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ABSTRACT

Design theory should identify candidate designers, specify design behavior to be measured, and discriminate between behavior of designers and nondesigners. A study evaluated different formats of computerized structural display and data entry to measure design behavior. A program using graph theory as an internal data structure in the computer and as a display to the operator was developed. Graphics display was used to construct a learning task with directed graphs and graphic data entry. The subjects were given varying portions of the spatial cues ordinarily available in fixed display. Results showed that spatial cues offered through interactive graphics were a significant advantage in the learning of directed graphs. When spatial cues were available, no difference between different learning formats was found. When spatial cues were denied during learning, delay of the posttest was detrimental to performance. Regularly ordered formats of displays of directed graphics led to confusion for some individuals. In general, the use of interactive graphics for learning structural digraphs was better than the use of nonspatial media. (CH)

# MAN-MACHINE COMMUNICATION OF THE STRUCTURE OF ENGINEERING DESIGN PROBLEM INFORMATION

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## PREFACE

It is crucial in both Engineering Design Education and in the development of Computer-Aided Design systems that the activities involved in design be well defined.

Early in the work of applying computer graphics, it quickly became apparent that no specific description of design behavior existed, nor had the form of the theory been rigorously defined. It also became obvious that the research methodology for developing such a theory would have to be synthesized from current work in Mechanical Engineering, Psychology, Mathematics, Information Sciences, and other disciplines. An important requirement for identifying this new research approach, because of its newness, was that portions of the method itself would have to be investigated to validate its usefulness as a research paradigm.

The major contribution to work in this area, although not stated in these terms, was the first truly behavioral theory of design. Allan[1] was substantiating the view that the designer was an information processor, and cited as evidence several specific kinds of information the designer communicates to his environment. It is the detailing of the kinds of communication that constitutes a behavioral theory.

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[1] John J. Allan III, Man-Computer Synergism for Decision Making in the System Design Process, CONCOMP Report No. 9, Office of Research Administration, University of Michigan, 1968.

The present work will generalize Allan's initial notions into a workable hypothesis and will rigorously define a research methodology to test it. This work presents evidence about its usefulness and optimal implementation.

The author gratefully acknowledges the contributions of Dr. John J. Allan, III, Major professor, to the main theoretical thrust of the present study, and to the practical task of overcoming physical and emotional obstacles to the completion of this work. No smaller contribution was that of Dr. James M. Swanson, second reader, whose assistance was essential in the experimental design and analysis, and who taught the author that nothing is as embarrassing as confounded factors in an experiment.

The author also gratefully acknowledges discussions with Melvin R. Corley, Department of Mechanical Engineering, Dr. Sam J. Castleberry, Project C-BE, the comments of Mr. Jakob Vlietstra, N.V. Philips Gloeilampenfabrieken, Eindhoven, Netherlands, and the contributions of Mr. Tom Montemayor who encoded portions of the programs on the NOVA-BASIC CBERT system.

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# CHAPTER I

## INTRODUCTION

The problem addressed in this thesis is part of a larger problem, the solution of which will take several years in addition to the present work. This continuing effort has, as its objective, using the capabilities of computer-based media for augmenting the performance and teaching of Engineering Design.

If one desires to train an individual to perform as well as a designer in design tasks, then it is implied that performance can be detected and measured to evaluate that individual's progress. These behavioral descriptions of design activities are not available at present. They are a prerequisite to the main objective, as discussed in Chapter II, and therefore must be determined.

Thus, Chapter II is devoted to the fundamental considerations involved in developing a theory of design behavior. It outlines the constraints it must satisfy to be useful to the main objective. It elaborates a plan of research, and discusses an initial view of design behavior that permits the selection of the media and the experimental design.

Chapter III is devoted to the description of the system developed for both the experimental research and the classroom implementation. The theoretical background of the system is discussed, and an algorithm used in the training of individuals in a learning situation is presented. The use of interactive graphics as the interface between the man and the system is described in detail.

Chapter IV is the formal definition of the experimental problem addressed by this thesis, and several possible methods are discussed.

Chapter VI is a discussion of the results of the experiment and Chapter VII presents conclusions and recommendations.

## CHAPTER II

## ENGINEERING DESIGN AS A HUMAN BEHAVIOR

The task of designing systems for use by human beings has as its final objective the enhancement of human behavior. This is the essential and inherent purpose in the preparation of tools for humans. Behavior augmentation is the goal of creating tools. The specification of the operation of the tools must be in behavioral terms.

### Why a Behavioral Theory is Needed

Consider the tools used by engineering designers. The behavior to be enhanced is obviously more complex than, and different from the behavior generally enhanced by a hammer or a screwdriver. Computer-aided design has produced many hardware and software configurations intended to help solve problems. Their success has been limited because their originators forgot that it is still the designer, not the computer, that solves the problems.[2] Whether he solves his problems by decisions about (1) the meaning of the input and output of problem information to a computer program, or (2) goes one step more and performs the calculations and iterations himself, is of secondary importance. A clear behavioral theory of design is the proper starting place for the design of a CAD system.

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[2]John J. Allan III, "Interactive Product Design." Proceedings of NSF Manufacturing Industries Workshop," Ann Arbor, Michigan, May 2-4, 1973.

The lack of a theory of design behavior also affects engineering design education. The skill to be taught or encouraged in the classroom is usually described in the literature primarily in terms of processes which are internal to the designer and, therefore, not directly detectable.

Design Education is concerned with two general aspects of the students' behavior: (1) the acquisition of design skills, and (2) design behavior itself. The acquisition of design skills depends on what design behavior is. No pedagogical technology can be properly applied until the nature of design behavior is specified. A set of constraints that a theory of design behavior must satisfy in order to be pedagogically useful is developed below.

It is important to remember, when evaluating a theory about how something behaves, the value of the theory is dependent on how well it predicts and what that particular thing will do, given a certain situation. If one proposes that a designer performs analysis on a problem, that statement alone predicts nothing that we can directly observe. If the designer blurts out a quick solution, did it come from some skillful analysis, or a lucky guess? If one proposes that a designer tends to partition problem information into sub-tasks, sets of data, etc., and specifies topologies between those tasks and data---and if one fails to observe those activities---then according to that proposition, the subject has not "designed;" he has done something else. If the validity of this simple test is acknowledged, then lists of attributes[3] or otherwise, academic topics of

[3] P. Barkan, et. al., "On the Goals of Mechanical Design Education: A 1971 Report of the ASME Design Education," ASME Paper No. 72-DE-1.

study, are insufficient. They only imply, but cannot predict, the behavior of designers. Some attribute lists and academic topics are easily transformed into behavioral theory by authorities in the field, and thus are of great benefit in the initial stages of curriculum design.

In this chapter, the author proposes that design behavior can be accurately detected by measuring the information interchange between the designer and his environment. It is assumed, and hopefully can later be fully validated, that such an information processor model of design behavior is a specific description of what the designer does. It is assumed that some set of behaviors exist that are specific to designers, and that designers comprise some unique group that, when properly identified, will be somewhat consistent. The end result must be some specific description of their behavior, though not necessarily quantitative. One of the major tasks of engineering is finding unique descriptions of engineering situations.

Thus, this chapter will discuss design theory as it appears in the literature, and its value in the design of environments to assist human beings who are supposed to be designing or learning to design. Some current efforts in the modeling of human behavior that parallel the author's are also discussed. Constraints that a theory of design behavior must satisfy in order to be pedagogically useful are developed along with some physiological and psychological considerations. A plan of research and implementation in a course in machine design at the undergraduate level is outlined. A hypothesis about the nature of design behavior (intended to govern and delineate the choice of research and implementation methods) is discussed and explained. Finally, the information processor theory of design behavior is compared with other theories.

Theories of Design and Design Behavior

This discussion will have served an important function if only it makes clear the distinction between a theory or methodology of design, and a theory of design behavior. The study of design methodologies is essential to advancing design as a discipline, yet the research effort in and of itself is of little use to the engineering educator. The engineering educator can be seen as one who has been directly or indirectly hired by the student to change that student's behavior to that of a designer. Whether that objective can be obtained efficiently by lectures and homework problems on selected topics in design methodology has not been established. In any event, it is appropriate at this point to review the several theories of design and design behavior to see what general assertions about design behavior are being stated or implied.

Most theories of design are elaborations of a familiar theme: Design is the achievement of goals under constraint. Harrisberger[4] has collected several theories of both design and design behavior. Design methodologies are discussed as checklists of design steps. Creativity is presented as a means of generating alternate solutions, while critical decisions maintain control of the design process. Prescribed behaviors for designers that are implied by Harrisberger might be: creativity as shown by the number of alternates offered for consideration, or evaluative intuition and judgment as shown by criteria for rejecting and accepting candidate solutions. In this form, behavioral descriptions are missing.

[4] Lee Harrisberger, Engineersmanship, A Philosophy of Design. Belmont, California, Brooks/Cole Publishing Company, Inc., 1966.

Dixon proposes a theory of design behavior involving three processes: (1) inventiveness; (2) analysis; and (3) decision making.[5]

Inventiveness is defined as "the ability to get new or useful ideas for accomplishing engineering goals," and is determined by three qualities: (1) newness or uniqueness; (2) usefulness or appreciation by others; and (3) simplicity or elegance.[6]

Analysis is defined as "the process of applying basic principles to problems in order to arrive at meaningful answers in a reasonable time." The process of analysis is described in terms of eight steps: (1) developing a specific operational definition of the problem in a quantitatively answerable form; (2) model formation by assumption; (3) principle application or data gathering; (4) computation; (5) checking; (6) evaluation and generalization; (7) optimization; and (8) presentation and communication of results and recommendations.[7]

Decision-making is defined as "compromise" and has the essential characteristics of: (1) an objective; (2) alternate courses of action; and (3) relevant factors.[8]

Asimow[9] introduces the notion of "Activity Analysis," which is a description of intervening processes to be performed on problem data input to

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[5]John E. Dixon., Design Engineering: Inventiveness, Analysis, and Decision Making. New York, McGraw-Hill, 1966.

[6]Ibid., pp. 22-23.

[7]Ibid., p. 9, 10, 11.

[8]Ibid., p. 243.

[9]Morris Asimow., Introduction to Design. Englewood Cliffs, N.J., Prentice-Hall, 1962.

generate evidence for a decision. This decision is some process of selection according to appropriate criteria, and is sensitive enough to illuminate directions for improvement.

Asimow's approach was extended and supplemented by Woodson[10] with heavier emphasis on the informational aspects of design and a broader definition of the role that graphics can play in the information flow.

Woodson revitalizes the question of the value of graphics in the engineering design environment by offering an expanded definition of the role it plays as a communication medium. He discusses graphics as: "A coding technique, using the art and science of drawing together with the conventions of line and symbol to transmit information visually from sender to receiver."[11] Woodson lists the following engineering uses of graphics: (1) specification; (2) visualization/synthesis; (3) determination of dimensions; (4) computation; (5) showing relation and emphasis; (6) persuasion and selling; and (7) recording.[12]

Implied in the above list is the transmission of trends, distributions, topological directedness and connectedness, gradients, surfaces, and "feeling."

Other individuals have emphasized the importance of intuition[13,14]

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[10]Thomas T. Woodson., Introduction to Engineering Design. New York, McGraw-Hill, 1966.

[11]Ibid., p. 163.

[12]Ibid., p. 166.

[13]Perry H. Hill., "Teaching an Engineering Sixth Sense." Engineering Education, April, 1971, p. 834.

[14]C.T. Freund, "Information + Intuition = Decision," Mechanical Engineering. October, 1969, pp. 30-34.

visualization[15,16] and general "engineering judgment" in design acitivities.

To summarize, theories of design behavior in general consider: novel solutions (creativity), skill in quantifying solutions and their models (analysis), skill in interpreting and evaluating the characteristics representing those solutions (decision making, judgment, and intuition), and skill in implementing solutions in real-life situations.

## Usefulness of These Theories of Design

These and other published theories of design which are based on general speculation about the intellectual processes internal to the designer are inadequate for direct implementation. Their failing is the lack of a description specific enough to allow detection and measurement of the behavior.

A curriculum developer must extract those behaviors which are to be the objectives of his particular course. He must then detect or measure these behaviors in his students as an indication of the degree to which they have acquired design skills, These behaviors cannot be extracted from the work cited above.

Thus, the usefulness of these theories is in providing background for the elaboration of a behavioral theory in an implementable form. The constraints that such theories must satisfy will be discussed later.

## Current Efforts

To the author's knowledge, there is no research effort exploring information processing behaviors specific to design as inferred from empirical studies

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[15] Robert H. McKim., "Visual Thinking and the Design Process," Engineering Education. March, 1968, pp. 795-799.

[16] Rolf A. Faste., "The Role of Visualization in Creative Behavior." Engineering Education. November, 1972, pp. 124-127, 146.

in the manner described in this paper. There is, however, related work which has been reviewed elsewhere. Schrenk[17] has discussed a decision process model of human decision making which involves three phases: (1) problem recognition, (2) problem diagnosis, and (3) action selection. Annett[18] proposes a feedback model of behavior involving information about a task, and feedback comparisons of task requirements and a subject's behavior. Annett also discusses the superiority of this model in complex perceptual and cognitive tasks. Carbonell[19] has modeled man's relation to the computer as simple state vectors.

Parallel with these attempts to model individual behavior is the growing realization in the behavioral sciences that in a probabilistic world, the properties of tasks must be considered in accounting for behavior.[20] Slovic and Lichtenstein[21] discuss the two predominant models used in the study of information processing in probabilistic judgment situations: regression analysis and Bayesian analysis. Models of design will require some treatment of the problems of constraint

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[17] L.P. Schrenk, "Aiding the Decision Maker---A Decision Process Model,: IEEE Tran. on Man-Machine Systems, Vol. MMS-10, No. 4, Part 2, 1969, pp. 204-218.

[18] John Annett, Feedback and Human Behavior. Middlesex, England, Penguin Books, 1969.

[19] Jaime R. Carbonell., "On Man-Machine Interaction: A Model and Some Related Issues," IEEE Trans. on Systems Science and Cybernetics, Vol. SSC-5, No. 1, January, 1969.

[20] Ward Edwards, "Bayesian and Regression Models of Human Information Processing---A Myopic Perspective," Organizational Behavior and Human Performance, Vol. 6, 1971, pp. 639-648.

[21] Paul Slovic and Sarah Lichtenstein, "Comparison of Bayesian and Regression Approaches to the Study of Information Processing In Judgement," Organizational Behavior and Human Performance, Vol. 6, 1971, pp. 649-744.

theory[22], decision theory[23], and utility theory. [24]

Wales has developed a behavioral theory called "guided design." While it does not examine the information interchange, it is in specific enough terms to allow the derivation of behavioral objectives and implementation in a course in design[25]. Results to date have been promising[26], but there is no information on the behavioral predictive quality of the theory, i.e., whether it can, with reasonable certainty, predict who can be a designer and what designers tend to do in given situations.

The Assumption of Psychology: Behavior Can Be Measured

It is assumed in psychology that behavior can be measured. Thus, when one talks about design behavior, one is hopefully referring to something that can be measured by some means. It is difficult to measure an idea, but comparatively simple to measure the products of ideas when they lead to behaviors such as drawing layouts, specifying materials and dimensions, etc. Thus, the author assumes that design behavior can be measured.

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[22] George J. Friedman and Cornelius Leondes., "Constraint Theory, Part 1: Fundamentals." IEEE Trans. on Systems Science and Cybernetics Vol. SSC-5, No. 1, January, 1969, pp. 48-56.

[23] Ronald A. Howard, "The Foundations of Decision Analysis," IEEE Trans. on Systems Science and Cybernetics, Vol. SSC-4, No. 3, September, 1968, pp. 211-219.

[24] R.S. Schermerhorn and M.I. Taft., "Decision Making with Utility Theory," Machine Design, February, 1969, pp. 122-126.

[25] Charles E. Wales, "Educational Systems Design," Engineering Education, March, 1969.

[26] M.S. Tseng, and C.E. Wales, "Effect of a Guided Design Course Pattern on Student Personality Variables," Engineering Education, Vol. 62, No. 7, pp. 812-813.

The Assumption of Education: Behavior Can Be Changed

The implementation of behavioral objectives is made possible by the pedagogical assumption that behavior can be changed, i.e., that existing entering behaviors can be changed to desired exiting behaviors. The technologies employed will depend on the entering and exiting behaviors defined.

This assumption implies that the form or direction of this change is somehow dependent on what is experienced in the classroom, which, in turn, should be dependent on the behavior of the student's environment. It is assumed, therefore, that the instructor is somewhat in control of how the behavior changes, either directly, or indirectly through design of the environment.[27]

Educational Requirements of a Theory of Design Behavior

A theory of design behavior must be able to withstand several demands made upon it for it to be of use in an educational environment. It must identify:

(1) Who can be a designer, and by what aptitudes and skills candidate designers can be identified,

(2) The specific set of behaviors by which designers can be descriminated from nondesigners, in such a way that they can be detected and measured, and

(3) The designer and nondesigner reference groups between which the set of behaviors will discriminate.

Descriptions of Candidate Designers Must Be Specific

The identification of prerequisite skills is too often left to some simple

[27]B.F. Skinner, Beyond Freedom and Dignity, New York, N.Y., Alfred A. Knopf, Inc., 1972.

specification of prerequisites for a course claiming to teach the discipline under consideration, i.e., materials or analytic geometry. Prerequisites required of candidate designers are more useful in the form: the student will be able to give a mathematical definition of normal stress and define each term from memory, or the student will be able, given a two-dimensional data graph, to indicate which regions satisfy inequality constraints. The first example is the operational definition of some prior bit of knowledge deemed necessary in learning more about machine element design. The second example is a demonstration of a skill in interpreting graphical information. These examples are different from requiring that: the student knows about normal stress, or that he knows how to interpret graphs. Better means of specifying graphical interpretation skill may be possible, as will be discussed later.

Descriptions of Design Behavior Must Be Specific

A designer has been judged to be someone who behaves in the same manner as a group of people generally agreed to be designers. The description of design behavior involves two parts:

(1) The set of behaviors which will discriminate between designers and nondesigners. These behaviors must be specific enough to be detected and measured, and the method of detection and measurement must be clear. It is pedagogically insufficient to specify that he gets a "right" answer to a particular problem, unless the finding of that particular answer has been shown

to discriminate between designers and nondesigners.

(2) The reference group of individuals taken to be designers and the group of individuals taken to be nondesigners (or poor designers), and their selection criteria. The arbitrariness of the selection of these groups is what gives credibility to the empirical approach. The criteria for selecting these groups depend on the kinds of designers to be discriminated. One researcher might select a group based on the number of patent applications in the last ten years, while another might use supervisors' evaluations of the amount and quality of individual work. The former criteria might select creative designers, the latter, a group of productive detailers.

Physiological and Psychological Considerations

This complex behavior called design has a heavy dependence on verbal and spatial media. In the testing process used for detection, it will be important to account for differences between left and right hemispheres. The left hemisphere is primarily concerned with writing and speaking, while the right hemisphere is concerned with spatial and contextual features. Because of this lateralization, it is possible that the hemisphere dominant in a particular acitvity may utilize different processes or strategies in the solution of a problem. This means that during the testing of designers, the use of a different media can give different results. Although lateralization has considerable empirical backing, theories as to the mechanism behind this effect differ greatly[28] and, for the present purpose, the possibility of bias from media in design activities must be investigated.

Without knowing which behaviors are those specific or attributable to designers, it is not possible to say which of the many technologies to aid learning will be best suited to changing the behavior of candidate designers. In view of the emphasis on judgment policy by Balke, Hammond, and Mayer,[29] Hammond and Boyle,[30] and in multiple cue probability learning by Hammond and Summers,[31] Hammond.[32] In addition, there is a theory of instruction available which places heavy emphasis on cognitive factors and cognitive transfer by Merrill.[33]

More documentation of the specific behavioral technologies to be used

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[28]Joseph E. Bogen, "The Other Side of the Brain II: An Appositional Mind," Bulletin of the Los Angeles Neurological Societies, Vol. 34, No. 3, July, 1969, pp. 135-162.

[29]W.M. Balke, K.R. Hammond, and G.D. Meyer, Application of Judgement Theory and Interactive Graphics Technology to Labor-Management Negotiations: An Example. Report No. 145, Institute of Behavioral Science in Conjunction with the School of Business Administration, University of Colorado, 1972.

[30]K.R. Hammond and P.J.R. Boyle, "Quasi-Rationality, Quarrels, and New Conceptions of Feedback," Bulletin of the British Psychological Society, Vol. 24, 1971, pp. 103-113.

[31]K.R. Hammond and D.A. Summers, "Cognitive Control," Psychological Review, Vol. 72, 1972, pp. 58-67.

[32]Kenneth R. Hammond, "Computer Graphics as an Aid to Learning," Science, Vol. 172, No. 3886, May 28, 1971, pp. 903-908.

[33]David M. Merrill, "Content and Instructional Analysis for Cognitive Transfer Tasks," unpublished paper, Brigham Young University, September 24, 1972.

in the pedagogical environment will be written as the theory of behavior takes shape. No technology can be intelligently implemented without a theory that predicts behavior in sufficient detail to indicate that technology's use. This constraint, that a behavioral theory exist, demands that a precise specification be formulated for the existing behavior of the people who will be users of the curriculum under development.

Stages in One Use of a Theory of Design Behavior

The constraints that a theory of design behavior must satisfy, and the implementation constraints that are placed on the set of educational modules that will be derived from this theory, dictate a characteristic phasing of curriculum development.

Phase 1. The definition of behaviors to be measured, and the conceptual design of a system which can be adapted to both empirical testing of experienced designers and instruction of candidate designers.

Phase 2. The empirical testing of experienced designers in a pilot study to insure that the system is sensitive enough to detect design behavior in a way that will discriminate between designers and nondesigners. This phase includes the revision of the criteria for selection of designers and the revision of the system capabilities, where required. In parallel, modules must be designed which will change student behavior in desired directions.

Phase 3. Final empirical measurement of designer reference group behavior. Documentation of criteria and procedures for selecting the designer reference group.

Phase 4. Final revision of modules.

Phase 5. Student use of the modules for validation of the curriculum showing the degree of design behavior present. Items of tests over aptitudes, prerequisites, etc., which show predictive value, will become the specific description of those who are candidate designers as defined by the theory developed.

An interactive graphics system has been selected as the research and pedagogical tool for the development of the information processor theory of design behavior. The authors are presently using IMLAC terminals. These are "intelligent" terminals with vector graphics capability. These terminals, coupled to various time-shared systems, give the authors precise control over alpha-numeric, spatial, and temporal features of information presented to an individual. This capability makes possible an unusual opportunity for the study of human behavior at a high level of complexity.[34] Two researchers in the use of interactive graphics for the study of cognitive behavior, Hammond and Boyle, state:

> "We would go so far as to argue that the psychology of learning is (mainly) a stimulus-response outcome-feedback psychology, not so much because it _wants_ to be, but because it _has_ to be; a low-grade technology will not let it be anything else."[35]

[34]William G. Beazley and John J. Allan III, "Interactive Graphics for Teaching Complex Design Skills." Sixth National Design Conference, ASEE, Detroit, Michigan, May 24-25, 1973.

[35]K.R. Hammond and P.J.R. Boyle, "Quasi-Rationality, Quarrels, and New Conceptions of Feedback," op. cit., p. 112.

The Information Processor Theory of Design Behavior

In a paper by Beazley and Allan,[36] they proposed the following theory of design behavior:

> Design behavior can be determined by the measurable information interchange between a designer and his environment. Furthermore, a designer is a person who interchanges information with the environment in the same manner as a group taken to be designers, and unlike a group taken to be non-designers---both groups are determined by popular recognition.

Activities internal to the designer, such as thinking, deciding, analysis, synthesis, etc., are represented in the communication of the designer with his environment. The authors further proposed that the qualities of the information interchange that can be shown to be specific to design are those which can discriminate between between designers and nondesigners. These qualities of information interchange will be some subset of the information interchanges between a designer and his environment.

Applying the Theory Without an Empirical Reference Group

It would seem at this point that no behavioral objectives can be derived from the theory without some empirical study of designers. This requires some idea of the information interchange the authors are investigating.

If design is characterized as information flow between a designer and his environment, that flow must necessarily pass through some sort of interface

[36]William G. Beazley and John J. Allan, III, "Engineering Design as a Human Behavior," ASME Paper No. 73-DET-43, 1973.

(written instructions, site photographs, layouts and views, spoken words, etc).[37] The information that flows will be either verbal, spatial or topological, will relate to real-time, and can be measured or identified if the interface is sensitive to it. For an initial assumption, the author characterizes this informaion flow as the following behavior by the designer:

(1) specifying the partitioning of design information

(2) specifying topologies of design information.

Specifying partitions might be viewed as a complex discrimination behavior, while specifying topologies might be viewed as cognitive-conceptual behavior. Before these two behavioral assumptions are drowned in cries of oversimplification, the author would like to explain them and how an imperfect, limiting environment is seen to dilute and distort them.

First of all, partitioning, as discussed here, is what a designer does while he specifies a lack of relatedness between one group of things or processes and another group of things or processes. It is the identification of the uniqueness of the collection with respect to another. Specifying, defining, choosing, deciding, are acts that are basically partitioning in nature. The author believes that analysis, as explained in the literature, is behaviorally represented as a subset of partitioning activities. Parititioning activities <u>can</u> be directly measured.

Topologies are seen as the relations between the design activities, processes, physical components, elements of information, or the system being designed. Other important relations are the comprehension that the outcome of

[37]John J. Allan III, <u>Man-Computer Synergism for Decision Making in the System Design Process</u>, op. cit.

one calculation is an input for another, and that calculations, reference lookups, and laboratory test results, form the evidence for the designer's decisions.[38] Topologies, as discussed here, mean more than the physical relationship of components, they also describe the formal and structural relations among the information manipulated in the design. There are topologies of topologies, just as there are functions of functions, systems of systems, etc. The author believes that synthesis, as usually explained in the literature, is behaviorally represented as the specification of topology. Importantly, topology can also be directly measured.

Thinking again about design environments, an imperfect "design environment" is one that cannot satisfy all the constraints or specifications, one that lacks the capacity to deal with a definition, one not capable of offering the choices and options available to the designer. It is the imperfect environment that forces the designer to engage in activities such as programming computer solutions, manual computations, etc.

By limiting the behavior of designers, the imperfect "design environment" distorts their behavior. As mentioned previously, there are indications that a designer's modes of communicating bias the solution strategies and may lead to differing and conflicting conclusions in different design environments. This is one example of possible distortion.

Thus, in an imperfect design environment, with its limited repertoire of options and its limited capacity for relating those options topologically, the designer is forced into behavior handled best by librarians when gathering

[38] Morris Asimow, Introduction to Design., op. cit.

information, by computers when performing calculations, by technicians and draftsmen when elaborating the details of a solution, etc.[39] The author is not advocating that designers not be skilled in these areas, not that they never work in these disciplines, but is proposing that only two detectable activities are specific to designers. Hence, any method of detecting behavior as assumed will be limited by its capacity to detect the specification of design partitionings and topologies, and should hold true for designers of physical, social, economic, and other systems.

Comparison with Other Theories of Design Behavior

The information processor theory of design behavior is partly based on a reluctance to speculate about what is going on inside a designer's head. Speculation about processes internal to the designer, without discussion of their behavioral outcomes, cannot be implemented because nothing has been predicted which can be observed. Hence, no behavioral objectives can be derived.

Another major tenet of the information processor theory of design behavior is its dependency on some empirical reference group for descriptions of design behavior. This is not to say that no insight can be gained by studying formalized theories of design as attempts at recording those design practices which have proved most efficient over the years. However, there is a point in a person's description of his own thinking processes where he is unable to express in words a judgment process that he can easily demonstrate. This has been shown in the

[39] P.A. Shears, "Engineering Design as an Information-Processing Activity," Electronics and Power, March, 1971, pp. 100-103.

clinical diagnosis of ulcers[40] and student evaluations of the socioeconomic development of hypothetical countries.[41]

It is of questionable value to teach students a designer's own verbal reports of his internal mental processes for two reasons:

(1) Even when a designer expresses his thoughts to others, his report may not, in fact, be an accurate description of what he is thinking.

(2) It has not been established that mere knowledge of a designer's thinking processes will result in the desired behavior. It is possible that inaccurate descriptions of design behavior presented to a receptive class of students is a simple case of cooperative delusion.

One final point must be resolved. Can an information processor model of design behavior account for processes internal to the designer? At first glance, the points of major disparity between the information processor theory and other theories of design behavior are the two internal processes: analysis and synthesis.

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[40] Paul J. Hoffman, Paul Slovic, and Leonard G. Rore, "An Analysis of Variance Model for the Assessment of Configural Cue Utilization in Clinical Judgements," Psychological Bulletin, Vol. 69, No. 5, 1968, pp. 338-349.

[41] David A. Summers, J. Dale Taliaferro, and Donna J. Fletcher, "Subjective vs. Objective Description of Judgement Policy," Psychonomic Science, pp. 249-250, Vol. 18, No. 4, 1970.

One of the better behavioral descriptions of analysis comes from Wales.[42] To demonstrate his ability to perform an analysis, each student should be able to:

(1) Break down a problem statement into its constituent parts and identify and classify its elements, including hypothesis, assumptions, facts, and conclusions. (ELEMENTS)

(2) Determine the relationship between the elements to explain their connections and interactions, including the ability to check the consistency of hypothesis, distinguish cause and effect relationships, and detect relevant and irrelevant ideas. (RELATIONSHIPS)

(3) Determine the arrangement, structure, and organizing principles, including the relation of materials and means of production, the purpose, and the techniques. (ORGANIZATIONAL PRINCIPLES) [43]

Wales, in the same paper, says:

Snythesis is defined as the process of putting together elements and parts, combining them in such a way as to constitute a pattern or structure not clearly there before. Therefore, to demonstrate his ability to perform a synthesis, the student should be able to draw upon elements from many sources and combine

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[42]Charles E. Wales and Robert A. Stager, "The Design of an Educational System" Engineering Education, Vol. 62, No. 2-5, February, 1972, pp. 456-459, 488.

[43]Ibid., p. 458.

these into a structure or pattern not previously known to him. Synthesis may result in the production of a unique communication, a plan, a design, or set of abstract relations.

Guidelines for the production of a plan, a proposed set of operations, or a design are: (1) the plan must satisfy the requirements or specifications (input, output, operating restrictions) of the proposed design; (2) the student may be given specifications, or he may have to assume them. These specifications furnish the criteria for the evaluation of the design.[44]

The communications between a designer and his environment that roughly corresponds to these two activities are the specification of processes, and the specification of the topology relating the processes. He does this such that an input of specified problem information will yield evidence for comparison to the evaluation criteria also derived from the problem. It is tacitly assumed that the communication for solution does not yet exist; i.e., it is novel for the receiver. Otherwise, he would not have requested the design. Thus, almost by definition, designs must be or seem to be new to the environment, even if large parts of the design are old.

Even in the specification of processes and toplogies, the authors are reluctant to view these behaviors as independent acts. A particular process may greatly influence the topology of a particular system, and likewise, topology already

[44]Ibid., p. 459.

specified can determine the remaining processes. Bennington and Rattray[45] see engineering system design itself as a special problem in mapping, as defined by Mesarovic in Bennington and Rattray, where a system is denoted by:

$$S = (X, Y, T)$$

where S denotes the system itself, while T represents a constructive procedure specifying how we obtain Y for a given $x \varepsilon X$. Thus, the analysis problem becomes:

given X and T - find $Y = T(X)$

while the synthesis problem is:

with X and Y given - find T such that $Y = T(X)$.

Since what is required in the information processor model is the communication of the system under study, complete with topology, the author feels safe in assuming that analytical and creative processes internal to the designer are being accounted for, if design behavior is defined in terms of communicated information only.

Recalling that analysis is popularly attributed to the intelligent, and synthesis is often attributed to the creative, one behavioral scientist, Cropley,[46] expounds the view that creatives and noncreatives differ only in their cognitive styles of processing information from the environment.

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[45] B.J. Bennington and C.M.I. Rattray, " A General Examination of Engineering Design," a paper presented at SHARE-ACM-IEEE Fifth Annual Design Automation Workshop, Washington, D.C., July 15-18, 1968.

[46] A.J. Cropley, Creativity, Longmans, Green, 1967, pp. 34-43, exerpted in E.P. Vernon (ed.), Creativity, Middlesex, England, Penguin Books, 1970.

"Thus, those people whose cognitive style involves the least censoring of the information available to them from the external world are most likely to be creative thinkers."[47]

This is a further indication that as complex a skill as synthesis can be accounted for in the information interchange.

Thus, it seems that the information processor model of design behavior can account for the internal processes of the designer. The author suggests that partitioning, as described here, corresponds to analysis, and that specifying topologies, considering the inclusive connotation given here, corresponds to synthesis.

Interactive Graphics as the Research Implementation Media

The media selected must be able to detect and measure specifically these behaviors in a controlled manner. The author decided that a vector-capable interactive graphics terminal with a lightpen could do most everything required. Besides satisfying the constraints on theory development, it automatically becomes the implementation media for the theoretical findings.

The use of interactive graphics as the research media gives the author important advantages in achieving the goal of implementing behavioral objectives in a course about machine design.

(1) The media for theory development is also the implementation media, reducing adaptation and technology transferability problems.

[47] Ibid, p. 123.

(2) The interactivity of the media increases the contingency of the media on the student response.

(3) The media is sensitive to both verbal and spatial inputs and allows displays and interaction that are close to real-life situations.

(4) The interface offers near-perfect repeatability and control as a stand-alone interface with host system, and an acceptable repeatability and control in a time-sharing environment.

(5) The authors anticipate that the highly iterative methodology of design makes the computer generation of interactive simulation outcomes more efficient than other methods of media preparation, when hours of programming per number of student solution attempts is compared to hours of lecture preparation, homework diagnostics, and quiz evaluation per number of student solution attempts.

(6) The vector-capable intelligent terminal permits testing and study with more differentiation <u>between</u> verbal and spatial responses, and <u>within</u> these two types of responses as well. With the lightpen it is possible to ask not only illustrated questions, but also graphical questions whose answer might be a line segment or a point.

(7) The biases in problem solving strategies induced by form of presentation (verbal description or graphical representation) and form of solution communication can be controlled and studied.

Some of the disadvantages of this choice of media might be unanticipated and/or uncontrolled factors introduced that might lead to confounded results and behavior that is not only specific to designers but specific to interactive graphics as well, causing serious transferability problems.

Potentials of This Type of Work

The most probable parameters for the measurement of the topology of the partitions, and the topologies specified in the course of design, will be the structure, directionality, and completeness of the specification. These measurements will depend on the capabilities of the environment, to measure them (as represented by the interface to the designer). These parameters will change with time and experience, and the tendencies of that change will yield valuable information about design behavior, too. The important factor is the capability and sensitivity of the environment.

When the lawful relationships between design situations and behavior are better known, then it should be possible to augment its acquisition. It becomes possible to conceive of a design environment which is not only capable of and responsive to design activities, but which can also enhance and be adaptive to the individual. Students might be able to select, or be tested and advised of the kind of designer their curriculum will teach them to be, and an adaptive instructional media could transform itself into an individualized course of instruction.

In considering the potential of modeling the designer himself, one should perhaps tentatively accept the fact that the most efficient form of design behavior is that of directing, (not performing) the solution of design problems.

This assertion does not ignore the fact that many present problems require massive human intervention in the achievement of the solution. It only means that the more effective the intervention, the more effective the designer. Just as the sliderule increased the effectiveness of the designer, so did the computer. The efficient use of more powerful tools depends on designing more powerful interfaces between designer and tool. This is where interactive graphics offers attractive possibilities.[48]

Surprisingly, little is known about human perception of spatial and topological configurations, even though this is a natural language of designers. designers. What design needs is a behavioral technology applied to engineering graphics to optimize its effectiveness as a communication media.

This technology, applied to an interactive, computer-based display system, makes three advances in the training and augmentation of design behavior: (1) the precise control of the training of design behavior so as to optimize the perceptual-cognitive skills the designer develops or acquires, (2) the precise control of the designer's exposure to problem information so as to optimize his use of perceptual-cognitive decision making skills, and as a result, (3) increase the effectiveness of the designer by allowing him to direct and control more powerful processes through a more efficient interface.

[48]William G. Beazley and John J. Allan, III, "Interactive Graphics for Teaching Complex Design Skills." op. cit.

## CHAPTER III

## AN INTERACTIVE, INTERDISCIPLINARY, ON-LINE GRAPHICS SYSTEM FOR PRESENTING AND MANIPULATING DIRECTED GRAPHS

In order to detect and to measure the man-machine communication of structure, a system of programs has been developed in Data General Extended BASIC. In this paper the parent system, the system for manipulating directed graphs, and the use of this system as applied to engineering design will be discussed.

The reasons and expectations for choosing interactive graphics for a research medium for man-machine communications is based on the assumptions made for work in engineering design in Chapter II. The goal of that effort is to measure performance of designers during the solution of real design problems. Such a measurement system requires that designers select from options available to them and specify a structure or structures among those options. These requirements are satisfied by the programs discussed in the present paper.

### The Parent NOVA-IMLAC CBERT BASIC Interactive Graphics System

The host computer system on which the routines of interest were developed has a unique set of advantages and disadvantages in the experimental educational environment. The central theme of the NOVA-IMLAC system is the use of an intelligent, vector-capable, interactive graphics terminal as an extremely sensitive interface to a relatively inexpensive minicomputer-disk configuration running Extended BASIC.

This results in a master-slave relationship between the NOVA mini-computer and the IMLAC graphics terminal in which the NOVA bears the burden of data manipulation. A heavy emphasis on data manipulation in the IMLAC terminal would have decreased the chances of transferring the routines to another system at a later date. As the amount of data manipulation at the intelligent terminal increases, the need for a graphics-oriented specialized configuration increases. As a result, the probability of adapting the developed software would decrease.

There were other advantages to this strategy. The NOVA mini-computer communicated with the IMLAC terminals through BASIC CALLS to machine language subroutines, leaving BASIC unchanged in syntax. The use of the developed software for the IMLAC requires, then, only the writing of the interface subroutines at a particular site. Software efforts for the NOVA and the IMLAC also could be begun and continued semi-independently with a minimum of revision when the combined parent system became operational.

The LOGOS executive is the resident software for the IMLAC graphics minicomputer. It was designed and written to take full advantage of the long-vector capability, lightpen, and push-down subroutine stack features of the IMLAC minicomputer.[49] LOGOS (Level-Oriented Graphics Operating System) permits the multiple use of a single set of drawing instructions, and, as a result, a single graphical item (such as a circle) can appear hundreds of times on the

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[49] K. R. Speaker, "Level-Oriented Graphics Operating System Documentation," Project C-BE, NSF Grant GY-9340, The University of Texas at Austin, Texas, 1973.

graphics screen by using LOGOS subroutine calls. In addition, each of these graph item appearances can be made to return a unique pair of parameters when detected by the lightpen.

The lightpen capability is not limited just to graphical items. Also, displayed letters or words (verbal displays composed of user-definable characters) can be sensitive to detection by the lightpen and return a pair of values.

A tracking cross can be positioned on the screen, and the raster values of the X-Y location can be requested allowing graphical data entry to a limited degree. This is entirely adequate where a point in space is to be communicated, or for similar tasks.

The result is a flexible interactive graphic display capability in a resident, but easily interfaced, executive. In experimental or educational tasks, a subject's responses can take the form of a character, a word, a sentence, a point, a line, an arc, or any arbitrary composite of drawing instructions. This is all in addition to plotting and alpha-numeric display and editing capabilities.

In summary, the NOVA/CBERT-IMLAC/LOGOS interactive graphics system is designed to minimize the hardware-dependent aspects of graphics interaction while maximizing the graphics interface capabilities and sensitivity. It represents a favorable combination of flexibility, transferability, and cost.

The System for Creating and Manipulating Directed Graphs

In Chapter II the author discussed the view that designers will specify structural information (topologies) among the options in their environment. The following discussion is devoted to the data structure and display characteristics of one method of communicating structural information which will be evaluated in later chapters. The communication technique is commonly known as directed graphs. It is discussed as applied to the design of a system for creating and manipulating data structures and also as applied to a display technique.

The use of directed graphs has long been advocated as a representation of the structure of a set of components in a network. These components can be anything from various parts of speech, options in a design, probabilities of certain events, individuals in a group, etc. In addition, there is a set of ordered pairs specified on those nodes which, together with the set of nodes, specifies the structure or topology of these nodes. In some kinds of problems one can specify weightings and/or attributes with both the nodes and the ordered pairs. In set notation, this is:

A = Set of Nodes

B = Set of Ordered Pairs

C = Set of Node Attributes

D = Set of Ordered Pair Attributes

$$B = \{ \langle x, y \rangle : (x \varepsilon A)\ (y \varepsilon A) \}$$

$$C = \{ c : (c \varepsilon C)\ (\langle c, x \rangle \varepsilon M)\ (x \varepsilon A) \}$$

$$D = \{ d : (d \varepsilon D)\ (\langle d, \langle x, y \rangle\rangle \varepsilon N)\ (\langle x, y \rangle \varepsilon B) \}$$

By no means is this way of communicating structure limited to that already described, but the system discussed is constrained for practical reasons as described above. With each node there is associated an attribute number, a parameter which defines what kind of option that node represents. Since it is possible to select an option more than one time for use, another number, a unique number, is associated with each node as it is chosen. The set of ordered pairs specified on the set of nodes can be represented in matrix form as an adjacency matrix. It is specified as follows:

$$a_{ij} = 0 \text{ IF } (< i, j > \notin B)$$

$$a_{ij} = 1 \text{ IF } (< i, j > \in B)$$

The adjacency matrix is constructed according to the unique number. Thus the system is capable of creating the adjacency matrix of any network of any attribute to any degree of redundancy with the hardware space limitations of the host NOVA-IMLAC system.[50]

In learning tasks, application difficulties arise with respect to available technology for use. Experimentally, it is not only desirable to record the directed graph created by the Subject, but also to compare it to a target graph, since experimental designs would be experimenter-created digraphs.

[50]For a more detailed discussion of the properties of adjacency matrices, see F. Harary, Graph Theory, Reading Massachusetts, Addison-Wesley Publishing Co., Inc., 1969.

This requires an algorithm that can compare a subject-created digraph with the experimenter-created digraph and determine whether they are the same.

Again, the approach of using directed graphs benefits directly from existing technology. A subject-created graph will be structurally the same as the experimenter-created graph if they are isomorphic. This presents an immediate problem in the case where the nodes are redundant with respect to attributes (same type of node used twice). It may not be possible to distinguish quickly between nodes which have the same attributes and similar or identical interconnections with other nodes of the graph.

The decision was made to delimit learning task digraphs to digraphs without attribute redundancy. The comparison routine became a simple matter of ordering the subject-created matrix according to the arrangement of attributes of the experimenter-created matrix and performing a subtraction. Execution time on the NOVA-IMLAC system for the directed graph of 15 nodes is less than 1/2 second in the single-user case, an entirely acceptable delay for this complex application. In addition, the remainder of the matrix subtraction furnishes valuable information about the closeness of the subject's attempt to create the desired graph. The zero result indicates equivalence; the non-zero result gives information about presence of unwanted connections and the absence of desired connections. This can serve as feedback to the student and data for evaluation.

In the ways described above, the designer, student, and experimental subject can be measured in an accurate, controllable way for research and pedagogical purposes. Subject to certain constraints, a digraph can be compared to a target digraph, allowing for the use of tutorial tasks for teaching subject matter or for studying patterns of learning.

Representing the Directed Graph to the Creating Individual

Any directed graph can be specified by the set of nodes and the set of ordered pairs of first and last points. Displaying this to the individual using the graphical system is an important consideration, as these representations to the designer or student can influence, bias, or even distort his behavior in the task. Here, the graphical representation of the directed graph will be discussed in detail for general use, while special modification of the display for experimental evaluation and discussion of the possible ergonomic factors involved in the design of the display will be discussed in Chapter IV.

In discussing the display format to the Subject when constructing an arbitrary graph, consider the Subject confronting the blank display, as shown in Figure 1. Creation of the digraph, how it is edited, and the appearance of the feedback information during a learning task will be discussed.

In structural communication tasks, the set of design options, etc., are displayed at the right of the IMLAC graphics screen as a menu of verbal phrases inside of circles or squares. Each of these phrases is sensitized for the lightpen. At the bottom of the screen are additional one-word comments like "END," "LINK," and "DELETE." These are commands used for creating, editing, and requesting checks on the directed graphs. To create a digraph, the tracking cross is positioned on the screen and the desired option is chosen with the lightpen. Then the chosen option appears on the screen at the location of the cross (see Figure 2).

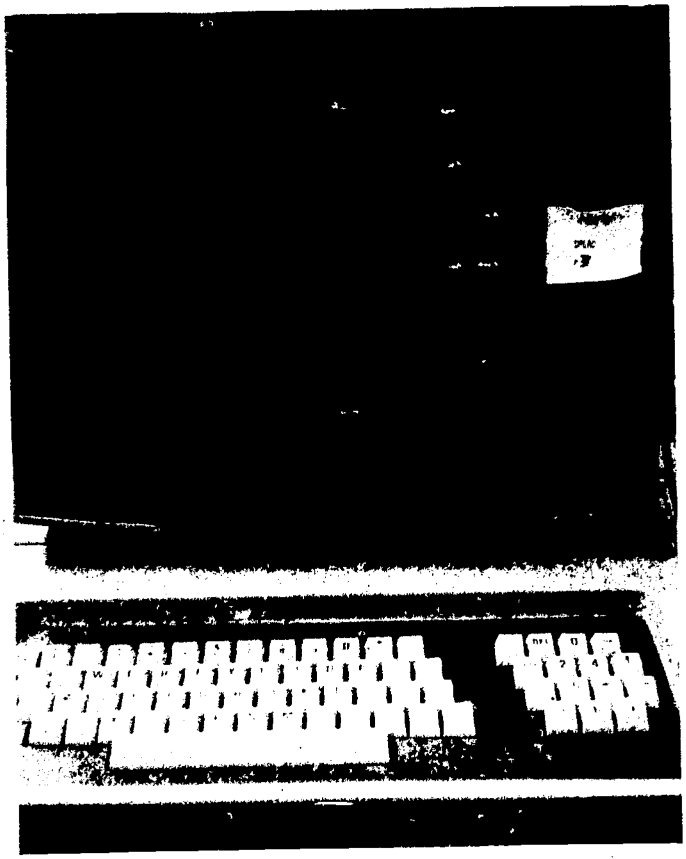

Fig. 1.---Initial appearance of the graphics screen.

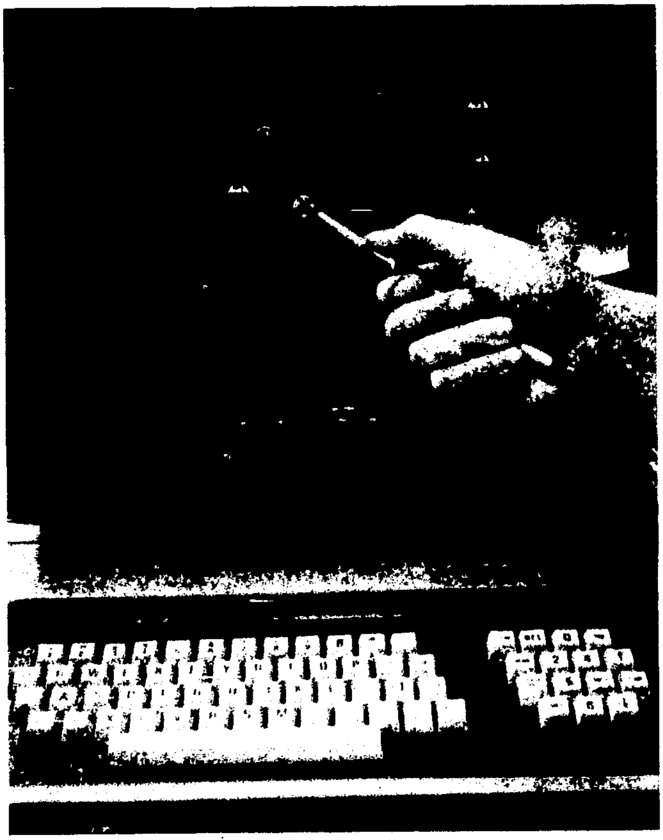

Fig. 2.---Student selects nodes from menu of options.

When an appropriate number (at least two) of options are assembled on the screen, the subject can link the options in a desired way by using the lightpen to select the "LINK" instruction at the base of the screen. Then the subject indicates the first and last nodes with the lightpen, and an arrow appears on the screen confirming his choice (Figure 3).

Fig. 3.---Student connects nodes to form directed graph.

Should it be desired to edit the graph, the subject merely hits the instruction marked "DELETE" and hits the node or line to be removed. The connection or node disappears and, in the case of a node, all connections to it disappear also.

During this creation and editing of the pictorial representation of the directed graph on the graphics interface, the NOVA BASIC main program accounts for the additions and deletions of nodes and connections by updating the adjacency matrix that corresponds to the graph. When the subject is satisfied with his response (Figure 4), he hits a lightbutton labeled "END" and the adjacency matrix is copied on a file along with important secondary information (like location on the screen, special names used for referencing nodes and connections in the IMLAC terminal). At this point, the main program can chain to any other desired routine.

In the situation where the routines are being used for student training in a design classroom application, the next routine in the chain is the one that compares the subject-created graph to a predetermined response graph. A matrix is formed which represents an adjacency matrix of the difference between the created and desired matrices.

This difference matrix is read by an interpretation-feedback subroutine which either indicates success, or blinks erroneous connections and draws in missing ones as dotted connections. This kind of spatial feedback is possible because of the capability of the system in detecting and interpreting the created directed graphs.

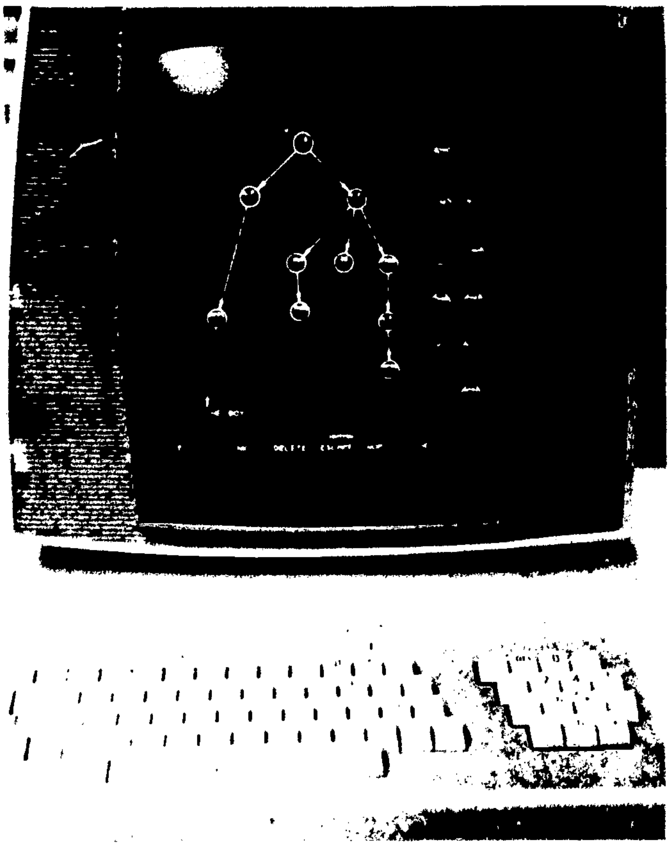

Fig. 4.---Complete student response.

The applications of system features described so far are not specific to any particular discipline. Rather, they can be applied to the measurement of any behavior with identifiable aspects that are unique and a structure described by ordered pairs. Examples of such behavior include the specification of sentence structure according to a transformation grammar (Linguistics), specification of group structure (Social Psychology), specification of material flow (Operations Research), specification of managerial authority (Business Administration), and the specification of design information flow (Engineering Design). The general nature of the approach and the widespread impact of its content-independent technology make the system described highly transferable at the conceptual level.

Before the system discussed here can be used to detect and measure designer performance in real design tasks, it must be investigated for the possible unwanted distortions of designer performance as discussed in Chapter II. Alternatively, it might be found that the use of any medium _other_ than interactive graphics induces unwanted decreases in performance when communicating structural information. As will be seen in the next chapter, this necessitated modifications to the system described so far to accomodate the experimental design.

## Summary

This chapter has discussed a program developed to detect and measure the communication of structure among known sets of options by the creation and editing of directed graphs. It represents the joint application of graph theory both as an internal data structure in the computer and as a display to the operator.

Digraphs are not the only structural relationships possible, but are applicable to a large class of problems in the laboratory and the classroom. Since the development of these routines, they have found application in Engineering Design education, Linguistics education, Journalism education, and graph format experimental investigations. Evaluations of the approach are discussed in Chapter IV.

# CHAPTER IV

## EVALUATION OF INTERACTIVE GRAPHICS AS A COMMUNICATION MEDIUM

The tentative selection of interactive graphics as the medium for presenting and manipulating directed graphs has permitted the development of the routines described in Chapter III. Before these routines can be used for research purposes in the measurement of designer performance, they must be investigated for usefulness and the presence of any unwanted decreases in performance due only to format. It is therefore necessary to determine what effects several possible formats of this communication method have on both learning performance and forgetting. Evaluation of the methods for using these kinds of tasks serves two important purposes. First, it will be necessary to train designers who will be participants in future studies on the uses of the medium during the course of which their performance will be measured. Second, the results of these initial investigations have immediate practical importance in classroom applications as described by Beazley, Swanson, and Allan.[51]

Since it is possible in practice to communicate digraph structural information without using interactive graphics, it is first necessary to determine if there is any improvement in performance when communicating using graphic

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[51] William G. Beazley, James M. Swanson, and John J. Allan, "An Interactive, Interdisciplinary, On-Line Graphics System for Presenting and Manipulating Directed Graphs," Third Annual Meeting of the National Conference on the Use of On-Line Computers in Psychology, St. Louis University, St. Louis, Michigan, October 31, 1973.

or non-graphic methods. Several possible methods are discussed in terms of their potential for controlling variables not of interest at present. The method finally selected involved certain limitations and assumptions, yet offered the best opportunity for accurate evaluation.

## Some Definitions

All of the methods that could be used to evaluate the value of interactive graphics as a communication medium involve an experimental condition that utilizes the spatial cues of interactive graphics, and compares them to some highly non-spatial communication method. This naturally follows from the observation that the primary advantages of interactive graphics are spatial cues available to the user in the display and data entry of information. Since the same information can be communicated, albeit more clumsily, over alpha-numeric terminals such as teletypes, the following question is to be evaluated: Does the spatial display of the directed graph offer any advantages over non-spatial displays for the communication of structure during learning and with various delays of retesting?

Spatial cues mean something more general than location in space; they are the appearance of the display as opposed to its content. In fact, even with total alpha-numeric displays of directed graphs (i.e., adjacency matrix displays), if the meaning of the particular terms or items of the display remains fixed throughout the task, the subject can base his decision that he has answered correctly less on a careful term-by-term check of entries in the display, and more on whether it "looks right." In highly spatial tasks, it is possible that the configuration or format of the response is in itself available as a cue to be learned.

In short, the subject in a learning task can formulate a "picture" of the correct response. It is not too difficult to argue that a graphics display is highly spatial.

The highly non-spatial display, on the other hand, is that type of display that could never be judged "correct" by appearance alone. Some item-by-item interpretation is required. Such would be the case when a student is required to communicate all the ordered pairs of a directed graph via teletype or other alpha-numeric terminal, and the order of entry of the ordered pairs did not remain fixed. In this kind of communication, it would be difficult for a student to give a completely correct response without memorizing the ordered pairs of nodes as ordered pairs. The author argues that in comparison to a graphics display, the alphanumeric terminal is highly non-spatial. It is otherwise capable of transmitting information in this non-spatial and perhaps less efficient format.

Possible Methods of Evaluation

There are three main experimental comparisons for evaluating the spatial cues of graphs to be discussed: (1) graphic display and graphic data entry, vs. alpha-numeric display and keyboard data entry; (2) graphic display and data entry vs. alpha-numeric display and display data entry; and (3) graphic display and data entry with spatial cues allowed vs. graphic display and data entry with spatial cues denied. Each will be discussed in terms of its value for finding an answer to the question of interest.

It would not be worthwhile to compare graphical vs. keyboard data entry directly to answer such a question because the two tasks differ so completely. A communication task paralleling any practical task would require some display of the present status of the task; i.e., structure communicated so far. In the graphic communication task, the data entry would take place at the point of display, while in a keyboard task, data entry occurs in a remote interface. Such an experiment fails to evaluate spatial displays by confounding type (spatial or non-spatial) of interface with location.

Similar arguments apply to the motor activities involved in data entry in the graphical vs. keyboard task. The motor activity involved in positioning and using a lightpen are grossly different than typing at a keyboard. More people have had previous exposure to typewriters than to lightpens.[52] In this type of experiment there is no control for previous experience with the use of a particular type of data entry. Again, type of data entry is confounded with another variable, experience.

The difficulties with spatial display and data entry vs. alpha-numeric display and display data entry are not as straightforward. It is possible to have an alpha numeric status display (highly non-spatial) and permit data entry through it. This could be done through the use of the adjacency matrix described in Chapter III. The LOGOS Executive could permit the entry of data into the matrix by making each entry on the matrix sensitive to the lightpen and by using the lightpen to change the entries. In this way it would have been possible to use only the lightpen (not the keyboard), for data entry, and have data entry for both conditions occur in the same place on the screen.

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[52]These difficulties are discussed further by Melvin R. Corley, "Graphical Data Entry in Man-Machine Interactive Problem Solving," Master's Thesis, Department of Mechanical Engineering, University of Texas at Austin, Texas, 1971, p. 41.

The central difficulty is still a problem of controlling experience. It is entirely possible for subjects to have more or different exposure to matrices and their use than to directed graphs. It was known during the design of the experiment that the subject pool would be senior Mechanical Engineerign students and that the probability was high that matrices would be a part of their engineering curriculum. Their exposure to directed graphs and graph theory could not be known. If this experience problem could be resolved, the comparison of graph and matrix displays could provide valuable information about the use of alpha-numeric terminals to communicate structure.

Since the primary objective of the present study was to evaluate different formats of structural displays and data entry and previous work[53] already pointed toward the superiority of graphics displays, an experiment would have to compare the spatial features of interactive graphic displays of directed graphs using experimental conditions differing only in the quality and quantity of spatial cues available to the subject during learning.

If the pattern of the display is ever-changing, the subject will have a difficult and perhaps impossible time trying to picture a correct answer. And if a correct answer is given, then learning can be said to have taken place with the subject deprived of spatial cues. This deprivation can be achieved in practice by randomizing the location of the graph nodes each time they are presented to the subject for an answer (See Figure 5). The unique picture confronting the

[53]Melvin R. Corley, op. cit.

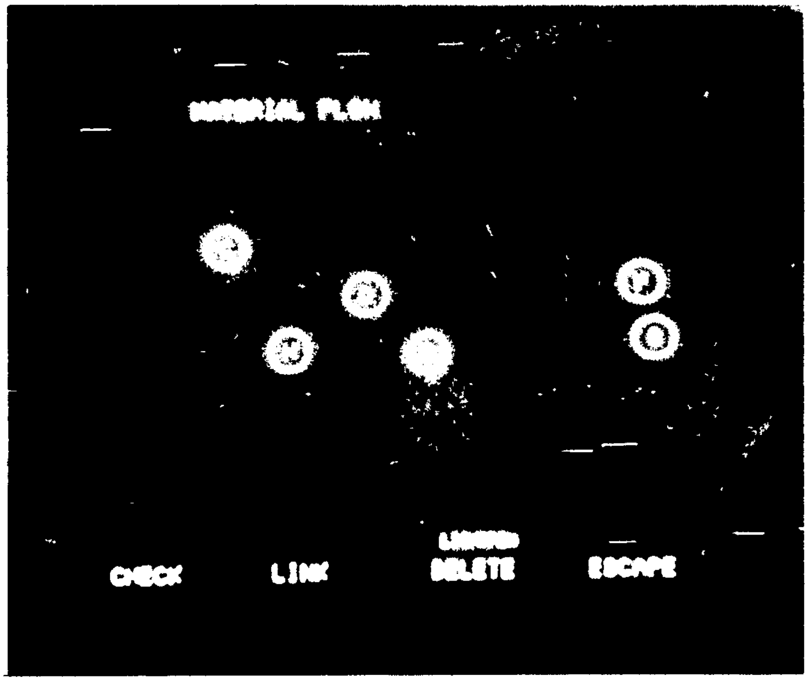


Fig. 5.---Randomized Node Location Format

subject each time he makes a response does not represent a change in the response requested (the graph to be communicated): it represents a change in the format of the response.

Using this technique of randomizing the node location, it is possible to construct a learning task which has graphic display of directed graphs and graphic data entry, and yet, denies to the subject large portions of the spatial cues ordinarily available in the fixed display. In all other respects the two tasks are identical. This randomizing technique will be the main experimental difference used for answering the question about the value of spatial cues.

Finally, it is equally arguable that the use of circles and arrows in the display of the directed graph "invite" the subject to utilize spatial cues. Then, any difference between conditions could be due to the mere frustration of the subject's expectations about the nature of the task or by the mixture of spatial (circles and arrows) and non-spatial (randomized location) cues. These possibilities will be reduced two ways. First, each subject must receive a message in the instructions that fully inform him as to what he may expect about the node location. Second, a consonant character will be provided inside each node as a cue which is usually associated with alpha-numeric or non-spatial displays.[54]

[54] Joseph E. Bogen, "The Other Side of the Brain II: An Appositional Mind," op. cit.

## CHAPTER V

## EXPERIMENTAL METHOD

This is a full description of how the subjects (S) in the experiment were tested by the experimenter (E). It discusses the modifications to the system of Chapter III made for this experiment, the two independent variables, training format, delay of post-test, the construction of the post-test, and the experimental session and instructions, and finally, the allocation of subjects to conditions.

For the experiment, several modifications to the apparatus of Chapter III were made to permit greater control over the display and session as a whole. First, the menu of nodes was eliminated, and the choice and placement of the nodes was entirely under the control of E (i.e., under program control). Nodes were circles with one of the consonants B,C,D,F,G,H, inside. The program could accomodate any number of problems to be learned and display them according to the training conditions specified by E. Node locations to be used several times as a constant display were merely read from data files when used.

The number of problems to be learned was set at three, and a routine was installed that displayed twelve presentations of the three problems in block randomized order; then the presentations were repeated. At the end of each trial after the feedback corrections were made to the S's response, the number of errors was recorded. In the case of zero errors, an entry was made on a criterion tally. The system allowed S to view the corrections for a fixed length of time (30 seconds) before going to the next question. If the routines detected that S had made at least one correct response on each problem, the total number of iterations was also recorded. After a short congratulatory message, the subject either halted or moved on to the post-test, depending on the post-test delay condition. After the end of the experimental session, another routine retrieved the data from the disk for a hard copy.

Experimental Variables

There were only two independent variables in the experiment. The first independent variable, training, consisted of four different format conditions. These four conditions were: (1) Ordered; (2) Fixed; (3) Specific; and (4) Random. The second variable consisted of two conditions of delay of post-test: (1) Immediate; and (2) One Day's Delay.

The experimental training conditions were as follows: The highly non-spatial learning condition had the nodes presented to the S in a new, randomly generated location each time they appeared. In the rest of the discussion, this condition will be referred to as the Random condition. In addition, there were three conditions of a highly spatial nature.

The easiest condition to describe was the Ordered condition. Here the nodes were presented to S in a regular pattern of three nodes across and two down, as shown in Figure 6. It is probably the easiest of the three spatial conditions to learn the locations of the nodes, if desired.

The Fixed condition had the spatial location of the nodes generated at setup time before any subjects were run. Although these node locations were randomly generated, they remained fixed throughout the experiment. Here, there was only one randomly generated node location for all three problems.

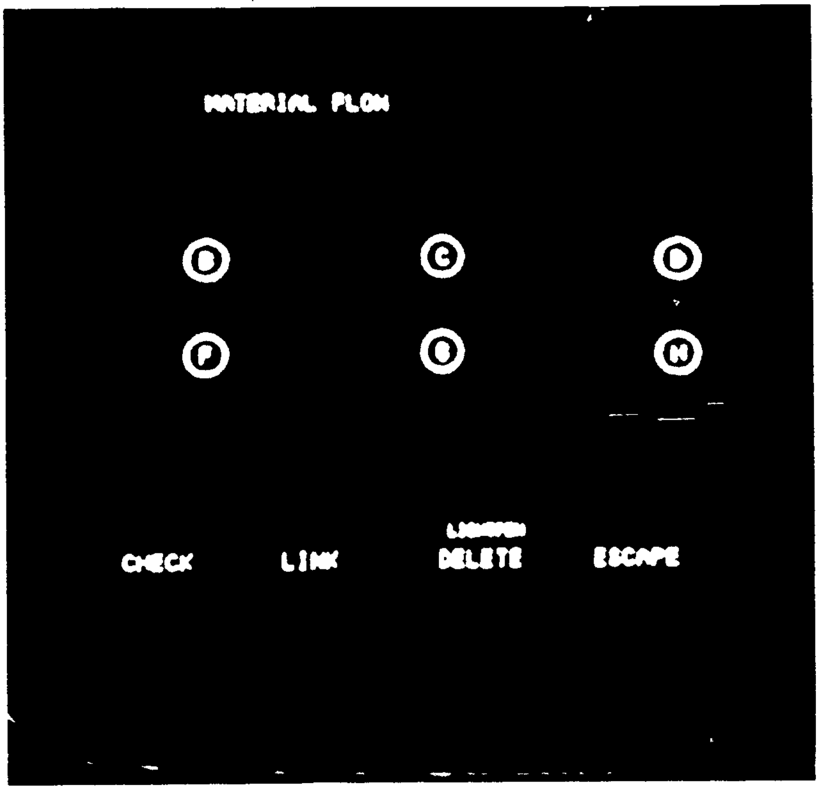


Fig. 6.---Ordered node location format.

In the Specific condition there was a specific node location scheme generated at setup time for each of the three problems presented to the student. If node locations were learned, then this condition required that three times as many node locations be learned than in the fixed condition.

Finally, the Random format presents a randomized location scheme on each trial. In this condition, non-spatial cues are denies to S during learning, while in the three spatial formats, spatial node location cues are allowed. The Ordered format has the nodes alphabetically ordered left to right down the page. The Fixed format has a constant disorder for each problem on the task, and the Specific format has a specific constant disorder for each problem on the task.

The post-test consisted of the three different problems learned during training, but was presented in each of the four different formats. The order of the problems was the same block randomized order of learning, with the formats of presentation being a repetition three times of Fixed, Specific, Random, Ordered.

Experimental Procedure

Experimental subjects were greeted at the door and led to the graphics terminal. E entered a parameter that specified the training condition of S and then typed in for S his name and social security number (this was done to avoid the use of the keyboard by S). The screen erased, and the instructions to S appeared. S read the instructions silently while E read them aloud. The instructions were:

INSTRUCTIONS

*************************************************************************

TODAY YOU LEARN THE THREE KINDS OF FLOW THAT OCCUR IN A CERTAIN FACTORY. THIS FACTORY HAS 6 DIFFERENT DEPARTMENTS THAT HAVE BEEN LABELED B,C,D,F,G,H. THE 3 KINDS OF FLOW ARE:

1) INFORMATION FLOW
2) CASH FLOW
3) MATERIAL FLOW

TO INDICATE FLOW BETWEEN TWO DEPARTMENTS, HIT THE LINK BUTTON BY POINTING THE LIGHTPEN AT THE WORK LINK AND DEPRESSING THE SWITCH ON THE LIGHTPEN. THEN HIT THE FIRST DEPARTMENT (FLOW FROM THAT DEPARTMENT) AND THEN THE SECOND DEPARTMENT (FLOW TO THAT DEPARTMENT). IT IS QUITE POSSIBLE TO HAVE FLOW IN BOTH DIRECTIONS BETWEEN TWO DEPARTMENTS.

YOU WILL NOT BE ASKED TO STAY FOR MORE THAN ONE HOUR.

YOU MUST MAKE 4 LINKS FOR EACH ANSWER. WHEN YOU HAVE MADE THE FOUR LINKS THAT INDICATE YOUR PRESENT ANSWER, HIT THE CHECK BUTTON. YOUR ANSWER WILL BE CHECKED. MISSING LINKS WILL BE DRAWN DOTTED. INCORRECT LINKS WILL BLINK.

IF YOU WISH TO BREAK A LINK BETWEEN TWO DEPARTMENTS, HIT THE DELETE BUTTON AND THEN HIT THE LINK TO BE BROKEN.

IF YOU CHANGE YOUR MIND WHILE DOING A LINK OR DELETE, HIT THE ESCAPE BUTTON.

At this point a special instruction about the location of the nodes was inserted. In the case of the Fixed, Ordered conditions, the instruction read:

YOU MAY EXPECT THE DEPARTMENTS TO BE ON THE SAME PLACE ON THE SCREEN FOR ALL 3 KINDS OF FLOW WHILE YOU LEARN.

For Specific:

YOU MAY EXPECT THE DEPARTMENTS TO BE IN THE SAME PLACE ON THE SCREEN FOR EACH OF THE THREE KINDS OF FLOW WHILE YOU LEARN.

And for Random:

YOU MAY EXPECT THE DEPARTMENTS TO BE IN A DIFFERENT PLACE ON THE SCREEN EACH TIME THEY APPEAR.

Then the final message:

PLEASE DO THE VERY BEST YOU CAN. ARE THERE ANY QUESTIONS?

Each S was also told that he would continue until he had answered all three flows correctly and that he would go on to a post-test or be finished for the day, depending on his delay condition. It was further explained that no feedback would be given on the post-test and that only answers already learned were required. Some foreign students misunderstood the last set of instructions and were not considered for post-test performance.

On each trial, S confronted the display with the nodes arranged according to his experimental condition. He then proceeded to enter the four links (represented as anwers) which comprised his answer. He was not permitted to have an answer corrected until it consisted of exactly four links. A short message was displayed reminding S of how the answer would be checked:

STAND BY FOR CHECK

DOTTED LINKS ARE MISSING

FLASHING LINKS ARE INCORRECT

and the response was checked by another routine. Missing connections would be drawn in on the screen as dotted lines and incorrect links would blink. Figure 7 shows a corrected subject response. S was permitted to view the corrected answer for thirty seconds, after which the screen was totally erased and the next trial began.

Post-test data entry was identical except that no feedback was given to S to avoid further learning. Most S finished both training and post-test well within the one hour session, however, an occasional S had great difficulty (especially in the Random condition) and ran slightly overtime.

Thirty-eight subjects completed the training condition successfully. Of these, twenty-nine completed one of the post-tests. Group size was as shown in Table 1. All subjects were male seniors in Mechanical Engineering and were recruited as volunteers from a course in machine element design and a senior design projects laboratory. Each subject was asked to sign up for a one hour

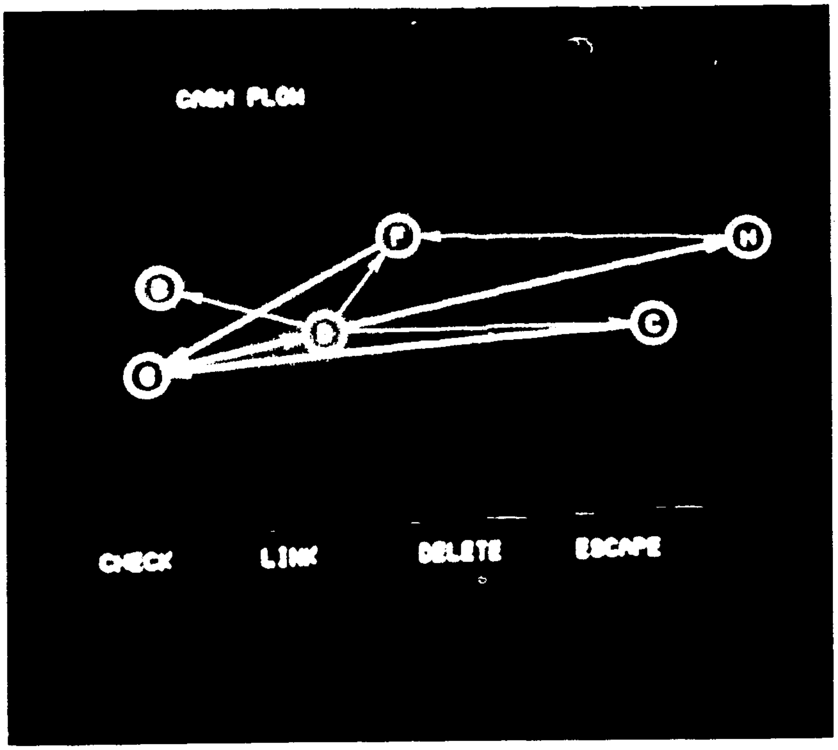


Fig. 7.---Corrected Subject Response

TABLE 1

NUMBER OF SUBJECTS ASSIGNED TO EXPERIMENTAL GROUPS

| Training Condition | Fixed | Specific | Ordered | Random |
|---|---|---|---|---|
| S's Completing Training | 8 | 13 | 8 | 9 |
| S's Completing Training and Immediate Post-test | 3 | 4 | 3 | 3 |
| S's Completing Training and Delayed Post-test | 4 | 4 | 4 | 4 |

session on one day and a half hour session on the following day. Subjects were randomly alloted to experimental conditions. Subjects were tested individually in the Project C-BE laboratory and were separated from other students by an enclosure, as shown in Figure 8. Exclusive use of the room was not possible. However, variations in system response were assumed to be controlled by both the random allocation of subjects and the fixed length of time the subjects were exposed to the corrections of the last response.

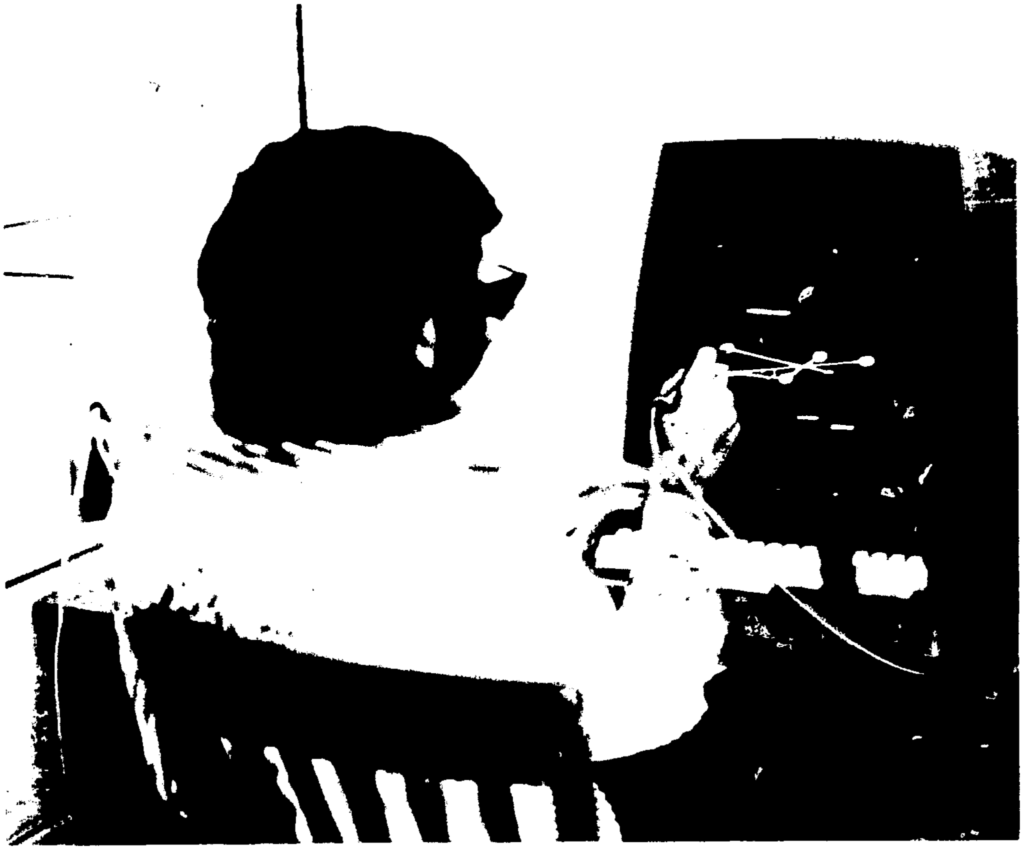

Fig. 8.---Enclosure Around Graphics Terminal

# CHAPTER VI

# RESULTS AND DISCUSSION

## Results

An analysis of variance of the dependent variable reflecting errors during learning "Errors to Criterion" indicated that the independent variable "Presentation Format" was statistically significant factor in the present experiment ($F(3,34) = 5.073$, $p < .01$). Group means are plotted in Figure 9. The Newman-Kuels multiple comparison method was used to determine which group means differed. As Table 2 shows, this analysis indicated that the three highly spatial presentation formats (Fixed = 12.000, Specific = 18.538, Ordered = 19.125) do not differ statistically from each other at $p < .05$; however, the highly non-spatial condition (Random = 37.333) was significantly greater in learning errors than the Fixed and Ordered formats at the $p < .01$ level, and significantly greater than the Specific format at the $p < .05$ level.

In an analysis of the other dependent variable "Trials Required to Reach Criterion" the independent variable "Presentation Format" was significant at the $p < .10$ level ($F(3,34)=2.440$). Group means are plotted in Figure 10. The ordering of the group means was consistent with the results above concerning "Errors to Criterion" which was significant at higher levels. A Newman-Kuels multiple comparison indicated that there was a significant difference at the $p < .05$ level between the non-spatial format (Random = 20.444), and one Spatial format (Fixed = 13.750),

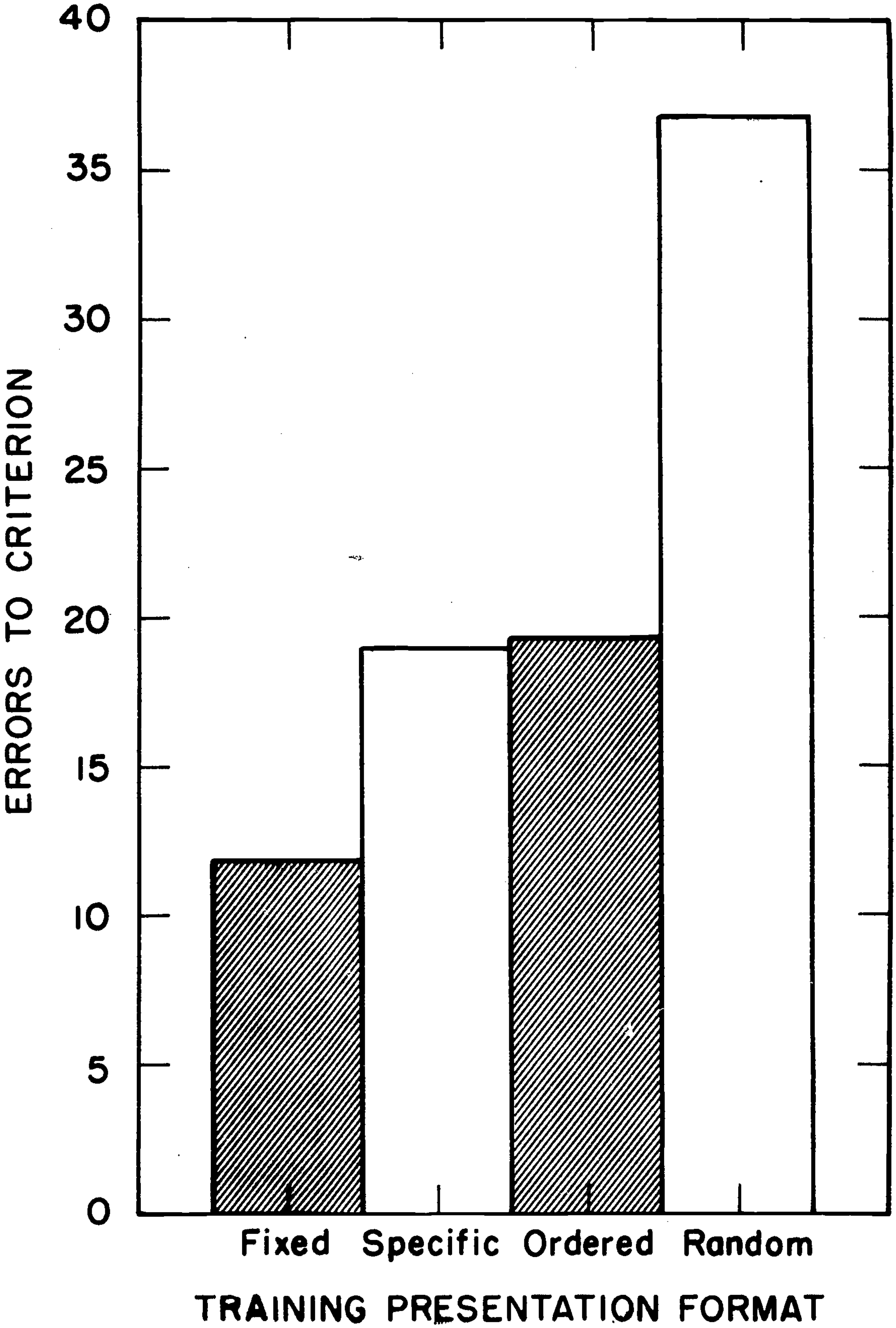


Fig 9.---Learning errors to criterion as a function of presentation format.

TABLE 2

NEWMAN-KUELS MULTIPLE COMPARISON OF GROUP MEANS OF ERRORS COMMITTED DURING TRAINING TO CRITERION

(i) Sources of Variation

| Source | SS | df | MS | F |
|---|---|---|---|---|
| Treatments | 3135.30 | 3 | 1045.10 | 5.22 |
| Experimental Error | 6798.10 | 34 | 199.94 | |

(ii) Differences Between Means

| Means | 12.00 | 18.53 | 19.12 | 37.33 |
|---|---|---|---|---|
| Format | Fixed | Specific | Ordered | Random |
| Fixed | --- | 6.53 | 7.12 | 25.33 ** |
| Specific | | --- | .58 | 18.79 * |
| Ordered | | | --- | 18.20 ** |
| Random | | | | --- |

(iii) Critical Value of Differences

| r | 2 | 3 | 4 |
|---|---|---|---|
| $q_{.99}(r,34)$ | 3.85 | 4.42 | 4.76 |
| $q_{.99}\sqrt{\frac{MS}{\tilde{n}}}$ | 18.01 | 20.68 | 22.27 |
| $q_{.95}(r,34)$ | 2.88 | 3.47 | 3.82 |
| $q_{.95}\sqrt{\frac{MS}{\tilde{n}}}$ | 13.47 | 16.23 | 17.87 |

* Indicates significant at the .05 level of confidence
** Indicates significant at the .01 level of confidence

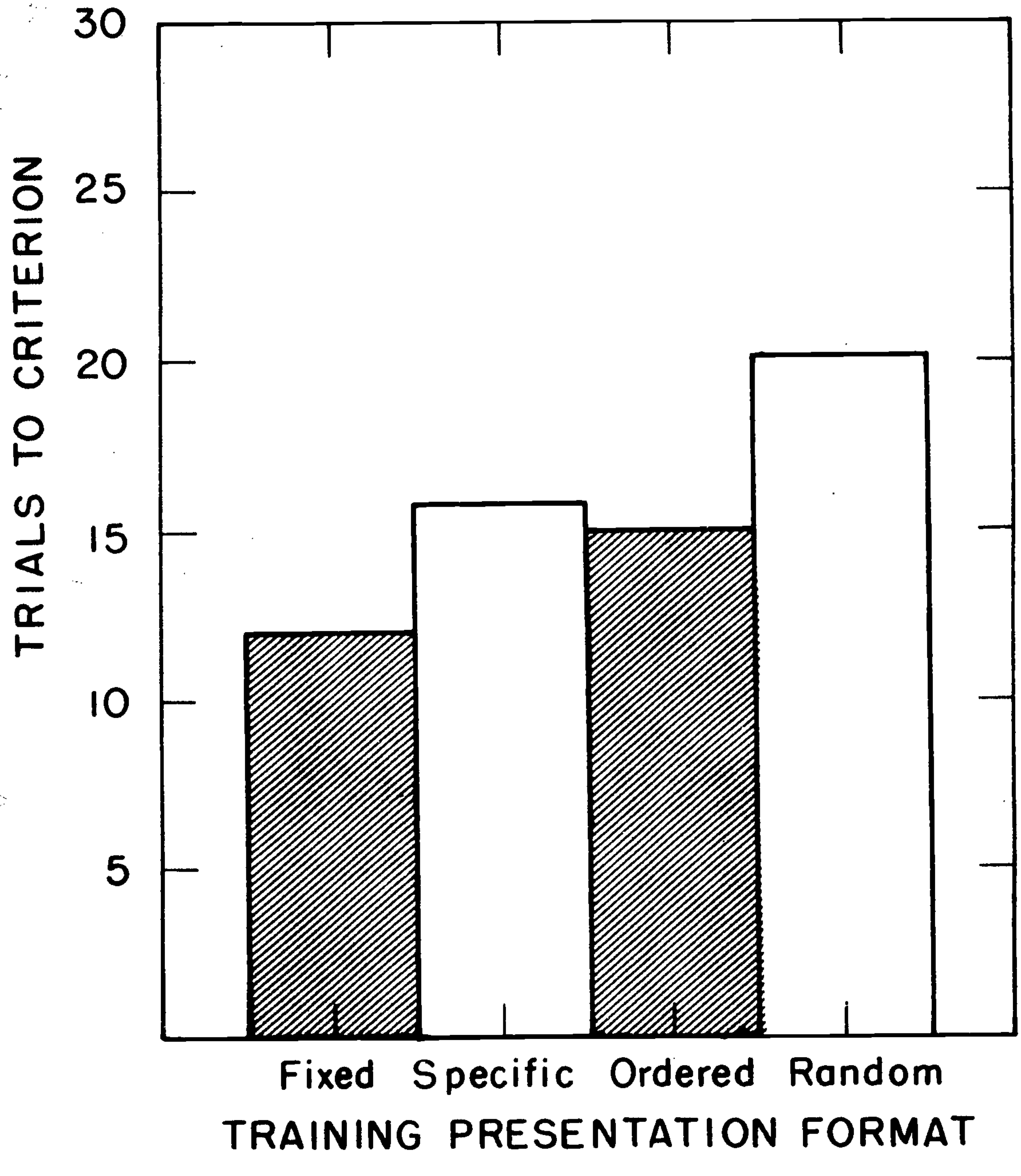


Fig. 10.---Trials required to reach criterion as a function of presentation format.

but not the other two (Specific = 15.154, Ordered = 15.750), as shown in Table 3.

An analysis to performance on the post-trials "Post-Test Errors" was also done using "Trials to Criterion" as a covariate. Group means are plotted in Figure 11. Training trials were found to be a significant predictor of post-test performance ($F(3,20) = 6.672$, $p < .025$). The analysis also indicated that "Presentation Format" was not a significant predictor of post-test performance ($F(3,20) = .1987$, $p > .10$); nor was the independent variable "Delay of Post-Test" ($F(3,20) = 2.571$, $p > 10$). The interaction of "Format" with "Delay" ($F(3,20) = 2.430$) was significant at $p < .10$. Table 4 shows the means and standard deviations of treatment groups for "Post-Test Errors." The range of the group means was considerable. The Ordered format training, Delayed post-test mean had the largest standard deviation ($\sigma = 19.380$); and the Random format training, Immediate post-test had the smallest ($\sigma = 2.082$). This means that the hypothesis of homogeniety of variance among sample means must be rejected ($F_{max}(8,28) = 238.7$).

An analysis of the simple effects of "Post-Test Delay" at each condition of "Presentation Format" was performed using "Trials to Criterion" as a covariate. Results indicated that "Delay of Post-Test" was a significant effect in the non-spatial formats; Fixed ($F(1,4) = 2.628$, $p < .10$), Specific ($F(1,5) = .0738$, $p > .10$), and Ordered ($F(1,4) = 1.981$, $p > .10$). Similar results were found for the "Trials to Criterion" covariate. The covariate was a significant effect in the non-spatial Random format ($F(1,4) = 9.607$, $p < .05$) and in one spatial format; Fixed ($F(1,4) =$

TABLE 3

NEWMAN-KUELS MULTIPLE COMPARISON OF GROUP MEANS OF TRIALS REQUIRED DURING TRAINING TO CRITERION

(i) Sources of Variation

| Source | SS | df | MS | F |
|---|---|---|---|---|
| Treatments | 225.90 | 3 | 75.30 | 2.50 |
| Experimental Error | 1020.91 | 34 | 30.02 | |

(ii) Differences Between Means

| Means | 13.75 | 15.15 | 15.75 | 20.44 |
|---|---|---|---|---|
| Format | Fixed | Specific | Ordered | Random |
| Fixed | --- | 1.40 | 2.00 | 6.69* |
| Specific | | --- | .60 | 5.29 |
| Ordered | | | --- | 4.69 |
| Random | | | | --- |

(iii) Critical Value of Differences

| r | 2 | 3 | 4 |
|---|---|---|---|
| $q_{.95}(r,34)$ | 2.88 | 3.47 | 3.82 |
| $q_{.95}\sqrt{\frac{MS}{\tilde{n}}}$ | 5.22 | 6.29 | 6.93 |

* Indicates significant at the .05 level of confidence

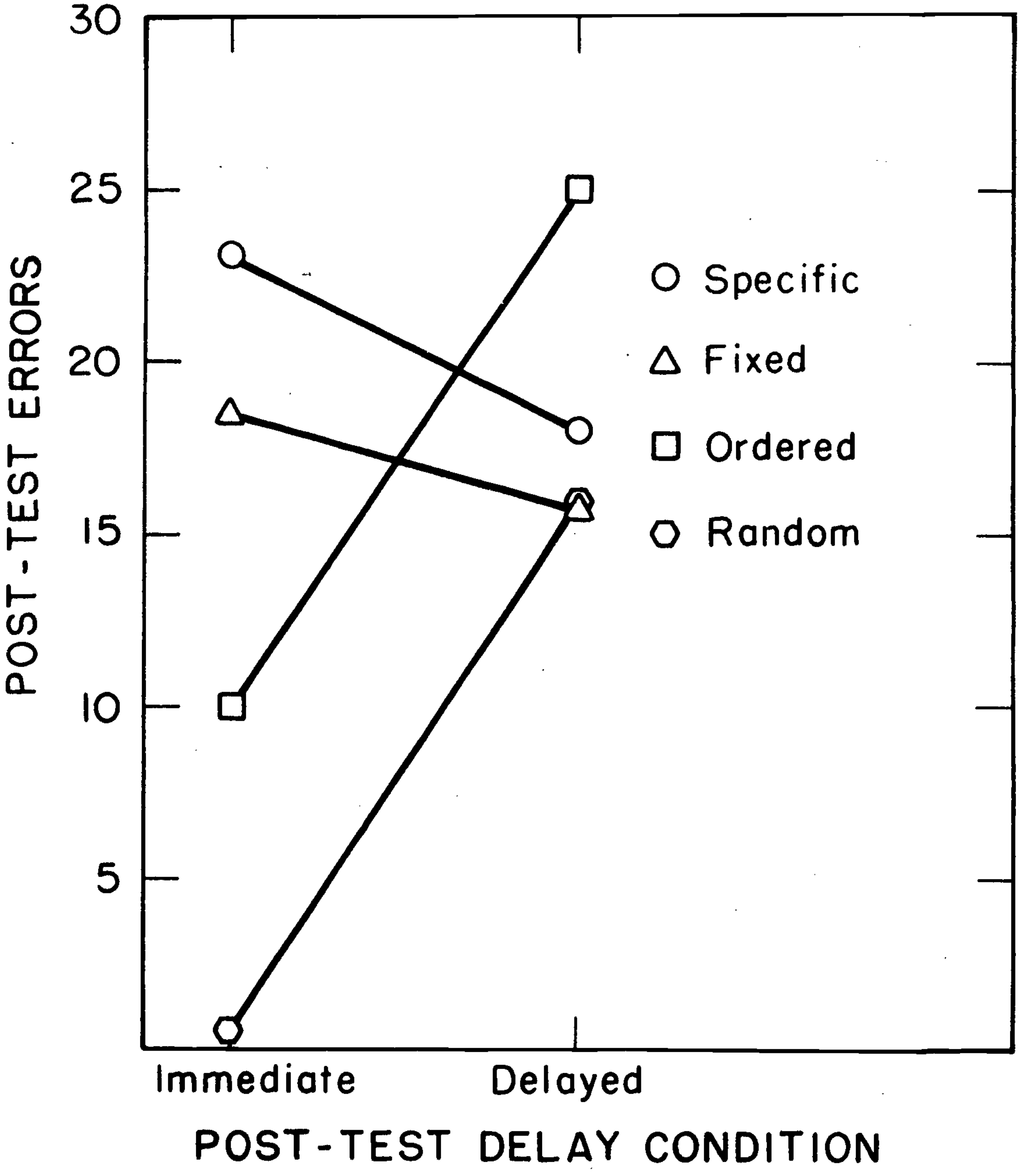


Fig. 11.---Post-test errors as a function of presentation format and post-test delay.

TABLE 4

MEANS AND STANDARD DEVIATIONS OF POST-TEST ERRORS
AND MEANS OF TRAINING TRIALS COVARIANT FOR
TRAINING AND DELAY CONDITIONS

| Condition | N | Post-Test Errors Mean Y | Post-Test Errors Std. Dev. Y | Mean of Training Trials Covariant |
|---|---|---|---|---|
| Fixed - Immediate | 3 | 18.66667 | 18.90326 | 18.00000 |
| Fixed - Delayed | 4 | 16.00000 | 16.14517 | 11.75000 |
| Specific - Immediate | 4 | 23.00000 | 10.67708 | 14.75000 |
| Specific - Delayed | 4 | 18.00000 | 11.51810 | 17.25000 |
| Ordered - Immediate | 3 | 10.00000 | 17.32051 | 14.00000 |
| Ordered - Delayed | 4 | 25.75000 | 19.37997 | 16.50000 |
| Random - Immediate | 3 | 1.66667 | 2.08167 | 20.00000 |
| Random - Delayed | 4 | 16.75000 | 9.06918 | 26.25000 |

4.440, $p < .10$) but not in the other two spatial formats; Specific ($F(1,5) = 1.209$, $p > .10$) and Ordered ($F(1,4) = .933$, $p > .10$). In both cases where the effect was significant, increased training trials meant a decreased number of errors on the post-test.

Discussion

The overall result that training conditions allowing spatial cues showed superior learning performance to the condition not allowing spatial cues is indicated by the data. Furthermore, an initial advantage in post-test trials for non-spatial training format was not present after delays of only one day. It is clear that the learning of digraph structures is greatly facilitated by spatial displays and data entry. Once learned, the digraphs were communicated with the same ease for spatial learners as for non-spatial learners on the various formats of the post-test after a short delay.

Difficulties were found with the Ordered format that were not clear until post-test trials. During training, the Ordered format did not distinguish itself from the other spatial presentation formats. However, on the post-test it seemed to show advantages on the immediate post-test and disadvantages on the delayed post-test over the other two spatial presentation formats. Considering the nature of the Ordered format as shown in Figure 12 , it can be seen that it is possible to have arrows indicating connections that overlap each other or are superimposed. It can also be seen that the regular ordering of the nodes might facilitate remembering node layout, since the layout followed the western convention of left to right and down the page. The latter mechanism may account for the trend towards increased performance on the immediate post-test, in that the

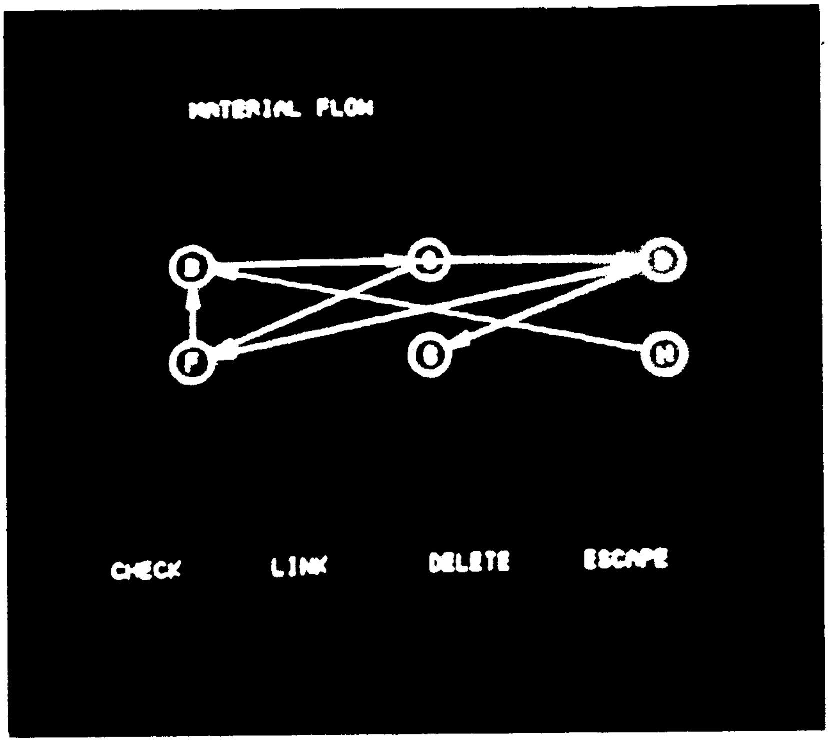


Fig. 12.---Overlay of Arrow Connections in the Ordered Format

Ordered format was easier to recall when confronted with a different format (three out of the four formats of the post-test would be unfamiliar). However, difficulties with recall due to overlay or superpositioning of connections during training may outweigh these initial advantages after a short delay. Hence, the decrease of post-test performance (indicated by the increase in the number of errors).

Also of interest is the inverse relationship between trials required during learning and errors committed on the post-test. Since the time S was allowed to view corrections to his response was fixed at 30 seconds, the number of trials can be considered a rough measure of the total amount of time S had to process information about node location, possible mnemonic relationships among nodes[55] and other retention aids. It is not particularly surprising that increased trials during learning meant increased recall of digraph features and thus decreased errors on the post-test. Several subjects in highly spatial conditions made statements to the effect that they had learned the "arcs but not the nodes" of the problems.

The main effects of post-test performance suggested by Figure 11 were, in general, not substantiated to a statistically significant level in the analysis of the data. The problem seems to lie in the high values and range of the variance of group means. This is further supported by the significance of the data for the Random "Presentation Format" where the variance was lower than the other three formats.

Finally, a general comment on what is learned in the spatial and non-spatial formats. The number of training trials was valuable as a predictor of subject performance on the varying formats of the post-test. This suggests either that it was possible to solve the spatial format problems to criterion with

[55] Since the mean for the Random format, Immediate post-test condition was low (1.66667), the low variance of this group mean is probably due to a "floor" effect.

less acquired information, that more information was required to overcome physiological difficulties incurred by the change in format[56], or both. In training with the Random format, the apparent disappearance of advantages with delay suggests that retention of problem information is at least comparable with the spatial formats. What is lost during the delay is the immunity to changing formats. In other words, whatever strategy S used to acquire information during training was also helpful immediately after training on the post-test, but these strategies were difficult to recall after a short delay.

[56]The initial design of the experiment was to use numbered nodes instead of lettered. A pilot study indicated that S was encoding connections such as "one to two" as "twelve," and showed equal training performance, which, besides being difficult to pronounce as pairs, was almost equally as familiar as numbers and led to much more interesting results.

## CHAPTER VII

## CONCLUSIONS AND RECOMMENDATIONS

The following results are shown by the data:

(1) The spatial cues offered by the use of interactive graphics (as defined in this study) are a significant advantage in the learning of directed graphs.

(2) Where spatial cues are available, no significant difference between several different formats was found during learning.

(3) When spatial cues are denied during learning, the delay of post-test administration (containing several different formats) was significantly detrimental to performance, while increased exposure to the material during learning was significantly helpful.

(4) Regularly ordered formats of displays of directed graphics may lead to confusion for some individuals.

In view of these results it is concluded that the use of interactive graphics for learning structural digraphs is significantly better than the use of non-spatial media. While the use of spatial displays of graphs is recommended, the use of regularly ordered formats, where overlap is possible, is not.

Future work must resolve the remaining questions centered around whether learning of structures using digraphs leads to better performance at learning structures in real-life problems. Alternatively, can structure in real-life problems be accurately communicated using digraph models? If problems exist requiring more sophisticated combinational capabilities, how would interactive graphics be applied and evaluated?

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