization tendency found in very young children. However, a visual analysis of protocols of the youngest examinees (Kindergarten students) provided no evidence of such a tendency at this age. The verticalization tendency may only be found in younger, preschool-aged children.

As hypothesized, the cross and square were ordered in difficulty and were of intermediate difficulty. These designs each contained a starting rule conflict (i.e., starting at the left-most point and starting at the top-most point). Clearly, the copying task becomes more difficult when there is a conflict in standard rule application. In addition, the copying task is more difficult when the standard rules must be replaced by alternate copying routes while copying the apexes in the triangle and a diamond (Note: this relationship was observed in Hierarchy 2).

Hierarchy 2 was developed to test hypotheses concerning the provision of alternative task representations. Based on previous research (Birch & Lefford, 1967), it was proposed that the provision of visual clues on examinee response sheets might lead to variations in task difficulty. The copying of a shape on a blank space versus copying on a space containing visual clues might necessitate the use of different response strategies for task completion and a concomitant change in task complexity. As predicted, tracing was the easiest task regardless of the geometric design under analysis. Provision of partial visual clues led to tasks of intermediate difficulty. Finally, free-hand copying was significantly more difficult. These results were consistent across age levels and indicated that all items related to the same degree to the domain under study.

The Hierarchy 2 model testing results contradict the suggestion made by previous researchers (e.g., Hirsch & Niedermeyer, 1973) that tracing may actually cause negative transfer in copying tasks. The current results indicate that tracing may be part of a natural progression in the development of graphic copying skills. The provision of visual clues may place less demands on the performer, facilitating accurate performance. The use of tracing in an instructional program to provide positive transfer to more complex tasks should be the focus of future research.

A number of previous investigations have focused on analyses of pertinent stimulus dimensions of geometric designs (Eldred, 1973; Ibbotson & Bryant, 1976). There is considerable debate concerning the differential difficulty of stimulus dimensions such as spatial orientation, angulation, and stimulus complexity. For example, it has been observed that young children make frequent orientation errors in their drawings (Goodnow, Young, & Kvan, 1976). Several authors have suggested that orientation errors may result from a figure being copied in terms of its perceived "right-side-up" orientation rather than the correct orientation (Eldred, 1971; Serpell, 1973).

Items for Hierarchy 3 were developed to test hypotheses concerning spatial orientation. The model testing for this hierarchy indicated that items provided in the perceived right-side-up orientation (as based on previous research) were significantly easier to copy than were those presented in the perceived up-side-down orientation. For example, the L-shaped figure was easier to copy than the inverted L-shaped figure. A visual analysis of examinee responses did not lend credence to the presence of orientation errors, however. In no instance did examinees' inaccurate copies of up-side-down orientations involve rotation errors. Rather, the cause of observed errors appeared to be more consistent with the previous discussion of rule application complexity. Items with few rule-related conflicts and less stimulus complexity (e.g., the L-shaped figure and the V-shaped figure) were drawn more accurately and were easier items. Items with starting and progression rule conflicts (e.g., the rectilinear U-shaped figure and the inverted L-shaped figure) were more difficult. Contrary to expectations, items with standard and inverted orientations were related to the same degree to the underlying ability.

Hierarchy 4 was developed to test hypotheses concerning the presence of right and oblique angles in a drawing system. Past research has consistently demonstrated that oblique angles are more difficult to copy than right angles (Bremner & Taylor, 1981). The effect of the spatial orientation of the baseline from which the bisector extends is not completely understood, however. The model testing for Hierarchy 4 provides a partial analysis of the role of baseline orientation in the differential difficulty of copying angles.

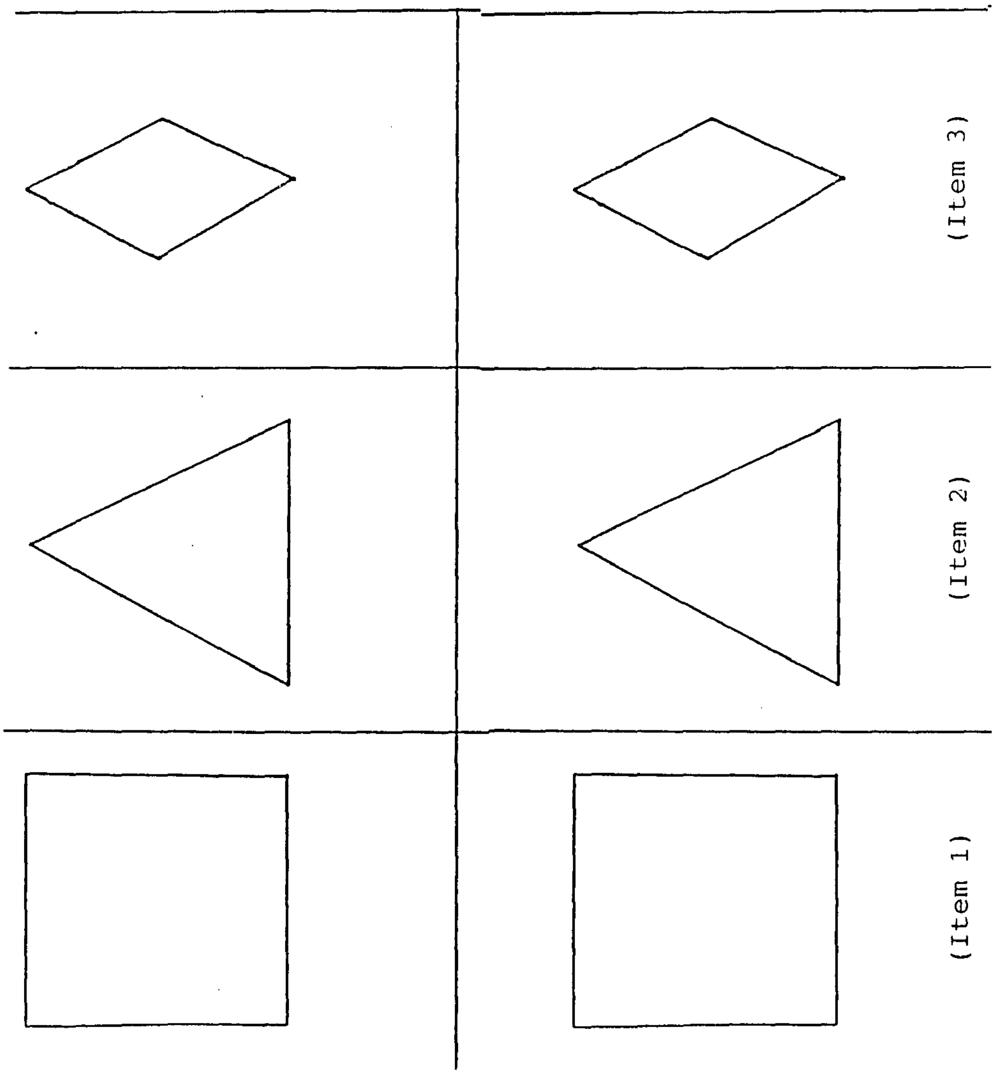
As expected, items containing vertical baselines were the easiest items whether or not the item had a perpendicular or oblique bisector. Items with oblique baselines were extremely difficult for all subjects. It is clear that children do tend to organize their responses around the vertical axis; a visual analysis of examinee responses suggested that inaccuracies in the copying of oblique baselines derived from a tendency toward verticalization. As hypothesized, within each baseline type, designs with right angle-perpendicular bisectors were easier to reproduce than were designs with 45^{o} angle-oblique bisectors. Consistent with previous research, these results support the contention that the switch from a vertical-perpendicular to an oblique-oblique drawing system constitutes a major milestone in the development of graphic copying skills.

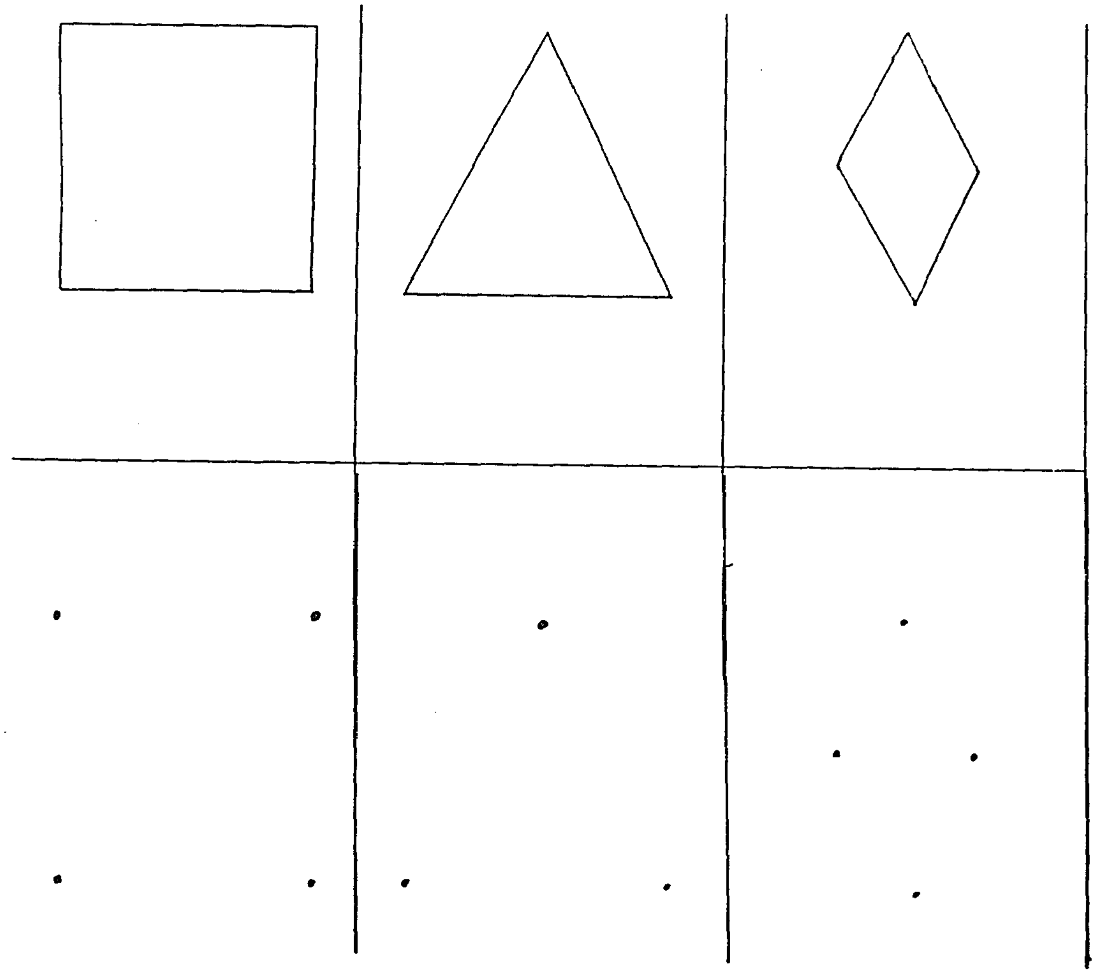
Hierarchy five was developed to test hypotheses regarding the effects of stimulus complexity on differential item difficulty. The model testing for Hierarchy 5 provided partial support for the suggestion that the addition of linear components (e.g., the addition of a vertical line to the L-shaped figure to transform it to the rectilinear U-shaped figure) increases task difficulty. Interestingly, the item involving the V-shaped figure and the item involving the rectilinear U-shape were of equal difficulty. This suggests that the inclusion of an additional linear component in an item and the inclusion of an acute angle in an item with one less linear component produce equivalent items. Additional research is needed to analyze possible interactions between specific stimulus dimensions and other variations in hierarchical structuring that might contribute to item difficulty.

The present study built on earlier suggestions that sequential, hierarchical patterns may be a feature of behavior that cuts across a variety of skill contexts. The processes associated with task difficulty were delineated based on an analysis of the theoretical literature; model testing via the application of latent trait models supported the presence of ordered relations between the items based on this analysis. The study demonstrated that there are tasks with predictable difficulty levels in the design copying domain. In general, such knowledge should facilitate the construction of tests that provide more accurate information about children's skill levels.

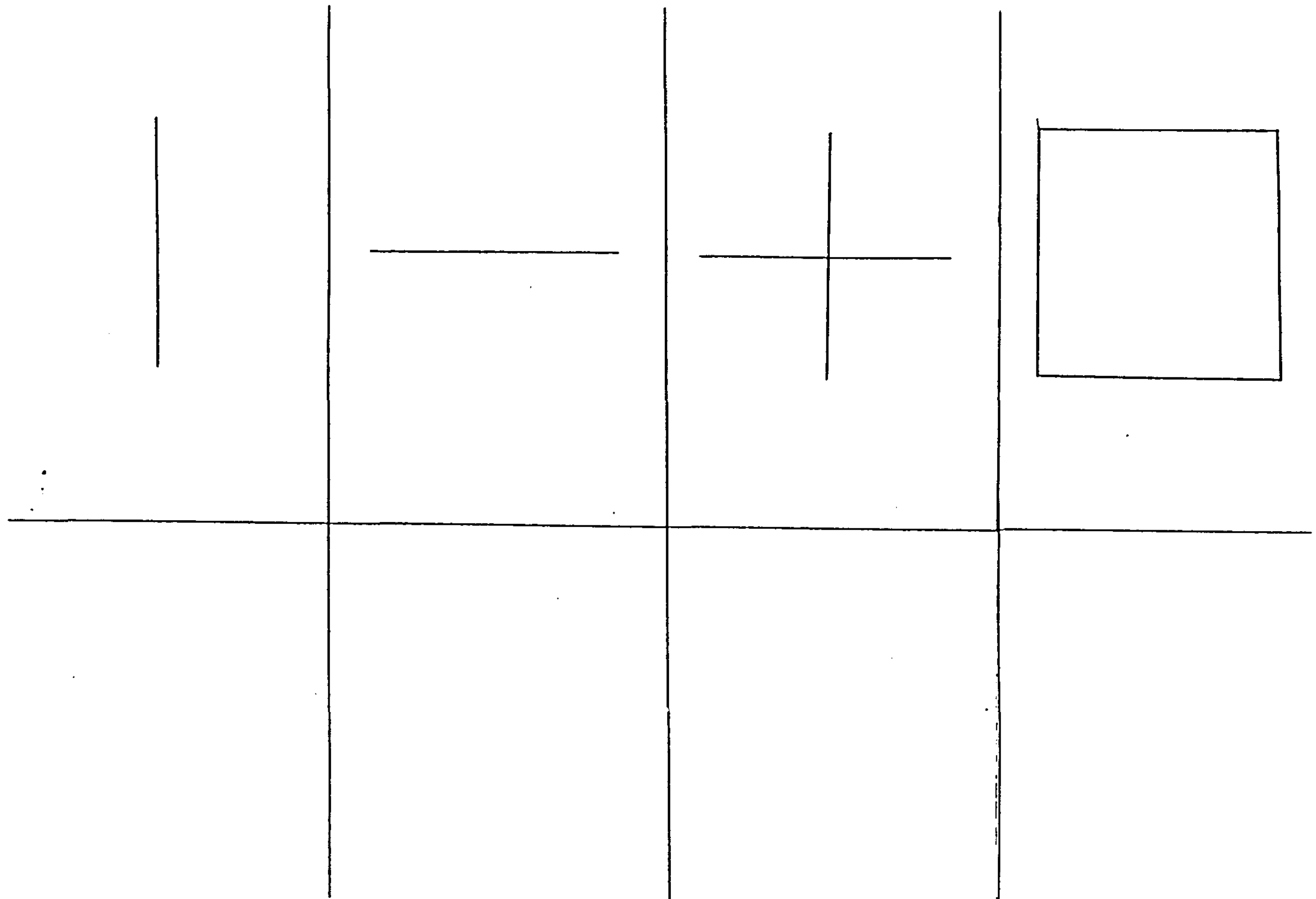
APPENDIX A

DESIGN COPYING TEST

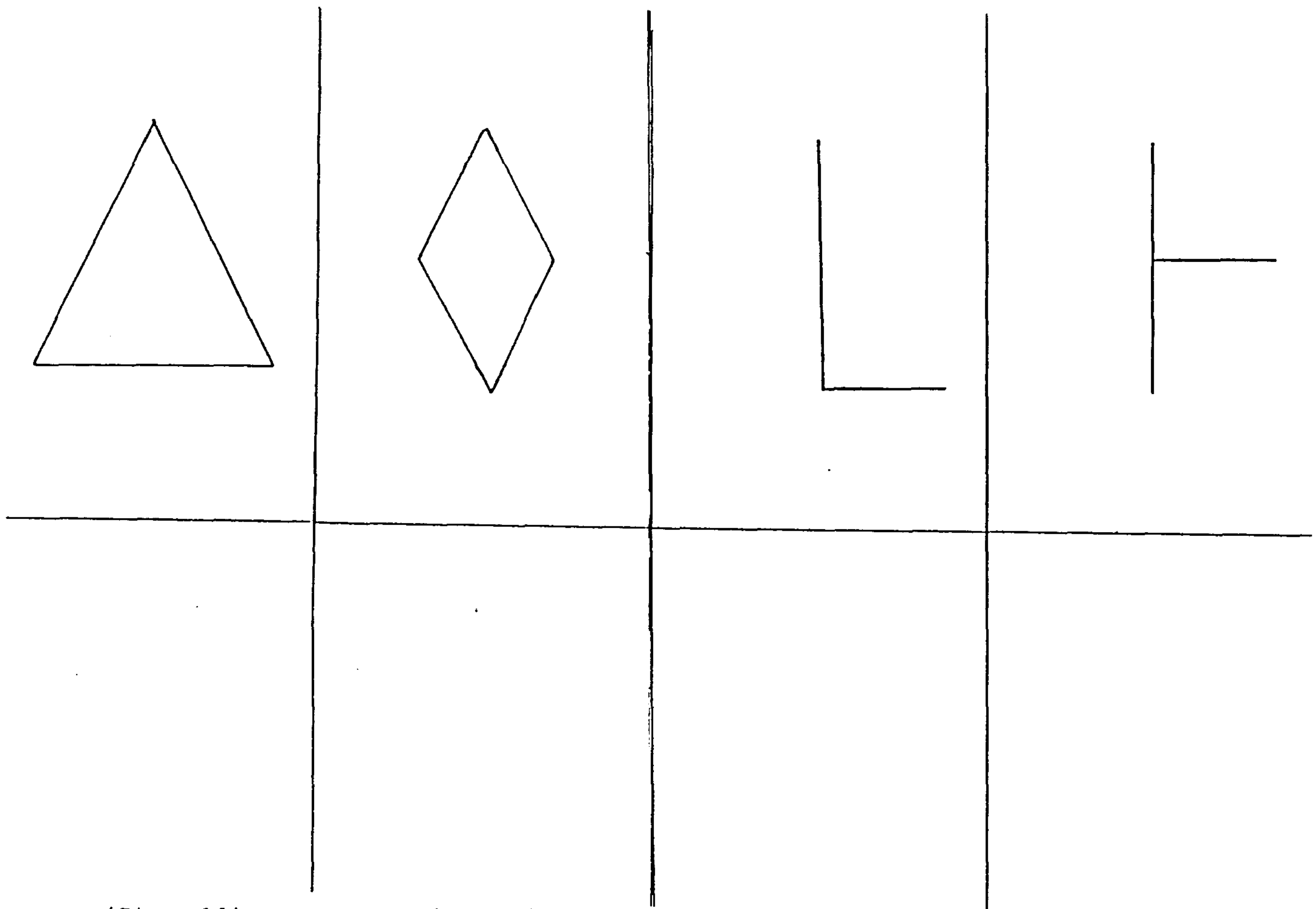

(Item 3)
(Item 2)
(Item 1)



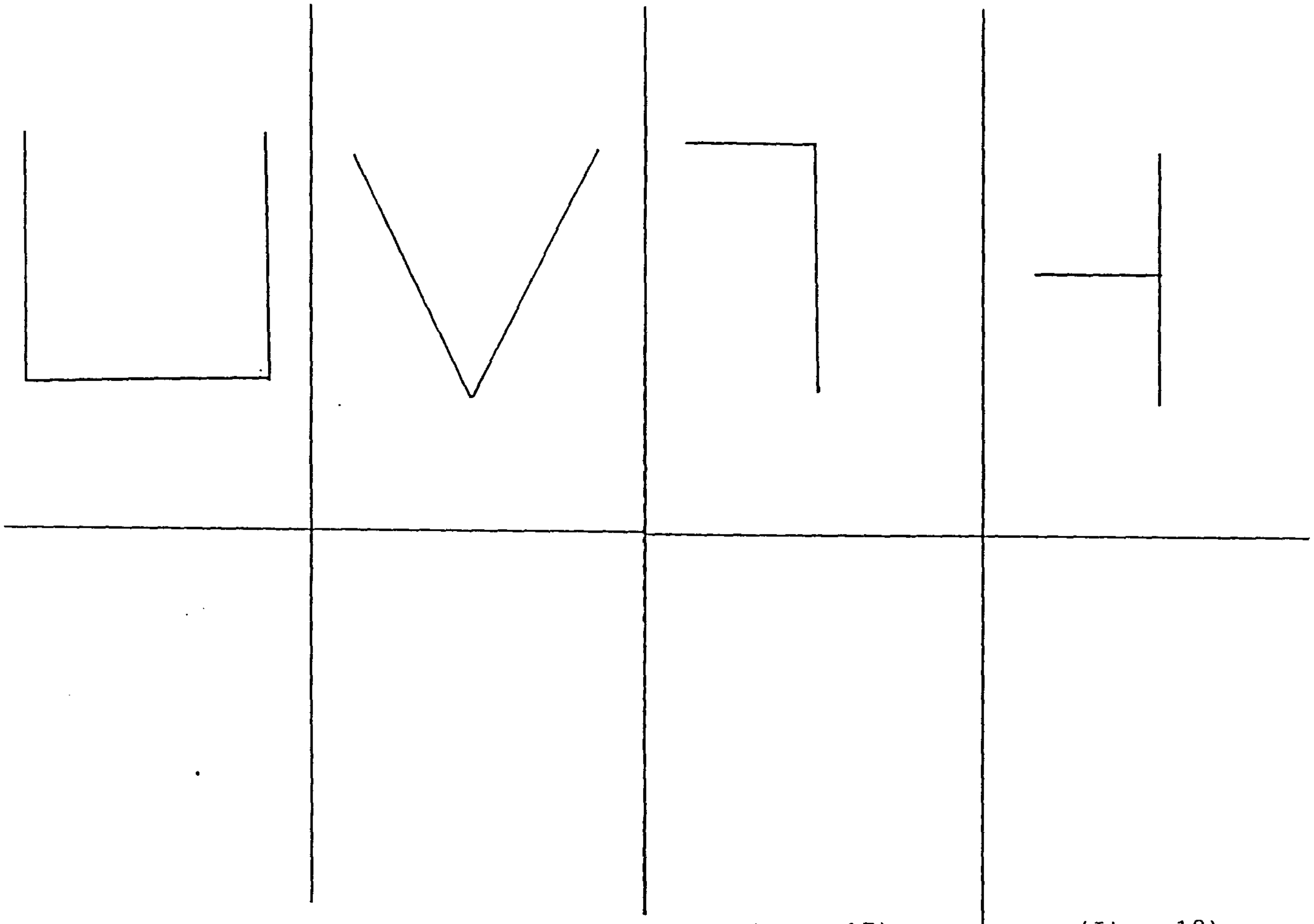
(Item 4) (Item 5) (Item 6)



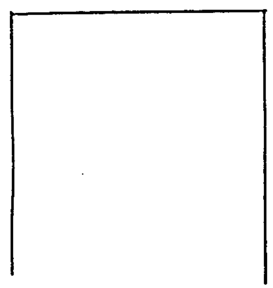
(Item 7) (Item 8) (Item 9) (Item 10)



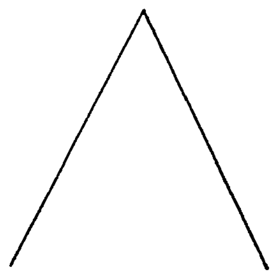
(Item 11) (Item 12) (Item 13) (Item 14)



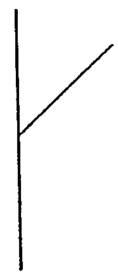
(Item 15) (Item 16) (Item 17) (Item 18)



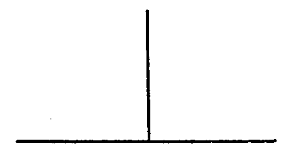
(Item 19)



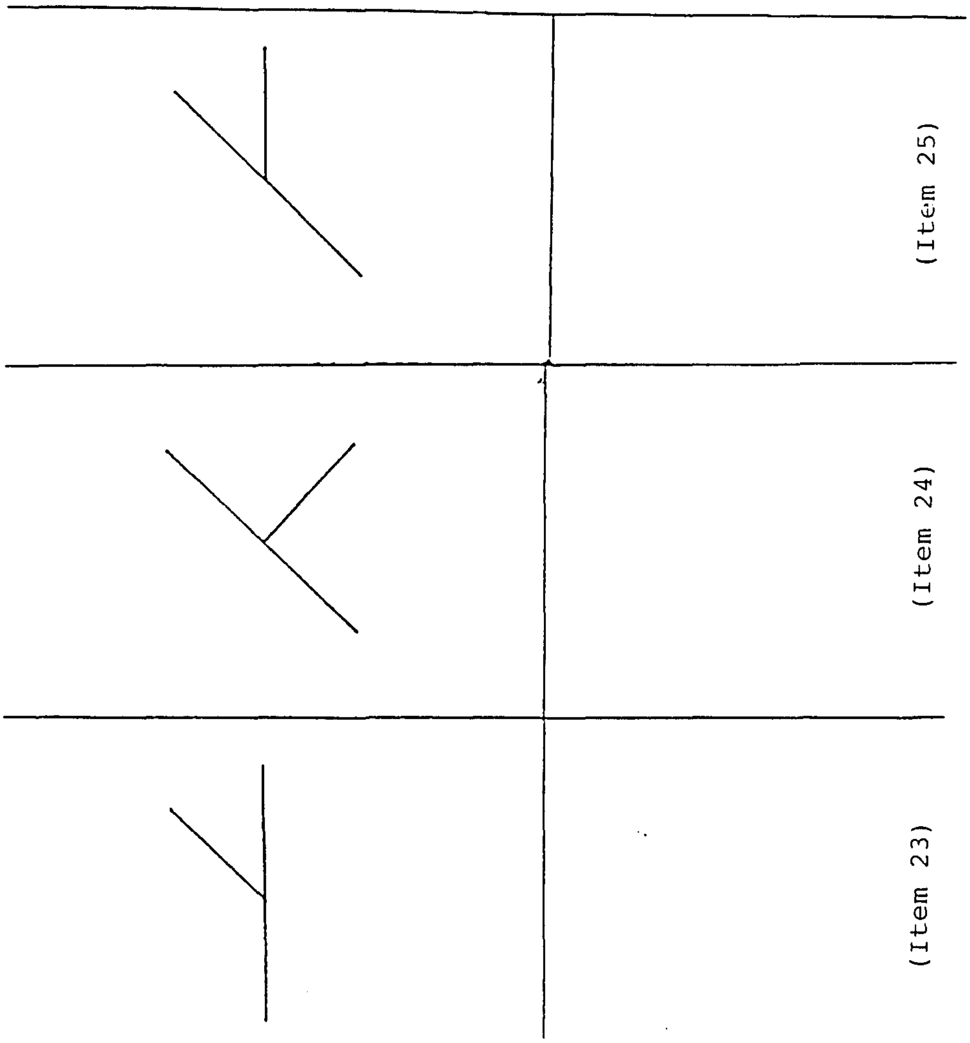
(Item 20)



(Item 21)



(Item 22)


(Item 23)
(Item 24)
(Item 25)

APPENDIX B

SCORING CRITERIA

The following pages contain the criteria that were used for scoring the 25 item design copying instrument.

GENERAL CRITERIA FOR ALL DESIGNS

Lines straight-Not curved or broken
Gap/overlap of lines not more than 1/16"
Horizontal/vertical sides within 10° of edge of paper

SQUARE

4 sided figure
No side more than 1/4 longer than other sides
Angles approximately 90° (No more than 10° deviation)
Angles not rounded

TRIANGLE

3 sided figure
No side more than 1/4 longer than other sides
3 well-formed acute angles
Apex not rounded and higher than other angles

DIAMOND

4 sided figure with 4 angles
Not kite shaped--No side more than 1/4 longer than other sides
Angles should be well-defined acute angles--not rounded
Vertical and horizontal angles approximately equal
Horizontal axis between 170° and 190°
Vertical axis between 80° and 110°

VERTICAL LINE

Line deviates less than 10° from vertical

HORIZONTAL LINE

Line deviates less than 10° from horizontal

VERTICAL-HORIZONTAL CROSS

Lines fully intersect at 90° angle
Intersection of lines does not deviate more than 1/8" from midpoint of either line
Horizontal line toward right
Neither line more than 1/4 longer than other line

L SHAPE

Junction of lines should not deviate from 90° by more than 10°
Corner square, not rounded
Horizontal line should be half as long as vertical line within +/- 25%
Horizontal line should extend right from bottom of vertical line

VERTICAL BASELINE WITH PERPENDICULAR BISECTOR TO RIGHT

2 lines approximately perpendicular
Horizontal line should be half as long as vertical line within +/-25%
Horizontal line should bisect vertical base line within 1/8" of midpoint
Horizontal line pointing toward right
Horizontal/vertical lines do not deviate from edge of paper by more than 10°
Junction of lines should not deviate from 90° by more than 10°

RECTILINEAR U SHAPE

Three-sided figure open at top
No side more than 1/4 longer than other sides
2 angles do not deviate more than 10° from 90°
Angles are not rounded

V SHAPE

Two-sided figure open at top
No line more than 1/4 longer than other line
Apex sharp, acute angle; not curved
Not tilted more than 10°

INVERTED L SHAPE

Junction of lines should not deviate from 90° by more than 10°
Corner square, not rounded
Horizontal line should be half as long as vertical line within +/- 25%
Horizontal line should extend left from top of vertical line
Horizontal/Vertical lines within 10° of edge of paper

VERTICAL BASELINE WITH PERPENDICULAR BISECTOR TO LEFT

2 lines approximately perpendicular
Bisecting horizontal line half as long as vertical base line within +/-25%
Horizontal line should bisect vertical line within 1/4" of midpoint
Horizontal line pointing toward left
Horizontal/vertical lines do not deviate from edge of paper by more than 10°
Junction of lines should not deviate from 90° by more than 10°

INVERTED RECTILINEAR U SHAPE

Three-sided figure open at bottom
Gap/overlap of lines not more than 1/16"
No side more than 1/4 longer than other sides
2 angles do not deviate more than 10° from 90°
Angles are not rounded
Horizontal/Vertical lines within 10° of edge of paper

INVERTED V SHAPE

2 straight lines--Not curved or broken
No line more than 1/4 longer than other line
Gap/overlap of lines not more then 1/16"
Figure open at bottom
Apex sharp, acute angle; not curved
Not tilted more than 10°

VERTICAL BASELINE WITH OBLIQUE BISECTOR UP AND TO THE RIGHT

Oblique bisecting line half as long as vertical baseline within 1/8"
Oblique bisecting line up from vertical baseline to right and bisecting vertical line within 1/8" of midpoint
Upper angle decidedly acute, lower angle more than 90^{o}

HORIZONTAL BASELINE WITH PERPENDICULAR BISECTOR

Gap/overlap of lines not more than 1/16"
Bisecting line half as long as base line within +/- 25%
Bisecting line vertical from horizontal and bisecting horizontal line within 1/8" of midpoint
Horizontal/vertical lines do not deviate from edge of paper by more than 10^{o}
Junction of lines should not deviate from 90^{o} by more than 10^{o}

HORIZONTAL BASELINE WITH OBLIQUE BISECTOR UP AND TO THE RIGHT

Bisecting line half as long as baseline +/-25%
Oblique line up from horizontal and bisecting horizontal line within 1/8" of midpoint
Oblique line within 10^{o} of 45^{o}
Horizontal line does not deviate from 45^{o} by more than 10^{o}

RIGHT OBLIQUE BASELINE WITH OBLIQUE BISECTOR TO RIGHT

Oblique baseline to right within 10^{o} of 45^{o} angle
Oblique bisecting line drawn downward to right within 1/8" of midpoint of oblique line
Bisecting line half as long as baseline +/-25%
Angle formed by intersection of lines within 10^{o} of 90^{o}

RIGHT OBLIQUE BASELINE WITH HORIZONTAL BISECTOR TO RIGHT

Oblique baseline to right within 10^{o} of 45^{o} angel
Bisecting line drawn horizontally to right within 1/8" of midpoint of oblique base line
Bisecting line within 10^{o} of horizontal edge of paper
Bisecting line half as long as baseline +/=25%
Angle formed by intersection of lines within 10^{o} of 90^{o}

APPENDIX C

DIRECTIONS

MATERIALS

1. 1 pencil with an eraser for each student
2. 1 test booklet for each student

PROCEDURES

AFTER DISTRIBUTING THE TEST BOOKLETS, SAY

"Today I want to see how well you can copy designs. Look at the front of your booklets. Please write your first and last name neatly on the first line. After you have written your name, turn the top page over."

"There are designs in boxes across the top of each page. You are to copy each design in the box below it. Sometimes there will be dots in the bottom box. Use the dots to help you copy the design. Please work carefully and be sure to copy every design."

WHILE THE STUDENTS ARE COMPLETING THE DESIGNS, CIRCULATE AROUND THE ROOM. IF A CHILD DOES NOT SEEM TO UNDERSTAND THE TASK, RE-EXPLAIN THE DIRECTIONS.

WHEN THE CHILDREN HAVE COMPLETED THE TEST, COLLECT THE BOOKLETS INDIVIDUALLY AND MAKE SURE THAT ALL ITEMS HAVE BEEN COMPLETED.

PLACE ALL BOOKLETS IN THE MANILA ENVELOPE.

APPENDIX D

OBSERVED AND EXPECTED FREQUENCY TABLES

Tables 26 through 43 include observed and expected cell frequency counts for Hierarchy 1 through 5 score patterns.

Table 26

Hierarchy 1 Expected and Observed Cell Frequencies for Models M1, M2, and M3

		Expected		
Pattern	Observed	M1	M2	M3
11111	17.0	17.1	14.1	16.3
11112	.0	.0	.0	.0
11121	.0	.0	.0	.0
11122	.0	.0	.0	.0
11211	2.0	2.7	1.4	1.2
11212	.0	.0	.0	.0
11221	.0	.0	.0	.0
11222	.0	.0	.0	.0
12111	6.0	6.7	11.2	10.7
12112	.0	.0	.0	.0
12121	1.0	.0	.0	.1
12122	.0	.0	.0	.0
12211	6.0	6.2	5.2	4.1
12212	.0	.1	.1	.1
12221	.0	.2	.2	.1
12222	.0	.0	.0	.0
21111	18.0	17.5	16.7	16.3
21112	.0	.0	.0	.0
21121	.0	.0	.1	.1
21122	.0	.0	.0	.0
21211	2.0	3.8	7.7	6.2
21212	.0	.0	.1	.1
21221	.0	.0	.2	.2
21222	1.0	.0	.0	.0
22111	54.0	59.1	59.6	57.1
22112	3.0	1.0	.7	.8
22121	3.0	2.6	1.8	1.9
22122	1.0	.7	.3	.2
22211	151.0	141.9	137.6	137.8
22212	8.0	10.5	11.8	15.3
22221	27.0	28.6	30.1	34.2
22222	34.0	35.1	34.9	31.1

Table 27

Hierarchy 1 Expected and Observed Cell Frequencies for Models M4, M5, and M6

		Expected		
Pattern	Observed	M4	M5	M6
11111	17.0	16.3	18.8	8.6
11112	.0	.0	.1	7.8
11121	.0	.0	.1	7.8
11122	.0	.0	.0	7.8
11211	2.0	1.2	9.8	8.3
11212	.0	.0	.1	7.8
11221	.0	.0	.1	8.3
11222	.0	.0	.0	8.3
12111	6.0	13.3	9.8	10.3
12112	.0	.1	.1	7.8
12121	1.0	.1	.1	8.3
12122	.0	.0	.0	8.3
12211	6.0	5.1	18.8	10.3
12212	.0	.1	.8	10.3
12221	.0	.2	.8	15.0
12222	.0	.0	.1	7.0
21111	18.0	13.3	9.8	8.3
21112	.0	.0	.1	8.3
21121	.0	.1	.1	10.3
21122	.0	.0	.0	8.3
21211	2.0	5.1	18.8	10.3
21212	.0	.1	.8	10.3
21221	.0	.2	.8	15.0
21222	1.0	.0	.1	8.3
22111	54.0	57.2	18.8	8.3
22112	3.0	.9	.8	10.3
22121	3.0	1.9	.8	10.3
22122	1.0	.2	.1	15.0
22211	151.0	138.0	142.5	10.3
22212	8.0	15.4	27.1	15.0
22221	27.0	34.3	27.1	15.0
22222	34.0	30.9	26.9	25.5

Table 28

Hierarchy 2A Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4

		Expected			
Pattern	Observed	M1	M2	M3	M4
11111	83.0	77.1	74.7	70.5	71.9
11112	1.0	.1	.3	.3	.2
11121	.0	1.2	1.4	1.0	.8
11122	.0	.0	.0	.0	.0
11211	.0	.1	.5	1.6	1.7
11212	1.0	.0	.0	.0	.0
11221	.0	.1	.1	.1	.1
11222	.0	.0	.0	.0	.0
12111	3.0	13.1	12.3	11.8	12.1
12112	.0	.1	.2	.2	.1
12121	1.0	.8	.8	.6	.5
12122	.0	.1	.1	.0	.1
12211	2.0	.9	.7	.9	1.0
12212	.0	.3	.2	.1	.1
12221	1.0	1.0	.7	.4	.4
12222	.0	.4	.3	.2	.2
21111	38.0	53.3	51.7	48.7	49.2
21112	.0	.4	.6	.7	.6
21121	5.0	2.5	2.8	2.3	2.0
21122	.0	.3	.2	.2	.2
21211	1.0	2.1	2.1	3.9	4.2
21212	.0	.7	.5	.4	.5
21221	2.0	2.4	1.7	1.5	1.7
21222	2.0	.9	.7	.7	.8
22111	37.0	28.5	27.9	29.5	29.5
22112	.0	3.1	3.3	3.4	3.5
22121	9.0	11.3	10.8	11.0	11.7
22122	5.0	3.7	4.2	5.1	5.2
22211	34.0	27.1	26.3	24.4	24.8
22212	3.0	10.4	11.9	11.9	11.1
12221	22.0	33.5	36.3	38.5	37.0
22222	84.0	58.7	60.6	64.0	62.4

Table 29

Hierarchy 2A Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8

		Expected			
Pattern	Observed	M5	M6	M7	M8
11111	83.0	75.9	73.7	73.8	75.6
11112	1.0	.9	.3	.3	10.9
11121	.0	1.4	1.2	1.0	10.9
11122	.0	.0	.0	.0	3.8
11211	.0	.5	1.2	2.2	10.9
11212	1.0	.0	.0	.0	3.8
11221	.0	.1	.1	.1	3.8
11222	.0	.0	.0	.0	3.8
12111	3.0	12.9	12.2	27.0	10.9
12112	.0	.1	.2	.4	3.8
12121	1.0	.8	.7	1.2	3.8
12122	.0	.1	.1	.1	3.8
12211	2.0	.8	.7	2.6	3.8
12212	.0	.2	.1	.3	3.8
12221	1.0	.7	.4	.9	3.8
12222	.0	.3	.2	.4	10.8
21111	38.0	51.6	49.7	27.0	10.9
21112	.0	.3	.6	.4	3.8
21121	5.0	2.9	3.0	1.2	3.8
21122	.0	.3	.4	.1	3.8
21211	1.0	2.6	3.0	2.6	3.8
21212	.0	.7	.4	.3	3.8
21221	2.0	2.3	1.8	.9	3.8
21222	2.0	.9	.8	.4	10.8
22111	37.0	28.9	29.5	31.9	3.8
22112	.0	3.1	3.8	3.4	3.8
22121	9.0	11.6	18.1	11.4	3.8
22122	5.0	3.9	7.8	5.4	10.8
22211	34.0	27.2	18.1	24.1	3.8
22212	3.0	10.8	7.8	11.5	10.8
12221	22.0	33.9	36.8	38.2	10.8
22222	84.0	59.3	61.2	64.6	73.8

Table 30

Hierarchy 2B Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4

		Expected			
Pattern	Observed	M1	M2	M3	M4
11111	207.0	180.7	180.2	183.4	184.5
11112	1.0	1.6	1.0	1.0	.8
11121	4.0	2.7	3.5	2.9	3.1
11122	.0	.1	.1	.1	.1
11211	11.0	7.9	8.8	8.3	9.0
11212	2.0	.4	.3	.3	.2
11221	.0	1.0	1.1	.9	.9
11222	1.0	.1	.0	.1	.0
12111	5.0	13.6	13.5	17.1	16.9
12112	1.0	.8	.6	.5	.4
12121	.0	1.9	2.0	1.7	1.7
12122	.0	.1	.1	.1	.1
12211	2.0	5.4	5.1	4.9	4.9
12212	.0	.4	.2	.2	.3
12221	2.0	1.0	.8	.9	1.0
12222	1.0	.2	.1	.4	.5
21111	17.0	24.0	23.4	26.7	27.4
21112	.0	1.4	1.0	.9	.7
21121	2.0	3.0	3.5	2.8	2.8
21122	.0	.2	.2	.1	.1
21211	4.0	8.7	8.9	8.2	7.9
21212	1.0	.5	.4	.5	.4
21221	2.0	1.2	1.5	1.8	1.6
21222	.0	.1	.2	1.0	.7
22111	28.0	17.0	17.5	15.3	14.9
22112	1.0	1.2	1.3	.7	.8
22121	3.0	3.3	4.3	2.5	3.0
22122	.0	1.0	1.9	.8	1.4
22211	9.0	9.6	11.0	8.3	8.7
22212	1.0	3.0	4.7	3.4	4.0
12221	13.0	20.2	16.1	15.5	15.6
22222	16.0	22.0	20.7	21.5	19.7

Table 31

Hierarchy 2B Expected and Observed Cell Frequencies for Models M5, M6, and M7

		Expected		
Pattern	Observed	M5	M6	M7
11111	207.0	184.2	186.5	192.2
11112	1.0	.8	1.8	11.9
11121	4.0	3.1	1.8	11.9
11122	.0	.1	.1	2.9
11211	11.0	9.0	9.3	11.9
11212	2.0	.2	.5	2.9
11221	.0	.9	.5	2.9
11222	1.0	.0	.1	1.7
12111	5.0	21.6	17.5	11.9
12112	1.0	.6	.9	2.9
12121	.0	2.2	.9	2.9
12122	.0	.1	.1	1.7
12211	2.0	6.5	4.8	2.9
12212	.0	.3	.6	2.9
12221	2.0	.3	.6	1.7
12222	1.0	.6	.6	1.7
21111	17.0	21.6	28.2	3.8
21112	.0	.6	1.5	11.9
21121	2.0	2.2	1.5	2.9
21122	.0	.1	.2	2.9
21211	4.0	6.5	7.7	1.7
21212	1.0	.3	1.0	2.9
21221	2.0	1.3	1.0	1.7
21222	.0	.6	.9	1.7
22111	28.0	15.4	14.4	3.8
22112	1.0	.8	1.8	2.9
22121	3.0	3.0	1.8	2.9
22122	.0	1.3	1.7	1.7
22211	9.0	8.7	9.1	1.7
22212	1.0	3.9	8.6	3.8
12221	13.0	15.6	8.6	3.8
22222	16.0	20.8	19.3	18.0

Table 32

Hierarchy 3A Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4

		Expected			
Pattern	Observed	M1	M2	M3	M4
1111	40.0	41.1	41.0	43.6	42.8
1112	8.0	5.5	6.9	7.5	8.4
1121	8.0	6.8	5.5	7.7	7.0
1122	9.0	4.0	4.1	4.1	4.2
1211	23.0	25.6	25.5	20.7	22.0
1212	10.0	11.6	12.5	12.8	13.3
1221	10.0	10.8	10.1	11.2	11.0
1222	18.0	20.6	19.9	17.9	16.6
2111	10.0	12.6	12.5	10.8	10.0
2112	3.0	5.7	6.1	5.8	6.0
2121	5.0	5.3	4.9	5.2	3.0
2122	8.0	9.8	9.8	6.6	7.5
2211	27.0	17.4	17.5	15.9	15.7
2212	22.0	22.5	19.9	25.2	23.8
2221	11.0	13.1	16.0	18.3	19.7
2222	122.0	122.2	121.8	120.7	120.8

Table 33

Hierarchy 3A Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8

		Expected			
Pattern	Observed	M5	M6	M7	M8
1111	40.0	43.3	42.9	43.3	43.2
1112	8.0	8.9	7.7	9.3	11.7
1121	8.0	7.4	7.7	13.3	11.7
1122	9.0	4.5	4.2	8.3	9.1
1211	23.0	15.3	22.1	13.3	11.7
1212	10.0	9.4	12.1	8.3	9.1
1221	10.0	7.8	12.1	11.8	9.1
1222	18.0	11.8	16.7	17.9	17.2
2111	10.0	15.3	10.0	11.0	11.7
2112	3.0	9.4	5.5	6.8	9.1
2121	5.0	7.8	5.5	9.8	9.1
2122	8.0	11.8	7.6	14.8	17.2
2211	27.0	16.2	15.8	9.8	9.1
2212	22.0	24.5	21.7	21.1	17.2
2221	11.0	20.3	21.7	21.1	17.2
2222	122.0	120.6	120.9	120.4	120.3

Table 34

Hierarchy 3B Expected and Observed Cell Frequencies for Models M1, M2, M3, and M4

		Expected			
Pattern	Observed	M1	M2	M3	M4
1111	128.0	130.7	130.6	130.5	130.5
1112	9.0	9.2	9.2	9.8	9.5
1121	12.0	10.4	10.2	10.2	10.5
1122	7.0	4.7	4.6	4.6	4.6
1211	23.0	23.0	23.0	22.1	21.8
1212	13.0	9.3	9.5	9.4	9.5
1221	6.0	10.3	10.5	10.5	10.5
1222	9.0	11.5	12.1	11.7	11.9
2111	12.0	11.5	12.2	11.6	11.9
2112	3.0	5.4	5.2	5.3	5.2
2121	6.0	5.9	5.8	5.9	5.8
2122	6.0	7.1	6.7	6.7	6.5
2211	15.0	11.8	11.9	11.9	12.0
2212	9.0	13.3	13.3	13.3	13.6
2221	14.0	14.6	14.8	15.2	15.0
2222	62.0	53.3	55.2	55.2	55.2

Table 35

Hierarchy 3B Expected and Observed Cell Frequencies for Models M5, M6, M7, and M8

		Expected			
Pattern	Observed	M5	M6	M7	M8
1111	128.0	130.5	130.6	130.6	130.5
1112	9.0	10.0	9.8	9.9	13.4
1121	12.0	10.0	10.8	15.7	13.4
1122	4.6	4.6	4.7	6.9	7.9
1211	23.0	21.8	16.5	15.7	13.4
1212	13.0	10.0	7.2	6.9	7.9
1221	6.0	10.0	8.0	10.9	7.9
1222	9.0	11.9	9.0	12.3	11.8
2111	12.0	11.9	16.5	12.4	13.4
2112	3.0	5.5	7.2	5.4	7.9
2121	6.0	5.5	8.0	9.7	7.9
2122	6.0	6.5	9.0	9.7	11.8
2211	15.0	12.0	12.2	8.6	7.9
2212	9.0	14.3	13.8	9.7	11.8
2221	14.0	14.3	15.3	15.4	11.8
2222	62.0	55.3	55.3	55.3	55.4

Table 36

Hierarchy 4A Expected and Observed Cell Frequencies for Models M1, M2, and M3

		Expected		
Pattern	Observed	M1	M2	M3
1111	49.0	49.2	49.2	53.7
1112	7.0	4.7	4.7	3.3
1121	9.0	6.6	6.5	11.3
1122	2.0	2.3	2.2	2.2
1211	5.0	8.2	8.6	9.0
1212	3.0	2.1	2.2	2.1
1221	6.0	6.7	6.8	6.0
1222	11.0	11.1	11.1	4.9
2111	44.0	43.5	43.4	32.4
2112	6.0	7.8	7.7	6.3
2121	13.0	13.9	13.4	18.5
2122	9.0	8.8	8.4	11.2
2211	20.0	14.9	15.6	17.2
2212	4.0	5.2	5.8	14.0
2221	33.0	33.9	33.9	30.6
2222	108.0	109.8	109.6	106.2

Table 37

Hierarchy 4A Expected and Observed Cell Frequencies for Models M4, M5, and M6

		Expected		
Pattern	Observed	M4	M5	M6
1111	49.0	52.9	55.1	55.5
1112	7.0	2.9	3.8	13.2
1121	9.0	8.7	10.0	13.2
1122	2.0	2.1	2.2	8.6
1211	5.0	12.0	9.8	13.2
1212	3.0	2.0	2.2	8.6
1221	6.0	6.1	5.7	8.6
1222	11.0	5.5	4.0	15.7
2111	44.0	33.7	30.6	13.7
2112	6.0	5.7	6.8	8.6
2121	13.0	17.2	17.7	8.6
2122	9.0	15.6	12.6	15.7
2211	20.0	18.7	17.3	8.6
2212	4.0	9.5	12.3	15.7
2221	33.0	28.8	32.3	15.7
2222	108.0	107.6	106.4	106.1

Table 38

Hierarchy 4B Expected and Observed Cell Frequencies for Models M1, M2, and M3

		Expected		
Pattern	Observed	M1	M2	M3
1111	56.0	52.6	53.9	57.0
1112	3.0	1.5	1.5	2.1
1121	5.0	3.6	3.2	4.3
1122	1.0	.7	.7	.6
1211	10.0	17.0	20.0	16.3
1212	3.0	2.8	2.1	2.1
1221	7.0	6.1	4.6	4.2
1222	5.0	5.0	2.9	4.2
2111	53.0	58.0	51.6	47.0
2112	5.0	4.4	5.4	6.1
2121	11.0	10.1	11.9	12.1
2122	3.0	4.6	7.6	5.5
2211	60.0	44.9	47.1	46.3
2212	10.0	17.9	17.0	21.1
2221	28.0	37.6	37.3	41.8
2222	74.0	67.3	67.1	65.7

Table 39

Hierarchy 4B Expected and Observed Cell Frequencies for Models M4, M5, M6, and M7

		Expected			
Pattern	Observed	M4	M5	M6	M7
1111	56.0	58.6	56.8	56.7	59.1
1112	3.0	2.5	3.2	2.6	17.1
1121	5.0	4.8	3.2	9.6	17.1
1122	1.0	.7	.6	1.4	11.6
1211	10.0	29.4	16.6	19.6	17.1
1212	3.0	4.0	3.1	1.4	11.6
1221	7.0	7.8	3.1	5.1	11.6
1222	5.0	3.6	2.0	2.3	17.9
2111	53.0	29.4	47.4	50.0	17.1
2112	5.0	4.0	9.0	2.3	11.6
2121	11.0	7.8	5.8	12.3	17.9
2122	3.0	3.6	2.8	1.9	11.6
2211	60.0	47.9	47.0	26.6	11.6
2212	10.0	21.8	30.4	12.3	11.5
2221	28.0	21.8	30.4	44.9	17.9
2222	74.0	65.4	66.1	65.4	11.6

Table 40

Hierarchy 4C Expected and Observed Cell Frequencies for Models M1, M2, and M3

		Expected		
Pattern	Observed	M1	M2	M3
1111	99.0	102.3	100.6	100.7
1112	5.0	3.1	3.2	3.0
1121	7.0	7.5	6.8	6.5
1122	3.0	.9	.9	.9
1211	7.0	9.0	14.1	14.6
1212	3.0	3.0	2.1	2.1
1221	7.0	6.2	4.4	4.5
1222	3.0	4.4	2.4	2.5
2111	44.0	45.7	39.0	39.5
2112	3.0	4.3	5.7	5.7
2121	12.0	9.6	12.1	12.2
2122	1.0	3.6	6.6	6.8
2211	35.0	25.9	27.5	27.4
2212	10.0	16.4	15.7	15.2
2221	24.0	33.1	33.2	32.6
2222	71.0	58.9	59.8	59.8

Table 41

Hierarchy 4C Expected and Observed Cell Frequencies for Models M4, M5, M6, and M7

		Expected			
Pattern	Observed	M4	M5	M6	M7
1111	99.0	100.1	100.6	100.8	99.9
1112	5.0	3.41	4.6	4.6	15.8
1121	7.0	7.2	4.6	4.6	15.8
1122	3.0	1.1	1.0	1.2	8.7
1211	7.0	25.6	14.9	15.0	15.8
1212	3.0	3.8	3.3	3.2	8.7
1221	7.0	8.0	3.3	3.2	8.7
1222	3.0	4.5	2.7	2.9	14.1
2111	44.0	25.6	40.0	42.1	15.8
2112	3.0	3.8	8.7	8.9	8.9
2121	12.0	8.0	8.7	8.9	8.7
2122	1.0	4.5	7.1	7.3	14.1
2211	35.0	28.6	28.0	31.0	8.7
2212	10.0	15.9	22.9	24.9	14.1
2221	24.0	33.6	22.9	24.9	14.1
2222	71.0	60.3	60.6	61.3	62.4

Table 42

Hierarchy 5 Expected and Observed Cell Frequencies for Models M1, M2, and M3

		Expected		
Pattern	Observed	M1	M2	M3
11111	84.0	88.7	91.6	81.4
11112	2.0	.6	1.2	2.2
11121	11.0	9.3	8.6	16.9
11122	1.0	.5	.4	.8
11211	6.0	1.1	2.5	3.0
11212	1.0	.1	.1	.1
11221	.0	1.0	.9	1.1
11222	.0	.2	.1	.1
12111	12.0	14.0	11.3	38.3
12112	1.0	.6	.6	1.8
12121	7.0	5.5	4.0	13.8
12122	.0	.6	.6	1.1
12211	.0	1.2	1.2	2.5
12212	.0	.3	.2	.2
12221	1.0	1.6	1.1	1.5
12222	.0	1.3	.4	.2
21111	64.0	63.6	56.2	38.3
21112	5.0	2.0	2.9	1.8
21121	16.0	20.4	20.0	13.8
21122	1.0	2.1	2.8	1.1
21211	5.0	4.2	5.7	2.5
21212	1.0	.8	.8	.2
21221	4.0	5.0	5.6	6.2
21222	3.0	3.3	2.0	1.5
22111	28.0	27.0	26.4	31.4
22112	1.0	2.5	3.8	3.4
22121	34.0	21.1	25.7	28.8
22122	.0	4.1	9.1	2.5
22211	6.0	5.8	7.4	19.1
22212	1.0	3.1	2.6	3.5
22221	9.0	13.5	17.8	2.5
22222	30.0	29.1	20.5	21.5

Table 43

Hierarchy 5 Expected and Observed Cell Frequencies for Models M4, M5, and M6

Pattern	Observed	Expected		
		M4	M5	M6
11111	84.0	91.3	91.6	92.4
11112	2.0	1.8	1.3	16.0
11121	11.0	8.7	9.9	16.0
11122	1.0	.7	.5	6.2
11211	6.0	1.8	2.5	16.0
11212	1.0	.1	.1	6.2
11221	.0	.7	1.0	6.2
11222	.0	.1	.1	4.7
12111	12.0	11.4	9.9	16.0
12112	1.0	.9	.5	6.2
12121	7.0	4.1	4.1	6.2
12122	.0	.8	.6	4.7
12211	.0	.9	1.0	1.2
12212	.0	.2	.1	4.7
12221	1.0	.8	1.1	4.7
12222	.0	.4	.4	6.6
21111	64.0	56.4	56.3	16.0
21112	5.0	4.3	2.9	6.2
21121	16.0	20.1	23.0	6.2
21122	1.0	4.1	3.3	4.7
21211	5.0	4.3	5.8	6.2
21212	1.0	.9	.8	4.7
21221	4.0	4.1	6.5	4.7
21222	3.0	2.1	2.3	6.6
22111	28.0	26.6	23.0	6.2
22112	1.0	5.5	3.3	4.7
22121	34.0	25.8	25.9	6.6
22122	.0	13.0	9.1	6.6
22211	6.0	5.5	6.5	4.7
22212	1.0	2.7	2.3	6.6
22221	9.0	13.0	17.9	6.6
22222	30.0	21.0	20.5	18.7

APPENDIX E

STATISTICAL FORMULAS

The 2-parameter logistic model is expressed as:

$$P(X_j=1|\theta) = \frac{1}{1+e^{-a_j(\theta-b_j)}}$$

The probability of a correct response to item j is:

$$P(x_{ij}=1|\theta_i)=\phi_j(\theta_i)=\frac{1}{2\pi^{1/2}}\int_{-z(\theta_i)}^{\infty} \exp \frac{t^2}{2}\, dt$$

where $Z_j(\theta_i)=a_j(\theta_i-b_j)$

Likelihood ratio chi-square statistic may be used to test the fit of a given model to the data and is expressed as:

$$L^2=2\sum_{t}^{s} r_1 \log_e \frac{r_1}{NP_i}$$

LIST OF REFERENCES

Ayres, A. J. (1978). Southern California Sensory-Motor Integration Tests Manual. Los Angeles, CA: Western Psychological Services.

Beery, K. I. (1982). Administration, Scoring, and Teaching Manual for the Developmental Test of Visual-Motor Integration. Chicago, IL: Follett Publishing Company.

Bender, L. (1938). A visual motor gestalt test and its clinical use. Monograph #3, American Orthopsychiatric Association.

Bergan, J. R. (1980a). Preferred model selection in the validation of scales involving hierarchical dependencies among learning tasks. Contemporary Educational Psychology, 5, 232-240.

Bergan, J. R. (1980b). The structural analysis of behavior: An alternative to the learning-hierarchy model. Review of Educational Research, 50, 625-646.

Bergan, J. R., & Stone, C. A. (1985). Latent class models for knowledge domains. Psychological Bulletin, 98, 166-184.

Bergan, J. R., Stone, C. A., & Feld, J. K. (1984). Rule replacement in the development of basic number skills. Journal of Educational Psychology, 76, 289-299.

Bergan, J. R. , Towstopiat, O., Cancelli, A. A., & Karp, C. (1982). Replacement and component rules in hierarchically ordered mathematics rule learning tasks. Journal of Educational Psychology, 1, 39-50.

Berman, P. W. (1976). Young children's use of the frame of reference in construction of the horizontal, vertical, and oblique. Child Development, 47, 259-263.

Berman, P. W., Cunningham, J. G., & Harkulich, J. (1974). Construction of the horizontal, vertical, and oblique by young children: Failure to find the oblique effect. Child Development, 45, 474-478.

Bernbaum, M., Goodnow, J., & Lehman, E. (1974). Relationships among perceptual-motor tasks: Tracing and copying. Journal of Educational Psychology, 66, 731-735.

Birch, H. G., & Lefford, A. (1967). Visual differentiation, intersensory integration, and voluntary motor control. Monographs of the Society for Research in Child Development, 32, (Serial #110).

Birnbaum, A. (1968). Some latent trait models and their use in inferring an examinee's ability. In F. M. Lord & M. R. Novick (Ed.), Statistical Theories of Mental Test Scores. Reading MA: Addison Wesley.

Bishop, Y. M., Feinberg, S. E., & Holland, P. W. (1975). Discrete Multivariate Analysis. Cambridge, MA: MIT Press.

Bremner, J. G., & Taylor, A. J. (1982). Children's errors in copying angles: Perpendicular error or bisection error? Perception, 11, 163-171.

Bock, R.D., & Aitken, M. (1981). Marginal maximum likelihood estimation of item parameters: An application of an EM algorithm. Psychometrika, 46, 443-459.

Bruner, J. S. (1970). The growth and structure of skill. In K. Connolly (Ed.), Mechanisms of Motor Development (pp. 63-92). New York: Academic Press.

Bruner, J. S. (1973). Organization of early skilled action. Child Development, 44, 1-11.

Bruininks, R.H. (1978). Bruininks-Oseretsky Test of Motor Proficiency. Circle Pines, MN: American Guidance Service.

Capie, W., & Jones, H. L. (1971). An assessment of hierarchy validation techniques. Journal of Research in Science Teaching, 8, 137-147.

Cotton, J. W., Gallagher, J. P., & Marshall, S. P. (1977). The identification and decomposition of hierarchical tasks. American Educational Research Journal, 14, 189-212.

Cratty, B. J. (1979). Perceptual and Motor Development in Infants and Children. Englewood Cliffs, NJ: Prentice-Hall.

Dayton, C. M., & Macready, G. B. (1976). A probabilistic model for validation of behavioral hierarchies. Psychometrika, 41, 189-204.

Eldred, C. A. (1973). Judgments of right side up and figure rotation by young children. Child Development, 44, 395-399.

Embretson, S. W. (1985). Test Design: Developments in Psychology and Psychometrics. NY: Academic Press.

Frankenburg, W. K., & Dodds, J. B. (1973). Denver Developmental Screening Test. Denver, CO: Ladoca Project Publishing Co, Inc.

Freeman, N. H. (1980). Strategies of Representation in Young Children: Analysis of Spatial Skills and Drawing Processes. London: Academic Press.

Freeman, N. H., & Hayton, C. (1980). Gross failure to utilise alignment cues in children's drawing of three-dimensional relationships. Perception, 9, 353-359.

Gagne, R. M. (1962). The acquisition of knowledge. Psychological Review, 69, 355-365.

Gagne, R. M. (1968). Learning Hierarchies. Educational Psychologist, 6, 1-9.

Gagne, R. M. (1977). The Conditions of Learning (3rd ed.). NY: Holt, Rinehart, and Winston.

Gesell, A., & Ames, L. B. (1946). The development of directionality in drawing. The Journal of Genetic Psychology, 68, 45-61.

Glaser, R., & Nitko, A. J. (1971). Measurement in learning and instruction. In R. L. Thorndike (Ed.), Educational Measurement (2nd ed., pp. 625-670). Washington, DC: American Council on Education.

Goodnow, J. L., & Levine, R. A. (1973). "The grammar of action": Sequence and syntax in children's copying. Cognitive Psychology, 4, 82-98.

Goodnow, J. L., Young, B. M., & Kvan, F. (1976). Orientation errors in copying by children in Hong Kong. Journal of Cross-Cultural Psychology, 7, 101-109.

Hambleton, R. K., & Cook, L. L. (1977). Latent trait models and their use in the analysis of educational test data. Journal of Educational Measurement, 14, 75-96.

Hambleton, R. K., & Swaminathan, H. (1983). Item Response Theory: Principles and Applications. Boston: Kluwer-Nijhoff Publishers.

Hirsch, E., & Niedermeyer, F. (1973). The effects of tracing prompts and discrimination training on kindergarten handwriting performance. Journal of Educational Research, 67, 81-86.

Ibbotson, A., & Bryant, P. E. (1976). The perpendicular error and the vertical effect in children's drawings. Perception, 5, 319-326.

Ilg, F. L., & Ames, L. B. (1964). School Readiness. NY: Harper and Row.

Jeffrey, W. (1966). Discrimination of oblique lines by children. Journal of comparative Physiological Psychology, 62, 154.

Kirk, U. (1981). The development and use of rules in the acquisition of perceptual motor skill. Child Development, 52, 299-305.

Laszlo, J. I., & Bairstow, P. J. (1985). Perceptual-Motor Behaviour: Developmental Assessment and Therapy. London: Holt, Rinehart, and Winston.

Lazarsfeld, P. F., & Henry, N. W. (1968). Latent Structure Analysis. Boston, MA: Houghton Mifflin.

Lepkin, S. R., & Pryzwansky, W. B. (1983). Interrater reliability of the original and a revised scoring system for the Developmental Test of Visual-Motor Integration. Psychology in the Schools, 20, 284-288.

Lord, F. M. (1980). Applications of Item Response Theory to Practical Testing Problems. Hillsdale, NJ: Lawrence Erlbaum Associates.

MacKay, C. K., Brazendale, A. H., & Wilson, L. F. (1972). Concepts of horizontal and vertical: A methodological note. Developmental Psychology, 7, 232-237.

Macready, G. B. (1975). The structure of domain hierarchies found within a domain referenced testing system. Educational and Psychological Measurement, 35, 583-598.

Macready, G. B. (1982). The use of latent class models for assessing prerequisite relations and transference among traits. Psychometrika, 47, 477-488.

Macready, G. B., & Dayton, C. M. (1980). The nature and use of state mastery models. Applied Psychological Measurement, 4, 493-516.

Mardell, C., & Goldenberg, D. (1975). For prekindergarten screening information: DIAL. Journal of Learning Disabilities, 8, 18-25.

Naeli, H. & Harris, P. L. (1976). Orientation of the diamond and the square. Perception, 5, 73-77.

Newell, A., & Simon, H. A. (1972). Human Problem Solving. Englewood Cliffs, NJ: Prentice-Hall.

Ninio, A. & Lieblich, A. (1976). The grammar of action: Phrase structure in children's copying. Child Development, 47, 846-850.

Nitko, A. J. (1980). Distinguishing the many varieties of criterion-referenced tests. Review of Educational Research, 50, 461-485.

Olson, D. R. (1970). Cognitive Development: The Child's Acquisition of Diagonality. NY: Academic Press.

Piaget, J., & Inhelder, B. (1967). The Child's Conception of Space. NY: Norton.

Piaget, J., & Inhelder, B. (1969). The Psychology of the Child. NY: Basic Books.

Rand, C. W. (1973). Copying in drawing: The importance of adequate visual analysis versus the ability to utilize drawing rules. Child Development, 44, 47-53.

Resnick, L. B. (1973). Hierarchies in children's learning: A symposium. Instructional Science, 2, 311-362.

Resnick, L. B., Wang, M. C., & Kaplan, J. (1973). Task analysis in curriculum design: A hierarchically sequenced introductory mathematics curriculum. Journal of Applied Behavior Analysis, 6, 670-710.

Serpell, R. (1971). Preference for specific orientation of abstract shapes among Zambian children. Journal of Cross-Cultural Psychology, 2, 225-239.

Thomas, H., & Jamison, W. (1975). On the acquisition of understanding that still water is horizontal. Merrill Palmer Quarterly, 21, 31-44.

Thissen, D. (1986). MULTILOG. Version 5 User's Guide. Mooresville, IN: Scientific Software, Inc.

Thorndike, R. L., Hagen, E. P., & Sattler, J. M. (1986). The Stanford-Binet Intelligence Scale: Fourth Edition. Chicago, IL: The Riverside Publishing Co.

Uprichard, A. E. (1970). The effect of sequence in the acquisition of three set relations; an experiment with preschoolers. Arithmetic Teacher, 17, 597-604.

Wechsler, D. (1967). Wechsler Preschool and Primary Scale of Intelligence. NY: The Psychological Corporation.

White, R. T. (1973). Research into learning hierarchies. Review of Educational Research, 43, 361-375.

White, R. T., & Gagne, R. M. (1974). Past and future research on learning hierarchies. Educational Psychologist, 11, 19-28.

Williams, H. G. (1983). Perceptual and Motor Development. Englewood Cliffs, NJ: Prentice-Hall.

Williams, H. G., Temple, E., & Bateman, J. (1978). Perceptual-Motor and Cognitive Learning in Young Children: Psychology of Motor Behavior II. Champaign, IL: Human Kinesthetics Press.