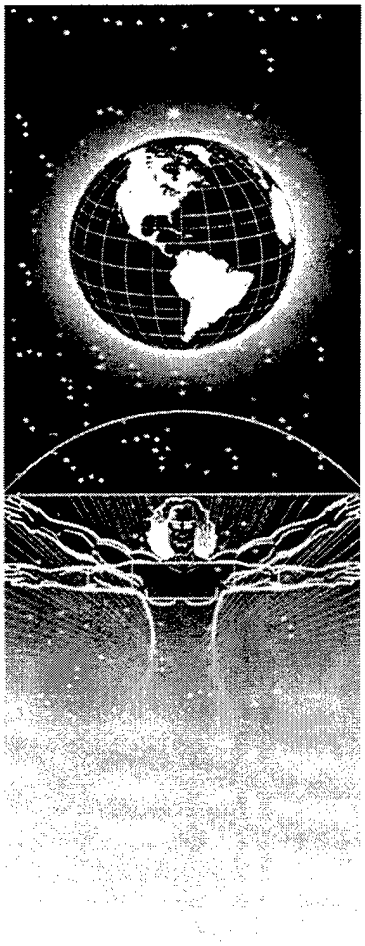
AFRL-HE-WP-TR-1999-0196



UNITED STATES AIR FORCE RESEARCH LABORATORY

Preliminary Recommendation for the Electronic Display of Graphical Aircraft Maintenance Information

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February 1999

Interim Report for the Period November 1995 to February 1999

20000217 088

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Human Effectiveness Directorate
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DTIC QUALITY INSPECTED 1

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AFRL-HE-WP-TR-1999- 0196

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FOR THE COMMANDER

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1999

3. REPORT TYPE AND DATES COVERED
Interim - November 1995 to February 1999

4. TITLE AND SUBTITLE
Preliminary Recommendations for the Electronic Display of Graphical Aircraft Maintenance Information

5. FUNDING NUMBERS
C: F41624-98-F-5017AB
PE: 62205F
PR: 1710
TA: DO
WU: 11

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-HE-WP-TR-1999-0196

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory, Human Effectiveness Directorate
Deployment and Sustainment Division
Air Force Materiel Command
Logistics Readiness Branch
Wright-Patterson AFB, OH 45433-7604

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The conversion of paper schematic diagrams to electronic display presentations requires identification and analysis of associated cognitive demands. Schematic diagrams are typically used by expert maintainers in troubleshooting aircraft faults. These expert maintainers must rely on skill, rule, and knowledge-based behavior to successfully use these diagrams. In this task, the Applied Cognitive Task Analysis (ACTA) method was employed to elicit knowledge associated with using schematic diagrams for troubleshooting. Eleven F-15 maintenance technicians were interviewed. Results showed that schematic diagrams not only support the basic abilities required for troubleshooting; they also allow for visualization of the dynamic flow of system relations and process activities on the aircraft. The ACTA method identified the cues and strategies used to mentally depict system flow. Efforts to convert schematic diagrams to electronic display presentations should support the basic troubleshooting abilities, as well as the cues and strategies that depict dynamic system flow.

14. SUBJECT TERMS
Schematic diagram
Troubleshooting
Diagnostics
Fault isolation

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

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PREFACE

The research documented in this technical paper was sponsored by the Air Force Research Laboratory, Human Effectiveness Directorate, Deployment & Sustainment Division, Logistics Readiness Branch. Work was performed by the University of Dayton Research Institute (Contract Number SPO900-94-D-0001), 300 College Park, Dayton Ohio, 45469. Work was accomplished during the period of Nov 95 through Jan 97. The program manager for this contract was Mrs. Laurie Quill (UDRI Human Factors Group).

Authors would like to acknowledge the 372 TRS Det 4 and Tyndall AFB, FL and the 653 CLSS at WRALC for their subject matter expertise on this program.

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INTRODUCTION

The U.S. Air Force has conducted research to enhance maintenance performance on the flightline, in the depot, during peacetime, wartime, and deployment environments. A primary focus of this research has been to determine the feasibility and capability of presenting, on a compact display device, all types of maintenance information required at the job site. The display devices of choice include notebook computer displays, personal hand-held displays, and head-mounted display devices. The types of information required for display on these devices include troubleshooting manuals, job guides, wiring diagrams, and complex engineering schematics. Complex engineering schematics are currently very difficult to display on small screens. An obvious challenge is fitting these large, complex schematics on small computer screens—some of the schematic diagrams fold out in paper to at least 11" x 17". However, secondary to this issue is the maintenance technicians' use of schematic information. Technicians do not use all the information on a schematic at the same time. Some of the information on the diagram relates specifically to the maintenance action being performed, while other information may be relevant to the system but not to the current maintenance action. Experienced technicians can readily determine the relevancy of such information; however, novice technicians have greater difficulty with such a cognitive process. In order for designers to identify the information requirements associated with schematic diagram use, three basic issues must be addressed. These issues are as follows:

1) A clear understanding of the maintenance troubleshooting process must exist;
2) An understanding of how schematics support this process must exist; and
3) There must be a determination of what differences exist between the expert and novice maintainer's cognitive processes and technical data use.

As technology is fielded, its efficient and effective application must be investigated and tested. But while many potential problems can be solved from the technological perspective of hardware or software, the basis for any solution must be founded in the needs of the user. For example, in the display of large complex schematics and diagrams, a great deal of work has been accomplished in developing methods for storing and presenting technical data. However, additional research is necessary to more precisely identify the actual schematic information used by maintenance technicians (use on schematic diagrams) to accomplish their tasks.

The user requirements obtained in the present study were gathered via a cognitive task analysis (CTA). This technique utilized knowledge provided by "expert" maintenance technicians. The technicians' knowledge involved their training, task performance, and strategies involving use of schematics based on lessons learned. Primary results indicate the following: (1) the need to maintain a global context, including references to the beginning and end points, of particular path(s) the technician is following; (2) the need to identify and mark the path(s) being traced; and (3) the need to reduce the density of information presented simultaneously. The technology necessary to target these needs exists in many forms; however, designers should design for the needs of the user rather

than for the sake of technological capabilities. Thus, acceptable usability of electronic schematic diagrams will be ensured.

Background

Maintenance Troubleshooting Process

In a review and evaluation of maintenance troubleshooting research, Morris and Rouse (14) identify three basic abilities used in maintenance troubleshooting. Consistent with Air Force troubleshooting methods, these three abilities are as follows:

1) Replace components;
2) Make tests to eliminate components from considerations; and
3) Search for the problem in a systematic way (i.e., split half or bracketing approach).

In their review, Morris and Rouse (14) identify the need for explicit instructions in approaching the problem, as well as the use of system knowledge in deciding appropriate actions. Morris and Rouse also specify three abilities which assist the subject: (1) system knowledge; (2) the use of algorithms as decision aides; and (3) the use of heuristics.

Schematics to Assist in Maintenance

In order to understand the applicability and use of schematic diagrams during aircraft maintenance, a basic understanding must exist of the other types of manuals used to support maintenance. Such Air Force maintenance manuals include: the General Vehicle (GV), Fault Isolation (FI), Job Guide (JG), Wiring Diagrams (WD), and Schematic Diagrams (SD). The GV is used for information about the functional requirements of a system—to gain system knowledge. The FI guides the technician, logically, through the troubleshooting process to help in diagnosing a problem. The JG guides the technician, step-by-step, through specific maintenance tasks such as component replacements and system checkouts. Wiring Diagrams are used to identify wiring connectivity throughout the airplane wire repairs. The SD identifies functional connectivity between and within systems. Of these manuals, the SD seems to require the most cognition to use effectively. This is evidenced in daily flightline maintenance: when faced with a challenging troubleshooting problem, an expert will invariably select the SD to support the maintenance activity.

The conversion of paper manuals to electronic format has necessitated a change in the storage and presentation of maintenance technical data. For example, FI manuals have been designed, electronically, as expert systems using Baesian logic (2, 3, 4). In the case of the F-16, these manuals exist as logic trees. Job Guides have been scanned into file formats such as PDF and have been authored into databases which permit increased interactivity and use of the data—Interactive Electronic Technical Manuals (IETMs) (5, 6, 7). Wiring Diagrams have been improved so that they can be readily displayed on small screens, as exemplified by several different research efforts (11, 17). The conversion of paper schematic diagrams to electronic data, however, has been less

straightforward. This is, perhaps, due to the cognitive requirements associated with using these diagrams (15).

Applied Cognitive Task Analysis in Determining Requirements for Schematic Diagrams

Since the late 1980s, several methods have been developed for eliciting the knowledge associated with expert decision-making (8, 9, 12). The purpose of these methods is to identify the cognitive aspects associated with performing tasks at an expert level. These methods have provided valuable insight into the cognitive aspects associated with the troubleshooting process of aircraft maintenance, and they have provided usable and useful means of gathering cognitive-specific information from experts.

The Precursor, Action, Result and Interpretation (PARI) method provides for the cognitive components of complex problem solving tasks (8). The method was developed and used to augment existing task analysis techniques by capturing both behavioral and cognitive components of troubleshooting. The current study emphasizes the importance of real world learning in development of expert knowledge. The study was in support of an integrated skill analysis and instructional development effort. While the study did not specifically address use of schematic diagrams, the emphasis on training and real-world learning in maintenance troubleshooting provided valuable perspective on the type of expert technicians required for the current study—instructors.

The Applied Cognitive Task Analysis (ACTA) method was selected for collecting cognitive information for the current study. This method has been found both useable and useful in collecting knowledge-based information from experts. Three techniques are associated with ACTA. The first technique is the Task Diagram interview. This technique gives a broad overview of the task through a simple task flow diagram (e.g., three to seven steps associated with the task). The Task Diagram is then used to highlight the complex decision-making steps associated with the task. The second technique, the Knowledge Audit, identifies the complex decision-making steps through a series of questions or probes. The intent of these probes is to differentiate the expertise associated with the knowledge-based decisions and those that are rule-based. The use of cues and strategies is emphasized as a method to identify differences between a novice's approach to the problem and an expert's approach. The third technique, the Simulation Interview, puts data collection within the context of a specific task scenario, thereby allowing the expert to give real-world examples of the expert decision making cues and strategies. Each of these three techniques was used in the current study.

Current Study

The overall objective of this effort was to identify and evaluate the types and levels of information detail used or needed by the technician in order to successfully perform tasks that require schematic diagrams. Upon defining the actual types and quantities of required pictorial information, appropriate display format strategies were investigated. The objective was not to merely address the display of large complex graphics on small

display devices, but to also identify the graphic support required to ensure successful task completion. The final requirement was to best meet the above needs in a flightline maintenance environment.

The current study drew subjects from the F-15 flightline training facility at Tyndall AFB and Warner-Robins ALC to collect cognitive components associated with using schematics for troubleshooting tasks. Participants at Tyndall included a total of six maintainers, all instructors. Participants at Warner-Robins ALC included three maintainers.

METHOD

Using the criteria of Hall et al. (8), the effort began with the identification of expert technicians. The current study recruited F-15 instructors for initial data collection. These instructors were chosen for their ability to provide a balanced emphasis on training strategies and knowledge obtained through experience in the operational environment. As instructors, these individuals were also identified as capable to identify and communicate the differences between novice and expert technicians. Because typical training techniques are scenario-based, selection of example tasks for use during the Simulation Interviews was accomplished during subject screening. The only requirement was that the chosen sample task required the use of a large, complex SD.

Subjects were not required to perform the actual task; rather, the three techniques associated with the ACTA method were employed to elicit information about the task. As per standard ACTA methodology, Task Diagrams were used to break down the overall task into approximately six or seven steps. Procedure-based steps were then identified and separated from those based upon expert decision-making processes. Subject matter experts were then probed, during the Knowledge Audit phase, about the knowledge-based steps to discover cues and strategies used to perform these complex tasks. Special emphasis was placed on identifying the cues and strategies not apparent to the novice technician. Overall, the interview focused on the information necessary to fulfill the technicians' decision requirements and improve performance in an electronic environment.

Two data collection trips occurred during this study. The first trip was to Tyndall AFB, FL to collect information from experienced flightline maintainers. The second trip was to Warner-Robins ALC (WRALC), GA. The second trip comprised three goals: (1) to collect information specific to depot maintenance; (2) to answer or clarify questions generated after the first data collection trip; and (3) to validate information collected from the first trip.

Subjects

To take advantage of the skills and knowledge available by experts, a total of twelve maintenance technicians participated in the ACTA. Eight instructors participated in the first data collection activity at Tyndall AFB, and three technicians participated in the second activity at WRALC.

F-15 instructors were from the 372 TRS Det 4 at Tyndall AFB, FL. Their specialties were as follows: six avionics specialists, one environmental control specialist, and one flight controls specialist. Subjects participated at the request of their supervisor.

Three maintenance technicians were from the 653 CLSS at WRALC. Two were avionics specialists; one each on the C-130, and C-141, respectively. The remaining subject was an environmental specialist. Again, subjects participated at the request of their supervisor.

Materials

ACTA materials used by the experimenters included data collection forms, a reference list of knowledge audit probes, and audio/video recording equipment. Materials supplied on-site included paper technical manuals (i.e., Fault Isolation manuals, Schematics Diagrams, and General Vehicle manuals), chalk boards (for drawing task diagrams), and large, transparent plastic boards. Maintainers commonly place these plastic boards over Schematic Diagrams and use grease pencils to trace flows, such as wire circuit signals, over the schematics.

Procedure

At Tyndall, two teams were established for data collection. Two experimenters comprised each team. Within each team, one experimenter was responsible for the primary dialog with the subject, while the other experimenter was primarily responsible for data documentation. Each team interviewed four instructors. Each instructor was interviewed for approximately two hours.

At WRALC, one team collected all of the data and there were two experimenters on the team. Again, one experimenter was responsible for interacting with the subject, while the other experimenter recorded information. Interviews lasted for approximately two hours each.

Upon arrival, each subject was given a brief description of the data collection activity. Data collection began with a Simulation Interview. These technicians were instructors and experienced technicians; therefore, they were asked to provide a troubleshooting example as the simulation. These scenarios are typically used for training purposes and subjects had no difficulty providing simulated problems. Subjects were asked to provide simulations that required use of schematics. Following selection of the simulation, the

Task Diagram interview was conducted. This provided a broad overview of the task and differentiated between portions of the task that were knowledge (cognitively) oriented versus those that were skill oriented (procedural). Following the Task Diagram interview, a Knowledge Audit was conducted for the cognitively oriented Task Diagram tasks or subtasks. Knowledge Audit probes were used to enhance this data collection activity. The Knowledge Audit comprised the majority of the interview. Supplemental materials were used throughout data collection activities (e.g., technical manuals), and audio tape recordings of the sessions were made. Following both data collection activities, experimenters convened to compile and analyze information gathered from the ACTAs.

RESULTS

Results from this effort not only validate information gathered in previous studies and reviews; they also provide valuable information concerning the cognitive activities associated with using schematic diagrams.

Morris and Rouse (14) reviewed the procedure of basic troubleshooting activities. They also identified differences between expert and novice approaches to troubleshooting. Air Force troubleshooting technical manuals have been designed to support the abilities identified by Morris and Rouse: 1) replace components; 2) make tests; and 3) search the problem in a systematic way.

Certain approaches, like PARI, have addressed cognitive components of troubleshooting; however, SCOPE specifically targeted cognitive use associated with schematic diagrams.

Cognitive Activities Associated with Schematic Diagrams

While typical troubleshooting activities must include replacement of components, testing, and systematic searching, these activities tend to be static, step-by-step procedures. For example, a Fault Isolation manual (FI) typically will recommend a systematic approach to testing (e.g., split half approach based on a given symptom). A test is recommended and, based on the test results, a component repair plan is implemented. This approach incorporates all of the abilities identified by Morris and Rouse (14). Interestingly, use of Schematic Diagrams is recommended in the FI for situations that could not be anticipated when the FI was developed. It may be that the SD aids the novice in envisioning a dynamic system state.

As a result of the ACTA data collection, a distinct difference is noted between troubleshooting with the FI and troubleshooting with SD. Experts do not view their systems as static components with checkpoints between components. The SD allow experienced technicians to envision the dynamic flow within and between systems on the aircraft. These experts envision the flow while using the three abilities to isolate the fault or system problem. While the troubleshooting T.O. can be used by experienced

technicians to envision this dynamic flow, the Schematic Diagram better depicts a dynamic flow of system activity. Furthermore, each experienced technician was able to identify the cues and strategies they use to mentally depict system flow.

Specific Examples of System Flow

This report uses the term "system flow" generically. In an electrical system, system flow refers to an electrical signal sent through a circuit. In a mechanical system, flow refers to mechanical interrelationships, such as force and distance, which cause some mechanism to move. In an Environmental Control System, flow may refer to airflow through ductwork or plumbing. The common thread between these definitions of system flow is a directional movement. This movement begins at a given location, follows a path or series of paths, and terminates at another location. There are, generally, many locations along the path where movement can be altered. Depending on the system, an "altered" movement may involve a change in direction, a modification to flow characteristics (e.g., transformation of signal), a change in intensity, or a change in type of flow. The following paragraphs provide specific cases in which dynamic system flows were identified during data collection.

Example 1

An Avionics expert provided an example of system flow through discussion of a logic circuit. In this example, the technician emphasized the importance of examining an AIM-120 logic circuit. First, he emphasized the need for an "initiate signal" as an input, then immediately emphasized the importance of knowing the specific inputs required for the given output. In this example, system flow was an electrical current and the technician followed the current throughout the circuit, systematically checking current and testing continuity at various locations along the path of the circuit. Throughout these checks and tests his main focus was on the flow of current through the circuit.

Example 2

An Environmental expert provided insight in system flow through an example of cockpit airflow. This technician indicated that he used the troubleshooting T.O. to identify components as a list of what to look for in the SD. This technician also identified that on the F-15 SD, there is descriptive information written inside boxes depicting aircraft components. This information is imperative in helping to visualize the airflow of the system. Similar to the avionics expert, this environmental specialist envisioned the flow of air from a point of origin along a path to some output location. Systematic testing along the path helped to identify abnormal changes in airflow. The SD helped to show the beginning, path, end and normal or expected airflow changes.

DISCUSSION

Efforts to convert paper schematic diagrams to electronic display presentations require analysis of the cognitive demands associated with use of the diagrams. Cognitive

activities include not only the basic tenets associated with maintenance troubleshooting, but also the techniques used for knowledge-based decision making. The three abilities, identified by Morris and Rouse (14), are clearly used by expert maintainers. The SD provides for visualization of system flow from a point of origin to a point of termination. The flow permits systematic searching on a limited set of information. Schematic diagram symbols like valves, sensors, and diodes help to visualize flow and flow direction. Along the flow path, systematic tests can be conducted using standard split half and bracketing approaches. Based on interruption of flow identified through making tests, components can be identified for replacement.

This effort used the ACTA to identify the three essential abilities used in maintenance troubleshooting, as well as the essential system relations and processes required for knowledge-based use of schematic diagrams. Identification of the cognitive requirements associated with use of schematic diagrams provides human factors designers with the information requirements associated with electronic presentation of schematic diagrams. When specific cognitive requirements (such as determining the power source or providing a global system perspective) are added to electronic schematic presentations, information needs of both novice and expert maintainers are addressed. The following section details the general requirements that the CTA uncovered.

CONCLUSIONS AND RECOMMENDATIONS

In developing computer graphics, many proposals have been suggested and effectively implemented. Differing levels of detail (13), differing types of information, and the use of transparency and blur (1) have all been researched.

For the use of schematics for aircraft troubleshooting procedures, one of the most important cognitive features seems to be the identification of signal flow through the system. Furthermore, novice technicians may or may not possess the ability to visualize such a signal flow. As the effort increases to computerize aircraft maintenance procedures, specifically schematic and wiring diagrams, the cognitive necessity of depiction of signal flow will need to be incorporated. This will not only provide expert maintainers with information they use on a regular basis, but also provide novice maintainers with an added, expert strategy to troubleshoot and repair aircraft systems.

Recommendations

The following is a set of eight recommendations based upon the results of the ACTA conducted at the two maintenance sites. It is important to note that these recommendations do not specifically detail interface formats such as screen layouts, input devices, or information encoding techniques. Rather, these recommendations are strategic requirements that should be implemented based upon the current, state of the art technology available at the time the electronic maintenance system is designed and developed.

1. **Global context of 'circuit' or flow**

A common theme among all technicians interviewed was the necessity to maintain a global perspective of the system. This effort can prove cumbersome; as mentioned earlier, paper-based schematic diagrams can fold out to sizes greater than 11"x17". However, this strategy was mentioned by every technician interviewed. Furthermore, the instructors at Tyndall cited the novice's lack of ability to maintain global context as a significant hindrance for those with little experience. Thus, the representation of global context is seen as one of the most important capabilities of an electronic depiction of SDs.

2. **Start and end points on same screen**

Throughout the CTA process, technicians repeatedly described the strategy of tracing the signal flow in reverse from its endpoint to its starting point. The strategy of a representing a global circuit context should include the representation of a given circuit's beginning and ending points.

3. **Flow visualization and direction of flow**

Correct identification of signal flow is necessary for the correct identification of components and wires which may need to be tested or repaired. The misidentification of malfunctioning parts can directly lead to increased times to repair and maintenance costs.

4. **Changes in flow direction**

At certain points along the flow of a signal, the direction or intensity of the signal may change. This is in part due to system state, but may also be due to a faulty system component. Technicians will often use such a disconnect between what *should be* and what *actually is* to identify possible malfunctioning system components (e.g., volume diodes, valves, sensors).

5. **Provide system information (general vehicle) on supplementary screen**

Most of the information used by the technician from the SD is pictorial in nature. However, there also exists the need to access detailed information about system components and wire bundles. While such information can be referenced from the SD, it is often found in a separate manual such as the job guide or general vehicle. Improving the access to such information will help to reduce technician workload and overall repair times.

6. **General aids for using split-half and bracketing methods**

Any electronic maintenance aid should support the task of troubleshooting. While this support could be implemented many different ways, the capability should be readily available to the technician via the electronic maintenance device. Such a capability will help to reduce the overall time and cost of maintenance.

7. **Symbolize major components on and A/C structures in the circuit**

Current schematic diagrams do not depict the relation between structural and functional aspects of the aircraft. However, maintainers indicated that such a depiction would be

valuable, especially when troubleshooting a system that is not localized on the aircraft. (e.g., bulkheads).

8. <u>Minimize representation of components and A/C structures not on circuit</u>

As per Tufte (16), only essential information should be highlighted as part of an electronic display format. For essential information, several graphical and text-based highlighting strategies exist, such as color coding and using large or boldface text. Also, many 'de-highlighting' strategies, such as graying out or using smaller fonts, can be employed to shift emphasis away from non-essential information.

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