DOCUMENT RESUME

ED 351 564 CE 062 442

AUTHOR	Johnson, Scott D.; Satchwell, Richard E.
TITLE	The Effect of Functional Flow Diagrams on the Technical System Understanding of Apprentice Aircraft Maintenance Mechanics.
INSTITUTION	National Center for Research in Vocational Education, Berkeley, CA.
SPONS AGENCY	Office of Vocational and Adult Education (ED), Washington, DC.
PUB DATE	Nov 92
CONTRACT	V051A80004-91A
NOTE	48p.
AVAILABLE FROM	NCRVE Materials Distribution Service, Horrabin Hall 46, Western Illinois University, Macomb, IL 61455 (order no. MDS-469: $3).
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Aviation Education; Cognitive Structures; Comprehension; *Diagrams; *Educational Strategies; *Flow Charts; Higher Education; Instructional Materials; Learning Processes; *Metacognition; Systems Analysis; Technological Literacy; Thinking Skills
IDENTIFIERS	*Functional Flow Diagrams; University of Illinois

ABSTRACT

A quasiexperimental study involved 18 male students enrolled in an aircraft systems course at the University of Illinois. The control group of 10 students studied 39 schematic diagrams of aircraft systems. The treatment group of eight students studied the same schematic diagrams plus conceptual diagrams of the systems. Otherwise, the instruction for the two groups was the same. The treatment group achieved significantly higher scores than the control group on tests to assess the students' knowledge of the structural, functional, and behavioral aspects of the systems. Further analysis of the scores indicated that the conceptual diagrams had little effect on treatment group members' understanding of system structure, but had a significant impact on their behavioral understanding. A card-sorting activity to assess the participants' ability to construct expert-like models showed that the treatment group members were better able to place concept cards in the correct location on knowledge structure maps. Conclusions were as follows: (1) functional flow diagrams increased students' understanding of structural, functional, and behavioral aspects of technical systems; and (2) functional flow diagrams enhanced students' conceptual models of technical systems. (Contains 46 references.) (CML)

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Supported by
the Office of Vocational and Adult Education,
U.S. Department of Education

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November, 1992

MDS-469

FUNDING INFORMATION

Project Title:	National Center for Research in Vocational Education
Grant Number:	V051A80004-91A
Act under which Funds Administered:	Carl D. Perkins Vocational Education Act P. L. 98-524
Source of Grant:	Office of Vocational and Adult Education U.S. Department of Education Washington, DC 20202
Grantee:	The Regents of the University of California National Center for Research in Vocational Education 1995 University Avenue, Suite 375 Berkeley, CA 94704
Director:	Charles S. Benson
Percent of Total Grant Financed by Federal Money:	100%
Dollar Amount of Federal Funds for Grant:	$5,918,000
Disclaimer:	This publication was prepared pursuant to a grant with the Office of Vocational and Adult Education, U.S. Department of Education. Grantees undertaking such projects under government sponsorship are encouraged to express freely their judgement in professional and technical matters. Points of view of opinions do not, therefore, necessarily represent official U.S. Department of Education position or policy.
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ACKNOWLEDGMENTS

This study could not have been completed without the guidance and assistance from many people. In particular, we would like to thank Mr. Glenn Saccone, an instructor in the Maintenance Technology Department at the Institute of Aviation, for providing technical support and assistance to the project. Special thanks go to Mr. Terry Ashbolt from Flight Safety International for providing technical expertise and Dr. Delwyn Harnisch for assisting in the knowledge structure analysis. Finally, we thank graduate students, Jeff Flesher and Ahmed Ferej, for reviewing our instructional materials during their development.

PREFACE

This report is part of the National Center for Research in Vocational Education's (NCRVE) continuing effort to improve vocational and technical curriculum and instruction. This study is one in a series of investigations being conducted by researchers at NCRVE that examine how people learn technical information and how that information can best be taught. This particular study describes the use of a type of conceptual map called a *functional flow diagram* for helping students gain an understanding of the structure, function, and behavior of complex technical systems. While it is acknowledged that the generalizability of the findings from this experimental study are limited due to the small sample size and the single data collection site, it does demonstrate that this type of research can be pursued rigorously. As such, the results of this study are presented tentatively in spite of their strong significant findings. It is hoped that this line of inquiry will serve as a pilot study for future research which includes larger samples in diverse educational settings and technical orientations. This developmental study will be of interest to researchers, practitioners, and policymakers in vocational and technical education who are interested in improving the quality and effectiveness of technical training in private industry, community colleges, and vocational schools.

EXECUTIVE SUMMARY

Current cognitive theory suggests that a key to expert performance lies in the organization of the expert's domain knowledge base. Experts possess a large knowledge base that is organized into elaborate, integrated structures while novices tend to possess less domain knowledge that is not as coherently organized. Empowered with this well-organized knowledge base, experts use less of their short-term memory when working on problems which allows them to concentrate on only the most relevant information. In contrast, novices whose domain knowledge is less well-organized are forced to focus on specific, individual components of problems. This restricted focus results in performance that is slow, redundant, and often flawed. In order to quickly bring the novice to the level of the expert, it appears that better technical instruction is needed which enhances students' knowledge organization. One area of research that may lead to better technical instruction in this area involves the development of mental models.

Mental Models

Mental models are our internal representations of situations or problems that confront us. These models help to predict or explain our interactions with the environment, other people, and technical equipment. One type of mental model relevant to workers in technical fields is a *causal mental model*. Causal mental models can be useful when initially learning how complex systems work and can also lead to improved technical performance because they are *runnable* in the mind through a form of mental simulation. Causal mental models can even serve as mnemonic devices which facilitate remembering.

Can causal mental models be developed through instruction? Technical instructors often use complex, abstract diagrams such as schematics in an attempt to help students understand the function and operation of technical systems and devices. However, when students do not have a sufficient background in the domain to fully comprehend the abstract diagrams, they have difficulty developing a conceptual understanding of the system or device because of the complex, abstract nature of the diagrams. If instructors were to use a simple conceptual diagram of a system as a starting point for technical instruction, students may be able to gain an understanding of the system much more quickly and accurately. Students may also develop more refined mental models which will enable them to mentally represent the system and determine the relationships existing between the conceptual entities. This is something that would not be possible through a cursory examination of schematic diagrams. Once the student has internalized the conceptual model of the system, it may then be possible to use the more complex schematic diagrams for instruction. The purpose of this study was to explore the effect of a type of conceptual diagram called a *functional flow diagram* on technical system understanding. The following research questions were addressed:

1. Do *functional flow diagrams* increase students' understanding of the structural, functional, and behavioral aspects of technical systems?

2. Do *functional flow diagrams* enhance students' conceptual models of technical systems?

Method

This quasi-experimental study explored the effect of functional flow diagrams on technical system understanding. Eighteen male students enrolled in an Aircraft Systems Course in the Institute of Aviation located at the University of Illinois at Urbana-Champaign participated in the study. An individualized field training package that teaches about the electrical systems and subsystems of a small aircraft and introduces numerous major electrical concepts was adapted for the study. This training manual contained thirty-nine schematic diagrams illustrating the systems and subsystems within an aircraft. A four-week treatment was designed. A control group learned from an unmodified instructional package containing only schematic diagrams. The treatment group received an instructional package containing the schematic and conceptual diagrams of the systems. Students studied one unit in the manual each week outside of class. Subjects were askeu to complete the units of instruction using the following procedures: (1) view a videotape that accompanied the manual, (2) read each unit of instruction, and (3) answer the questions at the end of each unit.

Two forms of assessment were used to compare the levels of system understanding of the students in the two groups. Unit tests were designed to assess each subject's knowledge of the structural, functional, and behavioral aspects of the electrical systems introduced in the training manual. These tests were administered during laboratory sessions following the completion of the four units of instruction respectively. In addition, four subjects from each group were randomly selected to perform several card sorting tasks at the end of each unit of instruction. During the first card sorting task, the subjects were individually given a sheet of paper containing the accurate skeletal structure of the system without any labels. The subjects were then asked to arrange a set of cards that were labeled with the concepts just covered in the unit on the paper. The second type of card sorting task had the subjects arrange a set of cards containing the concept labels on a blank sheet of paper. The subjects were then asked to draw lines to indicate the relationship between concepts and place arrowheads at the ends of each line to indicate the direction of current flow.

Test Analysis

Raw scores for the four unit tests, as well as the classification scheme (i.e., structure, function, and behavior) were statistically analyzed. A significant difference was found in the total test scores of each group, Mann-Whitney U test statistic = 6.50, $p < .01$. This finding shows that the students who used the instructional manual containing the conceptual diagrams achieved significantly higher scores on the unit tests. The test scores were also segmented into the classifications of structure, function, and behavior, and then analyzed to determine if there were differences between the groups on their level of system understanding within each of the three classification schemes. The results show that the use of concept maps had little effect on the subjects' understanding of the system structure and component function but had a significant impact on behavioral understanding. This finding suggests that the students who learned from the training manual that contained the functional flow diagrams achieved greater understanding of the behavior of the systems than the group who learned from the manual that contained only schematic diagrams.

Concept Map Analysis

A total of eighty-four knowledge structure maps were collected from the card sorting tasks. First, the knowledge structure maps were analyzed to calculate a measure of spatial association. In other words, the subjects' knowledge structures were analyzed to determine how similar they were to an expert mental model. The results of this comparison showed significant differences between the control and treatment groups in their ability to develop accurate knowledge structure maps. This finding suggests that the use of functional flow diagrams lead to the creation of more expert-like mental models of technical systems than was possible through instruction that used only schematic diagrams.

The card sorting results were further analyzed to identify differences in the subject's ability to construct an expert-like mental model. The results showed a clear difference between the two groups in their ability to place the concept cards in the correct location on the knowledge structure maps. This finding suggests that the use of functional flow diagrams during technical instruction enhances the student's ability to develop accurate knowledge structures of complex technical systems.

Implications for Vocational and Technical Education

Due to the small sample size, the results of this study cannot be generalized to a population other than the limited population of college-level aviation maintenance students from which the subjects were selected. The results do, however, illustrate the potential power of functional flow diagrams for enhancing technical system instruction and show that functional flow diagrams can improve overall system understanding related to electrical systems. The functional flow diagrams were also found to be an effective instructional media for enhancing students' conceptual understanding of the causal behavior of the system. In addition, the use of the functional flow diagram was found to significantly improve the subjects' ability to reconstruct conceptual models that were similar to those of an expert.

Investigations of instructional strategies that emphasize mental-model development will benefit technical training and vocational education in numerous ways, including a reduction in training time and cost. In addition, the technician who is able to develop an accurate causal model of a system will be better able to understand the structural, functional, and behavioral aspects of that system. The technician able to reason about the system in this way may become a more efficient troubleshooter, resulting in a reduction of the high cost of maintenance.

TABLE OF CONTENTS

INTRODUCTION

Research directed at expert and novice differences in domains such as financial reasoning (Bouwman, 1983), physics and mechanics (Chi, Feltovich, & Glaser, 1982; Larkin, McDermott, Simon, & Simon, 1980), medical diagnosis (Elstein, Shulman, & Sprafka, 1978), and electronic troubleshooting (Egan & Schwartz, 1979; Gitomer, 1988; Johnson, 1988, 1989; Rasmussen & Jensen, 1974) has explored the characteristics of expertise. As a result, an increased understanding of the nature of expertise has been developed. One of the primary distinguishing characteristics between experts and novices is the size and organization of the knowledge base they possess. These knowledge base differences seem to be a major contributing factor to the superior performance of experts in technical fields. The larger and better organized domain knowledge base of experts results in their having a greater understanding of how technical systems operate. This greater understanding of the function and operation of technical systems allows experts to better analyze faulty systems and make repairs.

A primary goal of technical training and vocational education is to help novices develop a full and accurate knowledge base that resembles the expert's level of understanding. From an instructional point of view, helping learners gain an expert-like knowledge base may involve the use of an expert's *causal mental model* which describes how a system works. Using an expert's causal mental model to facilitate instruction may help novices resolve any ambiguities about the system and clarify the components and their relationships within the system. Consistent with this line of reasoning, Brown and Burton (1987) advocate teaching novice technicians (1) conceptual knowledge, based on qualitative, causal models of how systems function; (2) how to develop causal mental models from the structure of the device; and (3) how to use the models to understand the rationale behind various troubleshooting procedures.

While the research literature suggests that technical instruction should emphasize conceptual learning and mental model development, it appears that many technical training programs emphasize other forms of instruction such as quantitative problem solving and theoretical learning. For example, a common approach in electronics instruction is to teach electrical theory by first introducing equations for calculating various circuit conditions (e.g., Ohm's law, Kirchhoff's laws) and then showing ways to apply these equations for the solution of circuit design problems. However, research shows that experts do not rely solely on these quantitative aspects of electronic circuitry; rather, they initially rely on their conceptual understanding of the problem (Chi et al., 1981; Larkin et al., 1980). In the case of electronics instruction, White and Frederiksen (1987) suggest that instructors help students acquire a *circuit schema* before introducing quantitative reasoning and calculations. By gaining the ability to reason about a technical system and understand the circuit's behavior, students may be more successful in analyzing the quantitative aspects of the system.

While technical instruction needs to place greater emphasis on conceptual understanding, the instructional materials used must also be improved. Technical instructors often use complex and abstract diagrams such as schematics to describe the function and operation of technical systems and devices. However, when students do not have a sufficient background in the domain to fully comprehend the diagrams, they will have difficulty developing a conceptual understanding of the system or device because of the complex, abstract nature of the diagrams.

If instructors were to use a simple conceptual diagram of a system as a starting point in technical instruction, students may be able to gain an understanding of the system much more quickly and accurately. Students may also develop more refined mental models which will enable them to envision the system and determine the relationships that exist between the conceptual entities—something that would not be possible through a cursory examination of schematic diagrams. Once the student has internalized the conceptual model of the system, it may then be possible to use the more complex schematic diagram for instruction. The purpose of this study was to explore the effect of a type of conceptual diagram called a *functional flow diagram* on technical system understanding. The two research questions were addressed as follows:

1. Do *functional flow diagrams* increase students' understanding of the structural, functional, and behavioral aspects of technical systems?

2. Do *functional flow diagrams* enhance students' conceptual models of technical systems?

KNOWLEDGE ORGANIZATION

Current cognitive theory suggests that a key to expert performance lies in the organization of the expert's domain knowledge base. Experts possess a large knowledge base that is organized into elaborate, integrated structures, while novices tend to possess less domain knowledge that is not as coherently organized. To be successful, problem solvers need to be consciously aware of all the facts and procedures that are required to solve a problem. Newell and Simon (1972) recognized that a major obstruction in performance is the limited memory capacity of humans that affects the amount of information that can be managed at one time. This limited memory capacity forces novices to focus only on specific, individual aspects of problems. This restricted focus results in performance that is slow, redundant, and often flawed. Even though experts have a limited memory capacity similar to novices (Chase & Simon, 1973), they are able to organize their knowledge into larger chunks that use less short-term memory and allows them to concentrate on additional problem information.

One example of how experts use their knowledge organization to enhance their performance was illustrated in a study by Egan and Schwartz (1979). During an investigation of expert and novice knowledge structures and their influence on a subject's ability to recall symbolic drawings, expert and novice subjects were asked to review electronic drawings and then reconstruct the drawings from memory. When presented with realistic drawings, the results showed that the experts were able to recall significantly more of the drawing than the novices. However, when the subjects were presented with drawings that had a random placement of electronic components in a circuit, the experts performed no better than the novices. This study suggests that the memory of expert electronic technicians is organized around "conceptual chunks" of information. The experts were able to recall portions of the drawings as groups of information (e.g., amplifier circuit and tuner circuit) rather than as individual components.

Gitomer (1988) provides another example illustrating the differences in knowledge organization between skilled and less-skilled technicians. The primary goal in this study was to compare the knowledge structures held by skilled and less-skilled technicians to an idealized system model. Technicians were asked to connect seven components to represent the actual functioning of a radar system and to use arrows to specify directionality of the system. The results showed that knowledge structures collected from skilled technicians were more consistent with the idealized model than those collected from less-skilled technicians. Less-skilled technicians also exhibited consistent deviations from the idealized model that were not found for the skilled technicians. This study suggests that the memory of expert technicians is structured around the functionality of components (e.g., transmitter, antenna, and receiver) which is in line with the "conceptual chunking" that takes place when experts organize their domain specific knowledge.

Schema Theory

The concept of knowledge organization is based on schema theory. Modern schema theory suggests that schemata are the unconscious mental structures and processes that underlie all human knowledge and skill. Schemata contain abstracted generic knowledge that have been organized into new qualitative structures (Brewer & Nakamura, 1984). For example, most adults have a "generic" schema for grocery shopping. In a grocery store, we expect to find certain things such as a cart to carry our purchases, several aisles of packaged foods, a freezer for frozen foods, a meat counter, and a checkout area. We expect to find these types of things in any grocery store we enter. Our grocery store schema is used to organize our knowledge and experiences about grocery stores and to facilitate the retrieval of information when completing tasks such as preparing a shopping list. When preparing a shopping list, we can imagine walking through the store to help us recall the food items we need.

Possession of a well-developed schema appears to have an influence on performance. Brewer and Nakamura (1984) have identified five basic processes through which schemata can facilitate performance. First, schemata can influence the amount of attention allocated to a particular type of information which leads to better memory. Second, schemata can operate as a type of framework in memory that serves to retain incoming episodic information. Analogous to this framework view is the belief that schemata serve as a type of *scaffolding* that is used to "anchor" new information to an existing knowledge structure (Anderson, Spiro, & Anderson, 1978). Third, the information in a generic schema interacts with new information to form a memory representation that is a combination of the old and new information. Fourth, schemata can guide the process of retrieving information from memory. Several studies support the hypothesis that memory recall is greater when a relevant schema exists (Anderson et al., 1978; Chiesi, Spilich, & Voss, 1979). Fifth, schemata are used to edit the information that is retrieved from memory.

Mental Models

In addition to having their knowledge better organized than novices, experts are able to use their knowledge to form mental and physical representations of situations or problems that confront them. These models help to predict or explain our interactions with the environment, other people, and technical equipment (Norman, 1983).

All individuals appear to form internal, mental representations of themselves and the things with which they interact. For example, most people can imagine how a thermostat might work to control the temperature in a home. They can develop a mental image of how the thermostat connects to the furnace and how those two devices might "communicate" with each other. While an individual's image, or mental model, of the thermostat system might be completely inaccurate, that image must be relied on to explain the operation of the system or to attempt a repair when it does not function properly. In order to develop a deeper level of knowledge of a technical system, people need to obtain a basic understanding of the system's physical structure, the function of its component parts, and the relationships that exist between the components and how they interact with each other. While our understanding of these underlining principles and concepts may not be complete or even accurate, we must possess some knowledge of these concepts if we are to gain an understanding of technical systems.

Causal Mental Models

The type of mental model that appears most beneficial for workers in technical fields is called *causal mental model* (Brewer, 1987; deKleer & Brown, 1981, 1983; White & Frederiksen, 1987). Causal mental models can be useful when initially learning how complex systems work. Kieras and Bovair (1984) investigated the role that mental models play in learning how to operate an unfamiliar piece of equipment. The results of their study suggest that a mental model is not needed for procedures that are very easy; although for more difficult procedures, the mental model is used to provide specific inferences about what the operating procedures must be. Results from several other studies support the importance of mental models for helping develop the understanding of systems and to aid in troubleshooting faulty equipment (Bouwman, 1983; Lajoie, 1986; Logan & Eastman, 1986; White & Frederiksen, 1987).

Causal mental models can also lead to improved technical performance because they are *runnable* in the mind through a form of mental simulation. When attempting to locate a fault in a technical system, a troubleshooter can mentally operate the system to either predict the behavior of the system, produce explanations or justifications, or facilitate the remembering of facts (Williams, Hollan, & Stevens, 1983). Causal mental models also influence not only how a problem is represented but also which and how stimuli are encoded. In this way, causal mental models serve as mnemonic devices that facilitate remembering in much the same manner as schemata (Borgman, 1982; Gott, Bennett, & Gillet, 1986; Norman, 1983).

TECHNICAL DIAGRAMS FOR INSTRUCTION

The use of graphic materials to complement regular classroom instruction has become a common instructional technique at all levels of education. After reviewing over 650 articles related to the use of visualized instruction, Dwyer (1978) concluded that the "present methods of selecting and using visual materials for instructional purposes are grossly ineffective and wasteful and that, in many cases, for specific educational objectives visualization of content material is no more effective than the same instruction without visualization" (p. xiii). Dwyer's conclusions and more recent concerns expressed in the technical training literature have guided this study which compared the use of two different types of technical diagrams: schematic diagrams and functional flow diagrams for improving student understanding of technical systems.

Schematic Diagrams

Schematic diagrams use abstract symbols to represent the component parts of a technical system and connects those abstract symbols with lines to indicate their relationships. They are used extensively to illustrate electronic circuitry and hydraulic flows, to diagram system structure in service manuals, and to provide visual information during technical instruction. The use of the schematic diagram for developing a technical system understanding is advocated by the U.S. Navy in an electricity and electronics training series produced by the Naval Education and Training Program Development Center (1985). This publication entitled *Introduction to Electrical Conductors, Wiring Techniques, and Schematic Reading* states that "the schematic diagram is the most useful of all the diagrams in learning overall system operation" (p. 39). Even though the schematic diagram is used widely as a visual aid for technical instruction and is highly advocated by the U.S. Navy as the most useful type of diagram for learning the operation of a system, little research has been conducted to test its instructional effectiveness.

Functional Flow Diagrams

Studies have suggested that different features of diagrams might convey different types of information. In this study, functional flow diagrams were used to represent the fundamental concepts or essential component parts of a system and to organize meaningful relationships between these concepts and component parts. Current literature has stressed the importance of learning concepts and principles in school (Ausubel, Novak, & Hanesian, 1978; deKlerk, 1987; Novak & Gowin, 1984; Stice & Alvarez, 1986). According to Ausubel's learning theory, concepts play an important role in the acquisition and use of knowledge. In order to learn meaningfully, students must relate ideas to one another and to their existing conceptual schema. Other investigations have attempted to "map" the concepts held by students (Novak, Gowin, & Johansen, 1983; Pankratius & Keith, 1987; Stice & Alvarez, 1986). These studies have shown that conceptual diagrams are effective for helping students gain initial understanding, for resolving misconceptions, and for assessing a student's conceptual knowledge.

Comparing Functional Flow Diagrams to Schematic Diagrams

The following differences between functional flow diagrams and schematic diagrams have been identified for this study:

1. Functional flow diagrams present a simplistic view of the system, displaying only the system's *essential* component parts, while schematic diagrams display all component parts within the system. As a result, students who learn from concept maps will initially gain an understanding of the big picture without all the detail.

2. Functional flow diagrams can convey causal relationships between the system's essential component parts (e.g., activating component A causes component B to activate), while schematic diagrams do not explicitly convey causal relationships.

3. Functional flow diagrams imply a time sequence within the system (i.e., component A must change before component B changes) while schematic diagrams represent the system at only one point in time.

4. The functional flow diagrams can explicitly display the motion of flow through the system by the use of arrows and action-oriented concept labels while schematic diagrams typically display the system in a stationary or static state.

5. Functional flow diagrams reinforce a critical system's view by explicitly showing common systems and subsystems. While schematic diagrams show subsystem circuits, they are not readily evident to individuals who lack a general understanding of the entire system.

METHOD

Helping students develop an accurate technical understanding is a difficult yet critical task. Students need to develop accurate mental models of the technical systems with which they will interact in order to empower them with the ability to analyze and repair faulty systems. However, little is known about the best ways to facilitate the development of accurate mental models. The purpose of this study was to examine one form of instructional illustration which may have the power to significantly improve technical system instruction. Functional flow diagrams were used to supplement existing technical training materials to see if students gained higher levels of system understanding.

This study is limited by the fact that it took place within an existing university program in aviation maintenance. This constraint prevented the random selection of subjects to participate in the study due to the structured nature of the curriculum and limited course offerings. As a result, a quasi-experimental design was developed to assess the effectiveness of functional flow diagrams and to control for various extraneous variables. While conducting educational research in actual settings can reduce the generalizability of a study, it does provide the opportunity to study instructional techniques in the natural environment in which students learn. Even though generalizability of this study is reduced, the results may have greater practical value because they stem from data collected from real students taught by actual teachers in authentic school-based settings.

Subjects

During the Fall semester of 1991, eighteen male students were enrolled in AVI 170, Aircraft Systems II in the Institute of Aviation at the University of Illinois at Urbana-Champaign. These students were divided by the Institute of Aviation into two laboratory sections. Section A met every Monday and Wednesday from 8:00 a.m. to 11:00 a.m. and Section B met every Monday and Wednesday from 1:00 p.m. to 4:00 p.m. Students from both sections attended a lecture and discussion class every Thursday from 1:00 p.m. to 3:00 p.m. Laboratory Section B had eight students and was randomly selected to be the treatment group while Section A, which had ten students, became the control group.

Studies have shown that prior experience (Chi, Glaser, & Farr, 1988), as well as skill level (Gitomer, 1988), influences the development of a person's knowledge structure. Therefore, it was important to establish that the two groups were equal in both aptitude and domain knowledge. Aptitude indicators for both groups were obtained from the archival records of the Institute of Aviation. Two standardized examinations were used as aptitude measures: (1) the American College Testing Program (ACT) examination, and (2) the Survey of Mechanical Insight examination. These exams are general measures of academic and mechanical aptitude and are used for entrance screening by the University of Illinois and the Institute of Aviation. The Survey of Mechanical Insight, developed by Miller (1955), has a reliability, as determined by KR-20, of .87 and a split-half reliability, as corrected by the Spearman Brown formula, of .88. Domain-specific indices included grades earned in a prerequisite basic electronics course and the final examination scores from their current course. The final examination was an instructor-developed comprehensive test comprised of seventy-five multiple choice and fifteen short answer items. This examination covered topics including instrumentation, navigational communications, and general electrical systems.

The aptitude and domain specific knowledge characteristics of the two groups were compared to ensure that the two groups were not significantly different in aptitude and domain knowledge. Standard t-tests were calculated to compare the two groups on five demographic characteristics and all comparisons showed no difference between the control and treatment groups. However, because of the small sample size and the fact that random selection was not possible, the Mann-Whitney test was selected as a more appropriate alternative to the t-test. This conservative nonparametic statistic compares two groups based on their ranks. As indicated in Table 1, there were no significant aptitude and domain knowledge differences between the two groups in this study.

Table 1
Means, Standard Deviations, and Mann-Whitney *U* Test Statistic for Demographic Data

	Treatment			Control				
Demographics	*n*	Mean	SD	*n*	Mean	SD	*U*	*p*
Mechanical Insight	4	.72	.15	8	.50	.29	8.50	.202
ACT	7	22.14	4.91	10	24.70	3.30	46.00	.279
AVI 145[a]	8	3.50	1.07	10	3.60	0.97	43.00	.777
University GPA[b]	8	3.79	.51	8	3.91	.23	53.30	.230
AVI 170[c]	8	84.37	5.50	10	87.40	5.87	55.00	.181

Note: [a] Maximum score = 5.0
[b] Grade Point Average on a 5.0 Scale
[c] Maximum Score = 100

Materials and Instrumentation

Instructional Materials

The field training package entitled *Introduction to King Air Electrical Systems* was an integrated part of the Aircraft Systems II course curriculum (Beech Aircraft Corporation, 1986). This individualized instructional manual teaches about the electrical systems and subsystems of the King Air 90, 200, and 300 series aircraft and introduces the major electrical concepts of DC generation, dual-bus DC distribution, multiple-bus DC distribution, and AC generation/distribution. The training manual contains thirty-nine schematic diagrams that illustrate the systems and subsystems within the King Aircraft. The first electrical system introduced in the training manual is voltage regulation. Figure 1 illustrates the schematic diagram used to depict the voltage regulation system. This diagram is typical of those used throughout the instructional manual to illustrate the systems being covered.

Figure 1

An Example of the Type of Schematic Diagram Used for the Control Group

VOLTAGE REGULATION

The generator output voltage is sensed at the generator side of the line contactor. The control panel supplies the generator field excitation current required to supply the electrical load and maintain a bus voltage of 28.25 VDC.

The generator voltage sense input to the generator control panel is at pin "B", voltage regulator power input is at pin "J" and the regulator output to the generator field is from pin "M" of the control panel connector.

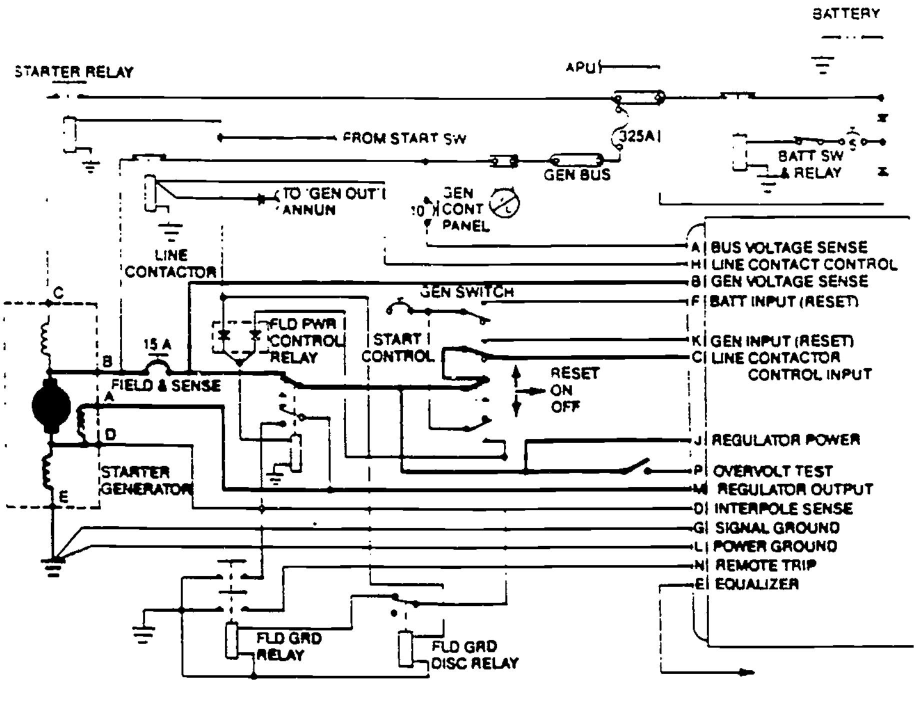


Figure 3-2 Voltage Regulation

BEECHCRAFT

Note: Taken from Beech Aircraft Corporation, 1986, pp. 3-4. Reprinted with permission.

Treatment Materials

The treatment for this investigation consisted of a modified training manual that preceded each schematic diagram with a functional flow diagram which shows the system at a conceptual level and indicates the causal nature of the system. A subject matter expert from Flight Safety International and one from Lucas Aerospace were consulted in the initial phase of this study to assist in the conceptualization and verification of the functional flow diagrams. As the diagrams were completed and verified, they were included in the treatment group's training manual. In addition, the existing text in the treatment manual was supplemented with a brief explanation of each functional flow diagram. Figure 2 illustrates the functional flow diagram used to depict a voltage regulation system. This diagram is typical of those used throughout the treatment version of the manual.

Units One and Two of the training manual provided a general introduction to electrical systems and covered common components. Because these two units did not include schematic diagrams of electrical systems, they were of little concern to this investigation. In total, thirty-nine schematic diagrams appear in the original training manual and twenty-five researcher-developed functional flow diagrams were added to the treatment version. The number of functional flow diagrams differs from the number of schematic diagrams because seven of the schematic diagrams were easily depicted by only one functional flow diagram. In addition, six schematic diagrams appearing in the control group's version of the manual were part of an application exercise where students were asked to identify the location of specific parts on a schematic diagram. It was not appropriate to include a functional flow diagram for these schematic exercises. The last discrepancy occurred because one functional flow diagram preceded two schematic diagrams illustrating the aircraft's reverse current protection system on both the multiple-bus and the dual-bus system. It was determined that the two systems function identically at the conceptual level; therefore, only one functional flow diagram was needed to represent both systems.

Figure 2

An Example of the Type of Functional Flow Diagram Used for the Treatment Group

VOLTAGE REGULATION

The generator output voltage is sensed at the generator side of the line contactor. The control panel supplies the generator field excitation current required to supply the electrical load and maintain a bus voltage of 28.25 VDC.

The generator voltage sense input to the generator control panel is at pin "B", voltage regulator power input is at pin "J" and the regulator output to the generator field is from pin "M" of the control panel connector.

Figure 3-2-1 provides a conceptual model of the voltage regulation system. The generator output voltage from terminal "B" enters the generator control unit at pin "J" where it is compared to the reference voltage from a sync oscillator. If the generator control panel detects too little voltage is being produced by the generator it increases the generator excitation and the shunt field strength increases. On the other hand, if the generator is producing too much voltage, the generator control panel decreases generator excitation and the shunt field strength is decreased. The regulated voltage exits the generator control panel at pin "M" and travels to terminal "A" of the generator where it passes through the generator armature and back to the generator output at terminal "B". This cycle continues as long as the generator is operating.

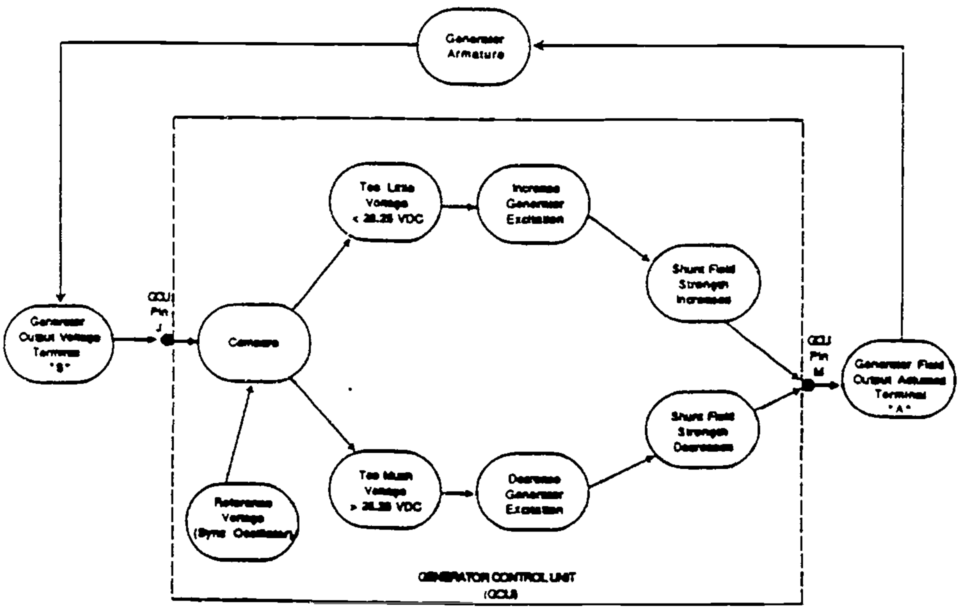


Figure 3-2-1 Voltage Regulation

BEECHCRAFT

Each functional flow diagram was verified for its content validity by technical experts at the Institute of Aviation and a technical expert at Flight Safety International located in Wichita, Kansas. Care was taken by the researchers when modifying the existing training manual to ensure that the existing page layout, font style, font sizes, and paper weight were replicated to eliminate possible treatment effects. To additionally reduce treatment effects, the training manual assignment was administered in the same manner that had been used in prior semesters.

Test Development

Royer (1986) indicated that if a person has acquired understanding, one should be able to use the new knowledge in a meaningful way. In addition, deKleer (1985) has indicated that, in order for a person to develop a causal mental model of a physical system, one must be able to reason qualitatively about the system's structure, function, and behavior. Combining Royer's notion of the demonstration of understanding with deKleer's theory of qualitative reasoning results in the following working definition of technical system understanding. For the purpose of this study, technical system understanding was defined as the ability to use system knowledge in a meaningful way and to qualitatively reason about three aspects of the system: (1) the structure of the system, (2) the function of the components within the system, and (3) the behavior of those components as they interact with other components in the system.

Guided by the above working definition system understanding, four unit tests were designed to assess each subject's knowledge of the structural, functional, and behavioral aspects of the King Aircraft's electrical systems introduced in the training manual. Three domain experts were provided with the unit tests and were asked to categorize each test item into structural, functional, and behavioral categories. An interrater agreement ratio of .91 was obtained which indicated that there was considerable agreement between the domain experts on their categorization of the test items. These tests were administered during laboratory class following the completion of each of the four units of instruction. Table 2 reflects several sample test items directed at each of the three types of system understanding.

Table 2

Sample Test Questions Directed at Three Types of System Understanding

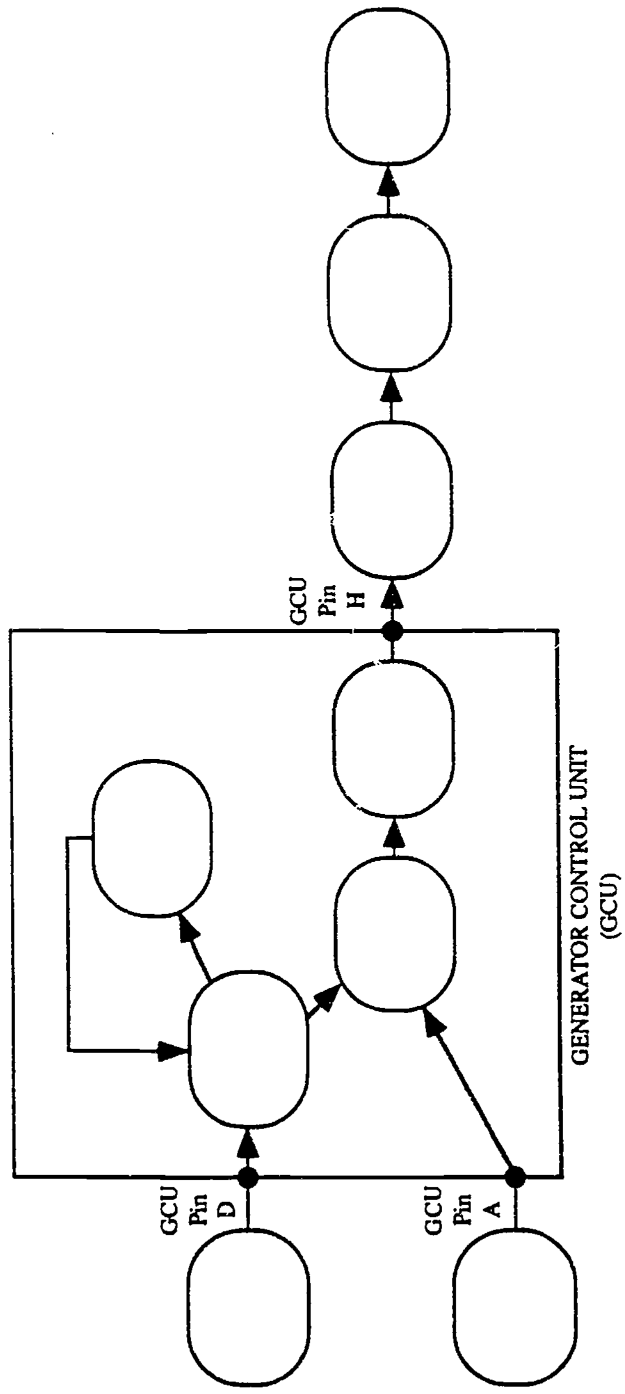
Type of System Understanding	Sample Test Questions
Structural	The regulator output to the generator field is from GCU pin ________.
Structural	Generator output voltage from terminal "B" is sensed at pin ________ of the generator control panel.
Structural	List the component(s) that current from the battery must travel through before reaching the battery switch.
Structural	Which bus does the battery feed directly into?
Structural	The external power unit supplies power to which bus(es)?
Functional	When both generators are on-line and producing power, which generator feeds current to the number 2 dual-fed bus?
Functional	Explain the function of a bus.
Functional	What component must close before the current from an operating generator can reach its respective generator bus?
Functional	What is the function of a diode?
Functional	Explain what happens within the generator control unit (GCU) during reverse current protection.
Behavioral	Explain why reverse current protection is provided on an aircraft's electrical system.
Behavioral	Explain the purpose of the voltage regulation system.
Behavioral	If the starter switch is activated with a generator on-line, the generator will ___.
Behavioral	Does current have to flow through the center bus to reach the right generator bus tie?
Behavioral	If the battery relay closes, can the triple-fed bus receive power from the battery?

Procedure

The treatment took place over a four-week period. Each week students were assigned one unit of the training manual to be completed outside of class. Subjects were asked to complete each unit using the following procedures: view a video tape that accompanied the manual, read each unit of instruction, and answer the questions at the end of each unit. Following each unit of instruction, the subjects were given unit tests that were designed around the structure, function, and behavior of the system. The unit tests were analyzed using appropriate statistics which compared the scores obtained by the two groups.

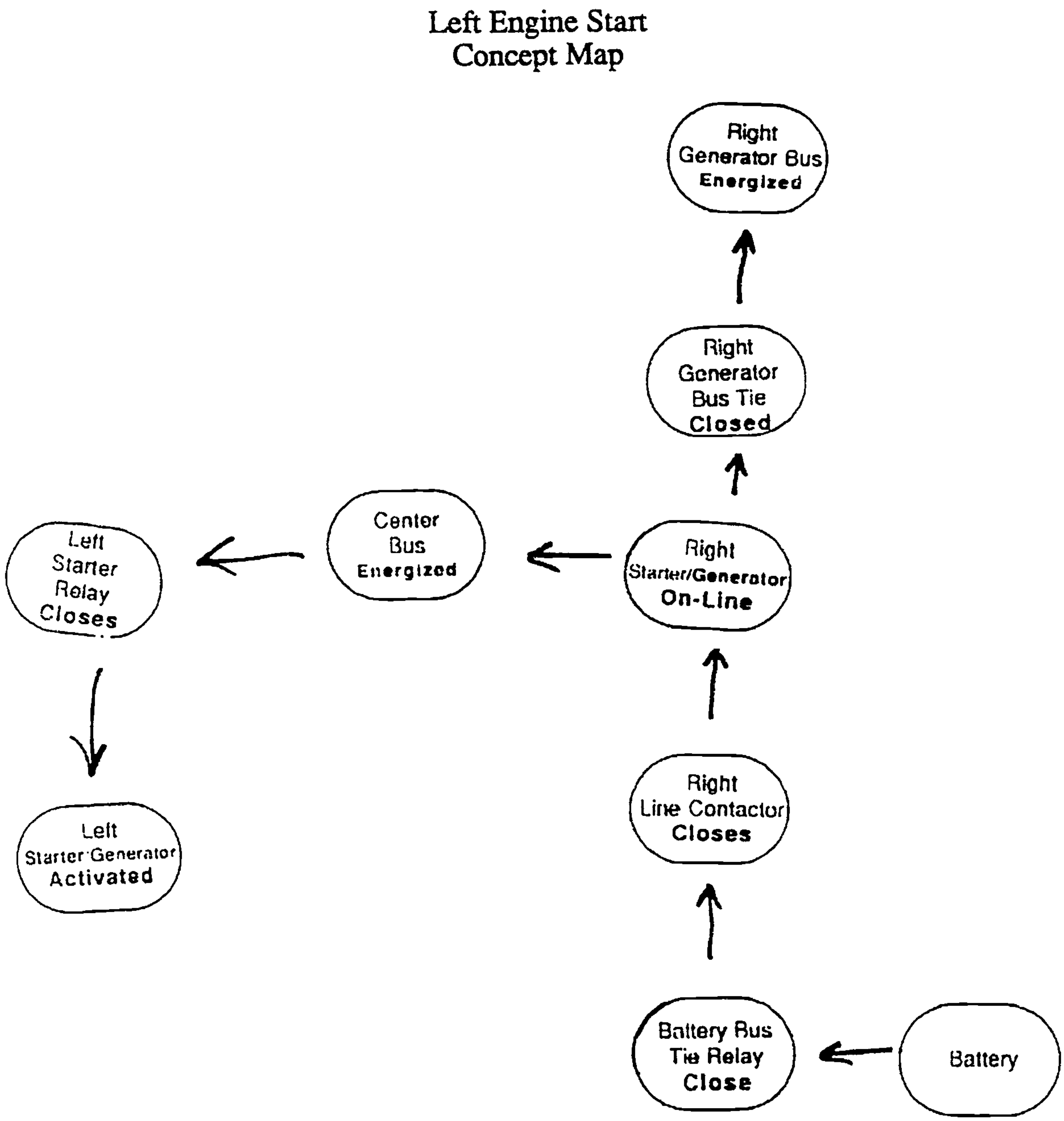
To provide additional depth of analysis, four subjects from each group were randomly selected to perform several card sorting tasks at the end of each unit of instruction. During each card sorting session, up to four conceptual maps were constructed by each subject in the subgroup. The card sorting task consisted of two types of knowledge structure assessments. The first type was a modified version of the fill-in-the-structure technique (Naveh-Benjamine & Lin, 1991) that assessed the students' conceptual understanding of the system. During this task, the subjects were individually asked to arrange their cards on a sheet of paper that contained the accurate skeletal structure of the system without the concept labels (see Figure 3). The complexity of this task varied from five to fifteen different concepts for each map. At the end of a five-minute period, the subjects were asked to glue their cards onto the paper. Each card sorting session began with this type of task because it was considered the easiest of the two.

Figure 3
An Example of the Skeletal Structure Map Used for the Modified Fill-in-the-Structure Card Sorting Task



The second type of card sorting task was slightly more difficult to perform. During this task, each subject was provided with a blank sheet of paper and a set of cards that contained the concept labels. The subjects were then asked to arrange the cards in a way that represented the proper functional flow of the selected concepts. At the end of five minutes, the subjects were asked to glue their cards in place, then draw lines to indicate the relationship between concepts, and place arrowheads at the ends of each line to indicate the direction of current flow (see Figure 4).

Figure 4
A Subject's Knowledge Structure Map Constructed During the Card Sorting Task That Did Not Provide the Skeletal Structure of the System



32

A total of eleven knowledge structure maps were collected for six of the eight subjects in the subgroup. One subject from the treatment group missed the card sorting session for Unit Five, resulting in a total of eight knowledge structure maps being collected for him, and another subject belonging to the control group missed the card sorting task for Unit Six, resulting in a total of ten knowledge structure maps being collected for that subject.

RESULTS

Test Analysis

Raw scores for the four unit tests, as well as the classification scheme (i.e., structure, function, and behavior) were statistically analyzed. Central tendencies of the two groups were computed and *t*-tests were used to determine if there were any significant differences between the group's general level of system understanding (see Table 3). A significant difference was obtained based on the total test scores of each group, Mann-Whitney U test statistic = 6.50, $p < .01$. This finding shows that the students who used the instructional manual containing the conceptual diagrams achieved significantly higher scores on the unit tests.

Follow-up analysis was then conducted to determine if there were treatment effects based on the classification scheme. Test scores were segmented into the classifications of structure, function, and behavior, and then *t*-tests were calculated to determine if there were differences between the groups on their level of system understanding within each of the three classification schemes. The results, as shown in Table 3, suggest that the use of concept maps had little effect on the subjects' understanding of the system structure and component function while a significant difference was found in their level of behavioral understanding, Mann-Whitney U test statistic = 2.50, $p < .001$. This finding suggests that the students who learned from the training manual containing the functional flow diagrams achieved greater understanding of the behavior of the systems than the group that learned from the manual that contained only schematic diagrams.

Table 3

Comparisions of Levels of System Understanding Across Groups

Unit Test Categories	*n*	*M*	*SD*	*U*	*p**
Total Exam					
Control	10	42.70	5.68	6.50	.003*
Treatment	8	49.37	1.60		
Structural Items					
Control	10	11.20	2.44	36.00	.717
Treatment	8	11.75	1.03		
Functional Items					
Control	10	8.10	1.52	21.50	.079
Treatment	8	9.12	0.83		
Behavioral Items					
Control	10	23.40	3.80	2.50	.001*
Treatment	8	28.50	1.07		

Note: $^{*}p < .01$

Concept Map Analysis

The data resulting from the card sorting tasks performed by the selected subgroup was analyzed in a number of ways. A total of eighty-four knowledge structure maps were collected from the subgroup. First, the knowledge structure maps were analyzed to calculate a measure of spatial association. The question asked at this point was, how closely do the knowledge structures of the subjects resemble those of an expert-like mental model? To answer this question and provide data for further analysis, data matrices were constructed for each concept map. The generalized measures of association between data matrices were then determined using MicroQAP, a microcomputer implementation of generalized measures of spatial association (Anselin, 1986). Correlation coefficients comparing subject maps to expert maps were calculated and averaged across all card sorting tasks. The results of *t*-test calculations identified significant differences between the control and treatment groups in their ability to develop accurate knowledge structure maps, $t(82) = -4.705$, $p < .001$. This finding suggests that the use of functional flow diagrams lead to the creation of more expert-like mental models of technical systems than was possible through instruction that used only schematic diagrams.

To provide another index of similarity and to further illustrate differences between the control and treatment group's ability to create an expert-like mental model, the total number of correct label placements were tabulated for each subject's knowledge structure map. This measure provides an overall similarity index between the subject's cognitive structures and that of an expert (Naveh-Benjamine & Lin, 1991). Table 4 shows the total number of correct concept placements by the subjects for each knowledge structure map. There was a clear difference between the two groups in their ability to place the concept cards in the correct location on the knowledge structure maps. As shown in Table 4, the group that learned from the functional flow diagrams was able to accurately place eighty-one percent of the concept cards while the group that learned from the schematic diagrams could only place fifty-eight percent of the concept cards in the correct location. This finding suggests that the use of functional flow diagrams during technical instruction enhances the student's ability to develop more accurate knowledge structures.

Table 4

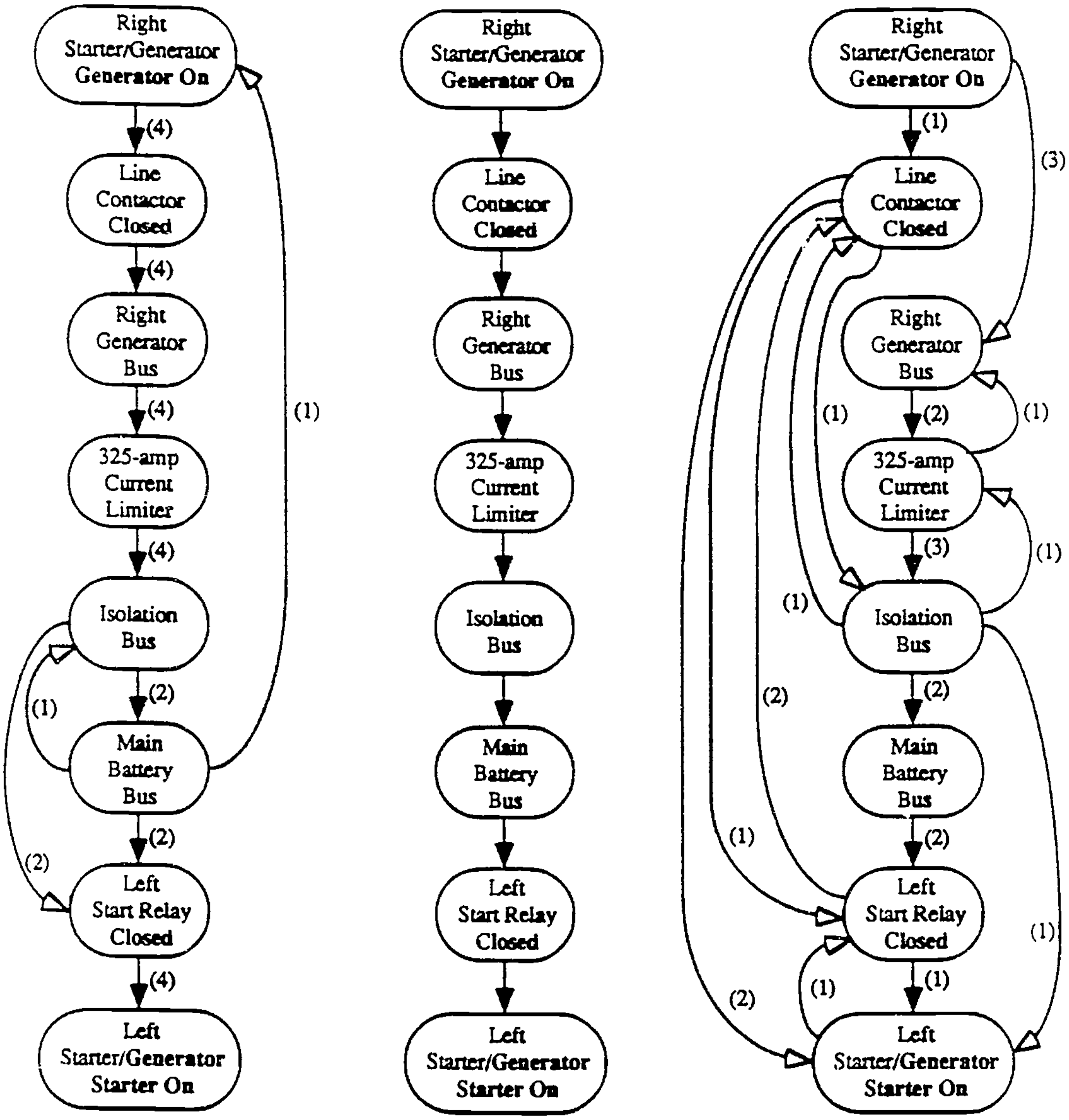
Percentage of Correct Concept Placements in Knowledge Structures

	Percentage of Correct Concept Placement	
Technical Concept	Treatment	Control
Voltage Regulation	100.0% (48 of 48)	56.3% (27 of 48)
Reverse Current Protection	87.5% (35 of 40)	60.0% (24 of 40)
Generator Reset-Generator on	66.1% (37 of 56)	28.6% (16 of 56)
Starter Removes Generator from Service	67.5% (27 of 40)	27.5% (11 of 40)
DC Bus Distribution	100.0% (6 of 6)	100.0% (6 of 6)
Electrical Load Distribution	93.4% (71 of 76)	85.5% (65 of 76)
Generator Assisted Start Right Engine Running	90.6% (29 of 32)	46.9% (15 of 32)
Right Engine Start	66.7% (12 of 18)	37.5% (9 of 24)
Left Engine Start	81.5% (22 of 27)	47.2% (17 of 36)
Both Generators On-Line	68.3% (41 of 60)	62.5% (50 of 80)
Power Select Relay	78.1% (25 of 32)	50.0% (12 of 24)
Total Correct Placements	81.1% (353 of 435)	57.9% (252 of 435)

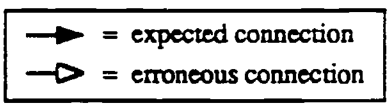
In addition to the similarity indices (i.e., generalized measures of association and the total number of correct responses), each of the remaining six knowledge structure maps were analyzed to determine how they varied from the ideal layout. Group knowledge structure maps were generated from the individual maps for each group to determine if any common misconceptions were held by the subjects.

Figure 5 shows the group knowledge structure maps generated from the fourth unit of instruction that covered the dual-bus DC distribution system. A comparison between the treatment group's representation of this concept, "Generator-Assisted Start With Engine Running," and the ideal representation shows that there are few inconsistencies. Of the eight expected connections (including left starter/generator to nothing), only two connections were not completed by all four subjects from the treatment group. An examination of Figure 5 reveals that one subject from the treatment group indicated a connection between the isolation bus and the main battery bus in a reversed relationship. The consistencies between the treatment group's representation and the expected links found on the ideal representation suggests that the group that learned from the functional flow diagrams had few misconceptions about the relationships between components.

Figure 5
Group Knowledge Structures for the Concept
"Generator-Assisted Start With Engine Running"



Note: The numbers in parentheses indicate the number of subjects (out of four) who represented this connection in their individual knowledge structure map.



A comparison between the control group's representation and the expert-like knowledge structure shows that there are several inconsistencies (see Figure 5). Three control group subjects erroneously connected the right starter/generator to the right generator bus. In addition, all subjects from the control group missed the connection between the line contactor and the right generator bus. This error indicates a misconception about the line contactor, a component which must close before power from the right generator can pass through the system. Only one subject from the control group represented the correct connection between the left starter relay and the left starter. One subject represented this connection in reverse, indicating the lack of an accurate understanding of the function and operation of the left starter relay. The starter relay must close before power can reach the left starter to assist with the starting of the left generator. When examining erroneous connections related to relays on the remaining knowledge structures generated for both groups, it was revealed that the control group made more errors than the treatment group. This suggests that the use of functional flow diagrams during technical system instruction may assist students in developing a more accurate conceptual understanding of the function of system components.

DISCUSSION

After reviewing the results of this study, it appears that complementing instructional materials with functional flow diagrams that illustrate the causal nature of technical systems may have a positive effect on a learner's overall understanding of the system. In addition, concept maps appear to support the development of behavioral understanding which is critical for complete understanding. This pedagogical approach appears to be an effective way to help students develop accurate knowledge structures for reasoning about the behavior of technical systems.

Why were the functional flow diagrams effective at increasing the subjects' level of system understanding? While other factors may have been involved, it appears that three major characteristics of the functional flow diagram may account for this effect. One obvious characteristic of the functional flow diagram is its simplicity. The functional flow diagrams developed for this study show only the *essential* components, in contrast to the schematic diagrams used in the control package that show *non-essential* parts of the system (see Figure 1). The simplicity of the functional flow diagrams may help to resolve any ambiguities about the system. The second characteristic that may account for the effectiveness of the functional flow diagrams is their ability to organize meaningful relationships between the concepts and the component parts of a given system. This characteristic is in direct contrast to the problems encountered when trying to understand the abstract symbols used in the schematic diagram. The ability to organize meaningful relationships may provide the student with a better conceptual understanding of the system. The third unique characteristic of the functional flow diagram is its ability to convey the causal nature of the system to the learner, thereby helping the learner develop a mental model that resembles the expert's causal mental model.

The card sorting task, although not the focus of this study, proved to be an effective way to quickly assess student understanding of technical systems. Students appeared to enjoy this task and viewed it as a challenge rather than as another test. This technique lends itself to a variety of applications where a person's knowledge structure needs to be assessed. Further refinements in this technique may lead to the development of an authentic assessment tool that can be effectively used in technical courses.

Care must be taken when interpreting the findings of this study. Because of the small sample size, the results of this study cannot be generalized to a population other than the limited population of college-level aviation maintenance students from which the subjects were selected. The results can, however, be used as indicators for future investigations of innovative pedagogical approaches for technical system instruction.

Implications for Instructional Media Development

This study was conducted with support from the National Center for Research in Vocational Education, University of California at Berkeley. This organization has vested interests in the improvement of materials used for technical training and instruction. The implications of this research should, therefore, focus on the improvement of the instructional media used to support and enhance technical instruction.

With constant innovations in sophisticated technical systems comes instruction that must continue to change and upgrade. These changes require teachers to constantly review, revise, enhance, and develop new instructional materials. At the onset of this investigation, one question of concern was how does an instructor develop meaningful conceptual diagrams for technical system instruction?

Developing Functional Flow Diagrams

The development of functional flow diagrams is not an easy process. The difficulty is primarily due to the fact that experts' knowledge of specific systems is so well-developed that they have trouble thinking at the level of the novice. People with a high degree of system knowledge tend to put too much information in the diagrams. This removes the advantages of the functional flow diagrams and makes it harder for learners to comprehend the illustrations.

The first step in developing effective functional flow diagrams for technical instruction is to gain access to as much information about the system as possible. Potential sources for this information include subject matter experts, technical reference manuals, service bulletins, and illustrations such as schematics, line drawings, and block diagrams. The goal of this first step is to become as familiar with the system as possible and to unlock the contents of all of the "black boxes" within the system to learn more about its structure, function, and behavior. Specific questions to be answered include the following:

- What does the system do?
- What are the inputs and outputs of the system?
- What is the purpose of each component in the system?
- What possible states exist for each component in the system (e.g., energized, activated, opened, and closed)?
- Who manufactured the system and components?

The next step in designing functional flow diagrams is to identify the essential components of the system. Components are essential only if students *must* know about them to better understand the entire system. It is important to keep in mind that not every component of the technical system needs to be included in the diagram. Reducing the system to its simplest form will help students develop a better understanding of the system, especially if they have little or no prior knowledge of the system. Does each student need to know what happens within the black box in order to understand the system or subsystem?

The third step in this design process is to develop an initial diagram of the system. One should keep in mind that the functional flow diagram will be used by the learner to aid in the encoding of information related to the technical system (Ausubel et al., 1978; Gott et al., 1986; Snodgrass, 1979). The finished diagram should closely adhere to the commonly accepted number of 7 ± 2 concepts so that the learner's short-term memory can handle the new information being presented (Miller, 1956).

It is often necessary to revise or rearrange the structure of the diagram after it has been drawn. Incorporating the use of a microcomputer will aid in this process, as almost all drawing programs will facilitate moving objects around the diagram. If the use of a mici ·omputer is not available, or as the initial diagram is being developed, the use of post notes and a large sheet of poster board are useful. By writing each concept on a separate sheet of paper, they can easily be moved around the board until the correct system structure is determined. Once the structure has been established, lines with appropriate arrowheads should be drawn between the concepts to indicate the direction of causal flow within the system.

If the functional flow diagram is to be an effective instructional aid, it should be easily understood by the naive learner. As a final check of the design, try using the diagram to explain the system to someone who is unfamiliar with the system. After testing the diagram in this way, have the person explain how the system operates. Any misconceptions that are displayed by the person should be used to make revisions in the diagram layout. It is also recommended that the functional flow diagrams be reviewed by a technical subject matter expert to ensure their technical accuracy.

Implications for Vocational and Technical Education

A major goal for vocational and technical training is to help students develop reasoning skills that will enhance their understanding of technical systems, as well as facilitate learning at a conceptual level. Investigations of pedagogical strategies that emphasize causal mental model development will benefit vocational education and technical training in several ways. One gain to be realized is the reduction in training time. The current training time to transform a person from the novice level to an expert level is enormous (Glaser & Chi, 1988; Posner, 1988). Through investigations of this type, we may find the optimum pedagogical methods to acquire expertise. In addition, a potential cost reduction of training may be realized. If methods can be found that more efficiently bring the novice closer to an expert, the costs of training will be reduced. Besides the reduction in time and training cost, vocational and technical education will realize a better product. The technician who is able to develop an accurate causal model of a system with which they are interacting should be better able to understand the structural, functional, and behavioral aspects of that system. The technician able to reason about the system in this way may become a more efficient troubleshooter, resulting in a reduction of the high cost of maintenance.

While a greater understanding of the effect of functional flow diagrams on system understanding has been gained through this study, there are still many relevant questions to be answered. The following specific recommendations are made to guide future research efforts:

- While this study demonstrated the positive effects of functional flow diagrams on technical systems understanding, its results are limited by the small sample size and the fact that it took place in one educational setting. To further enhance this line of research, this study should be replicated to verify the positive results. Future efforts should include larger numbers of students, should involve numerous educational settings, and should extend beyond the electrical system used in this study.

- This study suggests that functional flow diagrams are effective because they can visually simplify very complex systems. Studies should be conducted to assess the extent to which functional flow diagrams can be simplified before they lose their representational power.

- With the advances of instructional technology, it is possible to incorporate functional flow diagrams into computer-based instruction programs (Johnson, Flesher, Ferej, & Jehng, in press). Studies should be conducted to extend this line of research beyond textbook representations to hypermedia and animated representations to test the robustness of this type of graphical illustration.

- While an attempt has been made to describe the procedure for developing functional flow diagrams, it is clear that the procedure is limited in both depth and scope. A thorough analysis of the process of developing functional flow diagrams needs to be conducted. If the process of diagram construction is thoroughly understood, it will then be possible to teach that process to instructors, so they can develop the diagrams for their own curriculum.

- In this study, the diagrams were designed prior to instruction. It is possible that having students be involved in the design and construction of these types of diagrams will enhance their understanding of technical systems. Studies should be conducted to assess the learning of students as they actively create their own functional flow diagrams.

From the results of this study, it is clear that instructional materials used for technical system instruction can be enhanced to help students develop a more accurate conceptual level of system understanding. By developing conceptual diagrams of technical systems before they are introduced in class, instructors can develop a better understanding of the system and thus more effectively help students develop their own conceptual understanding of the technical systems. Additional research must be conducted to verify the use of the functional flow diagram across other systems, as well as other types of instructional media.

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