Designing a Graphical Decision Support Tool to Improve System Acquisition Decisions

by

Anna Elizabeth Massie

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Signature of Author: _____
Department of Aeronautics and Astronautics
May 22, 2009

Certified by: _____
Mary Cummings
Associate Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by: _____
Prof. David L. Darmofal
Associate Department Head
Chair, Committee of Graduate Students

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14. ABSTRACT

System acquisition decision makers are frequently charged with choosing a single system from a set of feasible possibilities that could best fulfill the needs of their organizations. While numerous rules and regulations are already in place for both commercial and government acquisitions to ensure the acquisitions are conducted fairly, decision makers need greater support than rules and regulations alone can provide. The acquisition decision is a complex data analysis problem, where the decision maker must analyze multiple candidate systems on a number of performance and cost metrics. To understand this multivariate environment, decision makers must analyze the system data at multiple levels of reasoning. This research proposes a decision support tool that best supports system acquisition decision makers by providing them with graphical representations displaying how well candidate systems fulfill their organizations? needs. System acquisition decisions require support of three basic levels of reasoning (Data Processing, Information Aggregation, and Knowledge Synthesis) in order to perform system trade-offs on relevant system metrics. To test how well decision support tools could support system acquisition decision makers, two graphical decision support tools were designed: a traditional separable display and a new configural display named Fan Visualization (FanVis). To compare the effectiveness of FanVis against a traditional separable display, an experiment was conducted where participants answered a series of system acquisition questions across the three levels of reasoning. Analysis of the experimental results indicate that FanVis and the separable displays support a system acquisition decision maker, but to different degrees across the three levels of reasoning. Comparatively, participants tended to have higher performance on Knowledge Synthesis tasks using FanVis, while they tended to have a higher performance on Data Processing tasks using the separable display. When examining subjective measures, FanVis was the preferred tool of choice. Through use of an eye tracking device, it was further determined that participants also exhibited erratic fixation patterns on those questions that were answered incorrectly compared to those answered correctly. Further, it was determined that FanVis allowed participants to maintain more efficient gaze patterns regardless of task, whereas participants used less efficient gaze patterns in the separable display for some tasks. Additionally participants tended to spend a greater frequency of time fixating on relevant elements in FanVis while completing Knowledge Synthesis tasks, while the opposite was true for Data Processing tasks, suggesting that performance and time spent fixating on relevant information is correlated. From the results of this experiment, a set of design implications was created for future system acquisition decision support tools.

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Thesis Supervisor: M.L. Cummings
Title: Associate Professor of Aeronautics and Astronautics

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Nomenclature

ANOVA	Analysis of Variance
AT&L	Acquisition, Technology, and Logistics
AUVSI	Association for Unmanned Vehicle Systems International
D	Distance to the target
DAWIA	Defense Acquisition Workforce Improvement Act
DoD	Department of Defense
FanVis	Fan Visualization
FAR	Federal Acquisition Regulation
f.r.	Functional Requirement
FY	Fiscal Year
GAO	Government Accountability Office
GUI	Graphical User Interface
ID	Identify
MACCS	Mobile Advanced Command and Control Station
RFP	Request for Proposal
S	Target size
UAV	Unmanned Air Vehicle
US	United States

1. Introduction

1.1. Motivation

Each year, billions of dollars of revenue are generated by acquisition and procurement processes, herein referred to as acquisitions. Acquisitions allow systems to be appropriated by an organization through a contractual agreement with a supplying organization. To determine which system best fits the needs of their organizations, decision makers must compare numerous candidate systems in a decision process known as source selection. The source selection milestone is a critical step to complete, yet is often the most difficult portion of an acquisition, since it requires decision makers to objectively understand large-scale system trade-offs through the analysis of a complex multivariate set of quantitative data.

In an attempt to ensure that acquisitions are completed properly, the federal government has created numerous rules and regulations that are followed by all federal executive agencies. In the commercial world, individual organizations have instantiated their own standards, rules or regulations. Frequently, however, in both the federal and commercial worlds, acquisition processes are conducted improperly. This mistake often results in the acquisition of a substandard or costly system and could result in the organization's failure to accomplish its end goal [1].

Various initiatives and studies have been implemented to improve the acquisition process including new acquisition processes within the construction industry [2, 3], the software industry [4-6], as well as advanced processes for any type of acquisition [7, 8]. However, these new acquisition processes focus primarily on creating methods and algorithms for data management with little regard for how best to display system acquisition data trade-offs to decision makers.

The quantitative data to be analyzed in a system acquisition decision consists of performance and cost metrics of the various candidate systems. Candidate systems meet these metrics to various degrees, typically represented to the decision makers as individual data points. Thus, the resultant data set for how well candidate systems meet an organization's needs is inherently multivariate in nature and can be quite large depending on the complexity of the system. Analyzing this large, multivariate set of data is complex, underscoring the importance of providing decision makers with an intuitive depiction of this information in an understandable format.

Additionally, while analyzing each of these data points individually is objective, the overall analysis of the data set can become subjective as trade-offs must be made between the various desired metrics. Decision makers will make the best system acquisition decisions when they understand the information being presented to the greatest degree possible. While there are a handful of displays that have been developed to provide acquisition decision support, these displays have typically been developed in-house with no documented demonstration that they provide the necessary information to improve decision-making. The lack of support for a decision maker, who is faced with a complex, multivariate decision, presents a significant research gap. To this end, this research focuses on displaying system acquisition information in a more intuitive, principled format.

This work proposes a new graphical display that supports ecological perception, that of presenting data in such a manner so that users directly perceive relationships within the data [9]. Displaying acquisition data in a graphical manner was chosen because graphical formats, in general, have been shown to be more helpful for understanding quantitative data than conventional statistical computations and data tables [10, 11]. Further, a configural display that supports ecological perception is conjectured to improve system acquisition decisions as compared to traditional spreadsheet-based bar graphs and line charts. This thesis describes the reasoning

behind this hypothesis, the design of a resultant configural display, and the experiment used to validate the configural tool's increased effectiveness in system acquisition decisions against a more traditional spreadsheet decision support tool.

1.2. Problem Statement

To complete system acquisition decisions, decision makers must understand how potential systems fulfill their organizations' needs. Through the years, an increase in the number of systems along with an enhanced range of system functionalities has caused system acquisition to become progressively more difficult. Decision makers must search through larger trade space sets, determining the similarities and differences among candidate systems in an attempt to choose the best system to meet the desired criteria. This choice requires that the decision maker utilize multiple levels of reasoning, ranging from simple data comparisons to complex knowledge synthesis. This thesis seeks to determine the type of decision support system that best aids decision makers as they utilize the multiple levels of reasoning required to successfully complete a system acquisition decision.

1.3. Research Objectives

To address this goal, the following research objectives were posed:

- Objective 1**: Determine the motivating principles for a system acquisition decision support tool.** In order to achieve this objective, current acquisition practices and standards were researched, as described in Chapter 2. In addition, current data analysis displays were analyzed including how they have been used in previous applications.

- Objective 2**: Develop a system acquisition decision support tool.** From the motivating principles described in Objective 1, a system acquisition decision

support tool was designed, described in Chapter 3. Included is a discussion of the design principles applicable to this display.

- Objective 3**: Evaluate the effectiveness of the system acquisition decision support tool.** To address this objective, human participant experimentation (Chapters 4 and 5) was conducted to analyze how well the system acquisition decision support tool was able to support an acquisition decision compared to a traditional, separable decision support tool.

1.4. Thesis Organization

This thesis is organized into the following chapters:

- Chapter 1, Introduction, describes the motivation and research objectives of this thesis.

- Chapter 2, Background, outlines the scope and current practices within system acquisitions. This chapter identifies current gaps within the system acquisition process, and how a new graphical system acquisition decision support tool can address these gaps.

- Chapter 3, Display Design, provides an analysis of the performance of current display designs on tasks similar to those of a system acquisition decision. The results from this analysis generate a set of criteria that provide guidance for the design of a configural acquisition decision support tool. This research proposes this tool will support system acquisitions decision maker to a greater degree than a separable decision support tool, which is also described in this chapter.

- Chapter 4, Experimental Evaluation, describes the human-performance experiment used to test the hypothesis of this research. Details include a discussion of participants, procedures, and experimental design.

- Chapter 5, Results, presents the results of the human-performance experiment on such metrics of accuracy, speed, subjective appeal, and eye fixation patterns.

- Chapter 6, Conclusions and Future Work, compares the results of the human-performance experiment with the research hypothesis. These results are described on the basis of performance, subjective appeal and the cognitive strategies of the participants. Based upon these results, a set of design and experimental recommendations are given. Finally, future work necessary to integrate a system acquisition decision support tool into current practice is described.

2. Background

When conducting an acquisition, decision makers within a soliciting organization must choose which system could best fulfill their organizational needs. Passing this milestone is often referred to as source selection and is accomplished by comparing proposed candidate systems to the organization's needs. These needs often include cost criteria, a set of requirements the system must meet, high-level system characteristics the system must exhibit, and other key system attributes. Information regarding the candidate systems are supplied by organizations responding to the soliciting organization's Request for Proposal (RFP).

Source selection for simpler systems may be fairly straightforward, as decision makers only have to analyze a small set of data and a single system could be quickly pinpointed as the best system to acquire. However, for sophisticated systems, decision makers must analyze a large, complex, multivariate data set where it is likely no one system will emerge as the one clear winner. Graphical decision support tools could greatly benefit decision makers in these situations by displaying the data in an easily understandable manner. This chapter describes the current practices of system acquisitions, the general scope of such decisions, and proposes how a decision support tool could best fulfill current needs.

2.1. System Acquisition Practices

Various practices have been established by both the federal government and individual organizations in order to address these complicated decisions. Current system acquisition practices in both commercial industry and the government strive to enable a system acquisition environment that focuses on obtaining the best value while maintaining a level of accountability, integrity and a degree of competition [12-14]. This section describes the various standards, rules, regulations, and practices that have been

established and how the proposed decision support tool can further enable the goals of these various organizations. Organizations within the United States were primarily studied, but similar standards, rules, regulations and practices have been established by organizations outside of the country as well.

2.1.1. Federal Government Standards

Federal agencies initiate and complete acquisitions through the use of government appropriated funds. One of the largest blocks of funds is allocated toward the various branches of the Department of Defense through the National Defense Authorization Act. In Fiscal Year (FY) 2008, the authorized funds for procurement purposes totaled $91.9 billion and were distributed across the various DoD branches, as illustrated in Figure 1 [15]. In an effort to ensure these funds are spent efficiently, the government has established a number of regulations to help federal agencies complete the acquisition process.
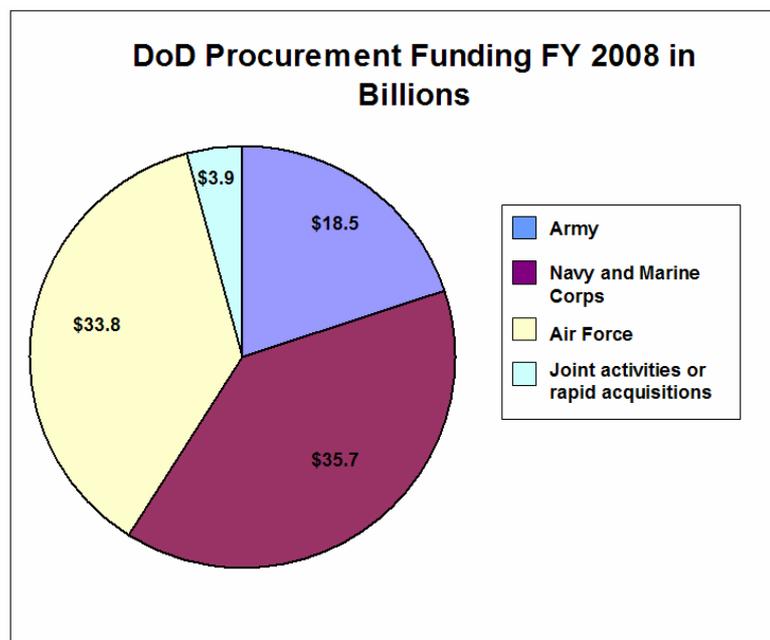
Figure 1: Department of Defense 2008 funding in billions

The Federal Acquisition Regulation (FAR) system is the primary set of regulations used by nearly all Federal Executive agencies when acquiring supplies and services

with government appropriated funds. There are 53 parts to the FAR, each of which consists of one or more subsections that dictates specific regulations. For example, subsection 7.105 outlines the contents a written acquisition plan should include, and subsection 13.106 outlines regulations for soliciting competition, conducting the evaluation of quotations or offers, the award process, and the required documentation when utilizing simplified acquisition procedures [12].

Through each of these subsections, the FAR outlines the many steps required to complete a system acquisition. To begin a system acquisition, the soliciting organization should first develop an acquisition plan which includes information pertaining to the acquisition objectives, the required capability of the system, design trade-off, budgeting, and more. In all, there are 29 different portions of the acquisition process that should be considered and documented. From this acquisition plan, the soliciting organization should create a request for proposal which includes the criteria they will evaluate candidate systems against. The exact evaluation criteria are dependent upon the system's specifications but could include cost or price, past performance, technical evaluation, cost information, and small business subcontracting. When candidate proposals are submitted, the decision makers within the soliciting organization must then decide which candidate system best meets their evaluation criteria.

However, the details of how this decision should be completed are left to the discretion of the decision makers. The FAR only stipulates that the decision "shall be based on a comparative assessment of proposals against all source selection criteria" in the request for proposal [12]. There are neither specific regulations as to how this evaluation should take place nor a commonly agreed upon set of tools the system acquisition decision team can use to make the final source selection decision. Yet decision makers require the most support in this task, as they are analyzing highly complex multivariate information for systems that are typically very costly. As there are currently no mandated or recommended tools, there is a significant gap in the federal

acquisition process. A graphical system acquisition decision support tool could help bridge this gap, allowing decision makers to make the best decision by enabling them to understand the complex information in the most objective manner possible.

2.1.2. Commercial World Standards

Individual organizations outside of the federal government must also obtain goods and services from various organizations, but unlike the federal government, are not subjected to the same rules and regulations. However, like the federal government, these organizations must also ensure acquisitions are completed correctly, efficiently, and with a high degree of accountability. In response, organizations have created their own acquisition strategies, standards and guidelines that are specifically tailored to their unique business model.

While these standards are extensive, flexibility within them allows individuals and organizations to establish innovative acquisition strategies. These strategies demonstrate new processes which companies can use to improve their source selection process. A variety of strategies have been suggested, ranging from simpler strategies, which add a new criterion to the selection process [3], to more complex methods, which introduce artificial neural networks to approximate the real world experience of an acquisition manager [8]. However, these strategies lack a formal analysis of how decision makers visualize the results of the analysis. Ultimately, the decision maker must be able to understand the results of each analysis, including why one system may be better than another. While the manner in which these results are obtained is critical, poor understanding of the results can break down the acquisition process.

2.2. Scope of Acquisitions

An acquisition is typically initiated through a Request for Proposal (RFP). The soliciting organization creates and distributes the RFP to request responses from

multiple supplying organizations. The soliciting organization will include details within the RFP regarding the metrics that each system must meet in order to be considered a viable option. While these metrics vary from project to project, they generally include detailed functional requirements and high-level system characteristics that must be satisfied by the system. Additional metrics could be included depending on the needs of the soliciting organization.

The RFP is submitted early in the life cycle of a system which consists of multiple phases, beginning at the User Requirements Definition phase, and ending in the Disposal phase [16], as shown in Figure 2 The system life cycle consists of many milestone decisions, two of which are displayed as diamonds (Figure 2) as they pertain to the focus of this thesis. In order to advance to the engineering, manufacturing, and development phase, the soliciting organization must choose which system to develop and implement. This source selection decision requires that the soliciting organization evaluate the various proposals received based upon the metrics outlined in the RFP. It is this evaluation process which could most benefit from the use of an advanced graphical decision support tool. This section describes the system metrics analyzed in the context of this research, and the resultant levels of reasoning that decision makers within a soliciting organization must use to complete this decision.
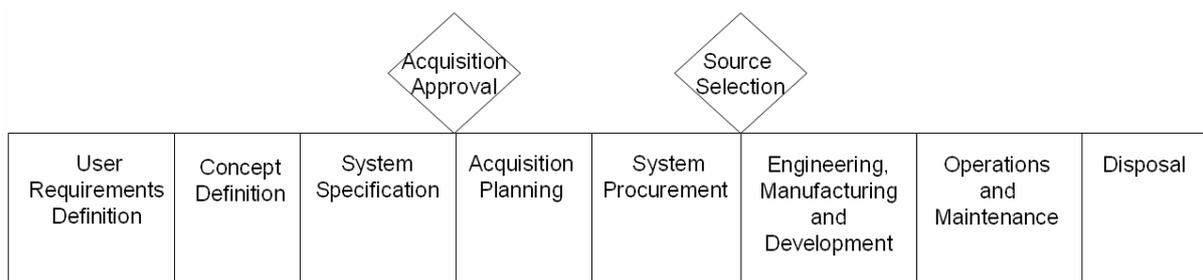
Figure 2: Generic life cycle of a system (adapted from [16])

2.2.1. System Metrics

Nearly all system acquisitions should consider at least the following three critical system metrics, based upon systems engineering principles described in the subsequent paragraphs. Other system metrics such as risk, delivery schedule, and past performance could be included as future work.

1) The degree to which functional requirements are met
2) The degree to which non-functional requirements ("-ilities") are met
3) System Cost by Life Cycle Phase

Functional requirements describe the actions necessary to achieve a specific objective [17]. For example, in the case of an aircraft, these functional requirements could include: ability to safely takeoff within a distance of 2,000 feet, establish a climb of at least 1,000 feet per minute, cruise at or above 200 knots, and land within a distance of 1,000 feet. The functional requirements in turn produce sub-functional requirements such as configure an aircraft to take off conditions, start engine, accelerate to necessary take off speed, and establish a positive rate of climb. From these sub-functional requirements, lower level requirements are defined until the necessary pieces of hardware and software are identified.

The "-ilities," are characteristics that a system must exhibit such as reliability, adaptability, sustainability, modularity and usability [17]. The "-ilities" can play as crucial of a role as functional requirements when choosing a system [18], as they define specific behaviors or attributes that must be met in order to be useful to the end user. The system must also be economically feasible, since the soliciting organization will often have a limited set of funds allocated to the acquisition. In some instances, these funds will be allocated during particular portions of the system's life cycle, thus it is critical that the decision maker understand the total cost and the cost of each life cycle phase (Figure 2).

The following trade space variables were identified to convey how well a system meets each of the system metrics listed. These trade space variables include:

- The degree to which functional requirements are met (f.r. met)

- The degree to which "-ilities" are met ("-ilities" met)

- Total cost

- Cost per sub-functional requirement (Cost per sub-f.r.)

- Life cycle cost

By including the system's cost allocations in addition to total cost and life cycle cost, decision makers can determine the cost-benefit of the system at the functional requirement level. In addition, decision makers can also perform a wide variety of tradeoffs, such as determining if a large allocation of funds was appropriated on a functionality that ultimately would not meet its requirement, or determine if a single functional or sub-functional requirement was driving cost unnecessarily.

2.2.2. Levels of Reasoning

The ultimate goal of a decision maker is to answer feasibility questions (i.e., does a system meets a set of selection criteria?), or optimality questions (i.e., in the case of deciding among competitive systems, which system best meets the desired criteria?). The selection criteria could emphasize cost over functional requirements met, or could emphasize that all proposed functional requirements be met, regardless of cost. Due to the cost-benefit nature of this process, a decision maker needs to make comparisons within and across the system metrics discussed in the previous section. Frequently, decision makers will use their subjective opinions to complete these cost-benefits trade-offs, especially in the acquisition of sophisticated systems. Thus, a decision support display should provide straightforward and intuitive data integration to support these comparisons in the most objective manner possible. In essence, there are three general levels of reasoning that will occur for these complex acquisition decisions.

1) Data Processing: Low-level reasoning that compares values within a single constraint. For example, determining which competitive system has the overall greatest cost.

2) Information Aggregation: Mid-level reasoning that integrates of data across a single constraint. For example, determining which system meets all the functional requirements, as multiple values of similar type must be integrated before a conclusion can be drawn.

3) Knowledge Synthesis: High-level of reasoning that requires the integration of information across multiple constraints. For example, determining which system has the lowest cost, meets all "-ilities," and meets all functional requirements.

These three levels of reasoning allow a decision maker to formulate answers to different questions. Given the data processing example above, the focus may strictly be a straightforward cost comparison among systems, which does not require any data integration. However, for a more complex problem such as determining the best system based on functional requirement analysis, the answer cannot easily be found from simple data manipulation. Thus, any systems acquisition decision support tool must be able to support both simple data manipulation and comparison, as well as higher order data operations.

2.3. Background Summary

Overall, there is a large body of literature that supports the claim that a decision support tool could help aid an acquisition decision for complex system. System acquisitions require decision makers to process complex multivariate data on multiple levels of reasoning, as well as understand all candidate system information and perform cost-benefit trade-offs to determine which system could best fulfill the needs of their organizations. While the processes leading up to this decision are highly structured,

there is an overall lack of guidance regarding to how the decision maker can best understand which candidate system meets the organization's needs in the most objective manner possible. The next chapter, Display Design, describes how a graphical decision support tool could help support system acquisition decision makers understand these complex multivariate problems.

3. Display Design

The primary function of a visual display device is to impart information to a user, which can be conveyed in different ways through any number of interfaces such as a website, a text document, or a data analysis tool. A data analysis tool could simply be a spreadsheet of numbers with digital or analog information, or a graphical representation of those numbers. Previous research has indicated the advantages and disadvantages of each display type on a variety of tasks. This chapter describes the results of this previous research and how it pertains to system acquisition decisions. Further, this chapter describes the design and implementation of two system acquisition decision support tools: one is a traditional separable display while the other is a new configural display.

3.1. Components of a Data Analysis Display

A data analysis display consists of elements that either represent data or tools that a user can manipulate to access additional data, manipulate the data or manipulate the representation of the data. Those elements that represent data are considered to be more useful to the end user, as the user can directly abstract the information he or she is trying to acquire [10]. Tools to manipulate the data can be extremely useful, but the majority of a user's time should be spent viewing the data elements rather than trying to understand the analysis tools. The data elements in a system acquisition decision support tool should encode the trade space variable data as defined in Section 2.2.1 for each of the candidate systems being analyzed, including the degree to which functional requirements are met, the degree to which "-ilities" are met, total cost, cost per sub-functional requirement, and life cycle cost.

It is the selection and arrangement of the data elements within a display that make a display useful for a certain set of tasks. Therefore, different types of displays were

analyzed in order to determine how to design the data elements within a system acquisition decision support tool to best fit the needs of a decision maker conducting a system acquisition decision.

3.2. Previous Display Designs

A digital (respectively, analog) display is a non-graphical display that simply shows a number or value for each continuous (respectively, discrete) variable being imparted to the user. For a system acquisition decision, these variables are the trade space variables described in 2.2.1. In this trade space, two of the trade space variables are discrete (the degrees to which the system requirements and "-ilities" are met) while three are continuous (cost variables). Users of digital and analog displays have been shown to have poorer performance compared to users of graphical displays in terms of analyzing complex data [19, 20], though the contrary has been shown dependent upon the task and the experience of the user [11]. However, for tasks requiring the integration of information, graphical displays have been found to be superior [11]. These types of tasks are necessary in system acquisition decisions, hence graphical displays are the focus of this chapter.

Most graphical data analysis displays can further be categorized as either separable or configural displays. Separable displays, such as bar graphs generated from a spreadsheet, assign unique representations to each state variable [21]. Configural displays map individual variables in such a way to create emergent features which allow users to perceive higher level interactions or constraints among individual state variables through the means of natural mapping [22]. These interactions are created by determining which relationships exist between the high and low-level information, and presenting the low-level information in such a way that these relationships are shown.

For example, Figure 3 illustrates how a set of system requirements (requirements A-E) are met in a digital display format (Figure 3a), a graphical separable display

(Figure 3b), and a graphical configural display (Figure 3c). The degree to which the functional requirement is being met is displayed on a five point Likert scale [23], where 1 signifies "does not meet" and 5 signifies "greatly exceeds". In this example, each display allows the user to extract the functional requirement information, but the user may find this task to be easier with one of the displays over the other.
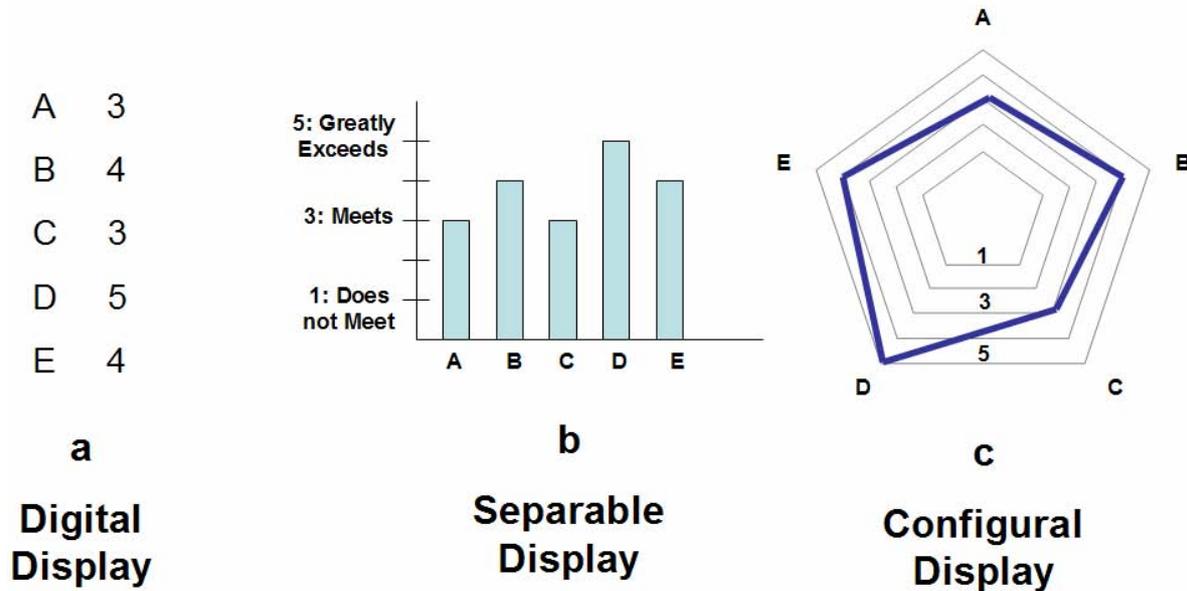
Figure 3: Examples of display types based upon functional requirement data

Previous research has been conducted to determine the advantages and disadvantages of separable and configural displays for varying degrees of reasoning processing difficulty. For data analysis tasks, it has been found that configural displays generally improve a user's performance while completing integration problems [24, 25] while separable displays result in improved performance while completing problems that do not require integration [26]. It is believed that because system acquisition decisions require both the integration and comparison of information, a configural display could best support these types of decisions. This hypothesis will be described in further detail later in this chapter.

3.3. Fan Visualization

Before the hypothesis that a configural decision support tool could support a system acquisition decision to a greater degree compared to a more traditional separable decision support tool could be tested, a configural decision tools had to be designed and implemented. Fan Visualization, or FanVis for short, is a system acquisition decision support tool which consists of a series of configural displays displaying both high and low-level information by incorporating emergent properties. Basic features such as color, shape, location, and size were integrated into the design display to promote preattentive processing [27]. Preattentive processing allows the user to quickly observe and extract large multi-element displays into the user's preattentive system to later be joined in the focused attention system into coherent objects [28].

In total, there are 5 different two-dimensional views in FanVis: 1) the System View, 2) the Multi-System View, 3) the Functional Requirement View, 4) the Comparison View, and 5) the "-ility" View. All the views were built upon the System View to provide the decision maker with different perspectives of the acquisition trade space.

3.3.1. FanVis Architecture

The views within the decision support tool are supported by an architecture programmed in Java. Each display is built within the shell shown in Figure 4. This shell consists of four parts:

1. The functional buttons: Allow the decision maker to add, or delete components of each system. These buttons are highlighted by the green dotted line.

2. Tree structure: Lists all trade space variables within the system acquisition trade space such as the functional requirements and "-ilities" for each candidate system. Also where the decision maker can change any of these trade space variables. In addition, the tree structure allows the decision maker

to switch which component of the trade space is being viewed. This structure is highlighted by the red dash-dot line.

3. Tabs: Allow the decision maker to select the view to be displayed. The tabs are highlighted by the purple dashed line.

4. View space area: Area where the actual view will be displayed. Currently no view is displayed. Decision makers can change between the views through the tab structure. The decision maker can also expand particular views to other screens, allowing access to either a single or multiple views.
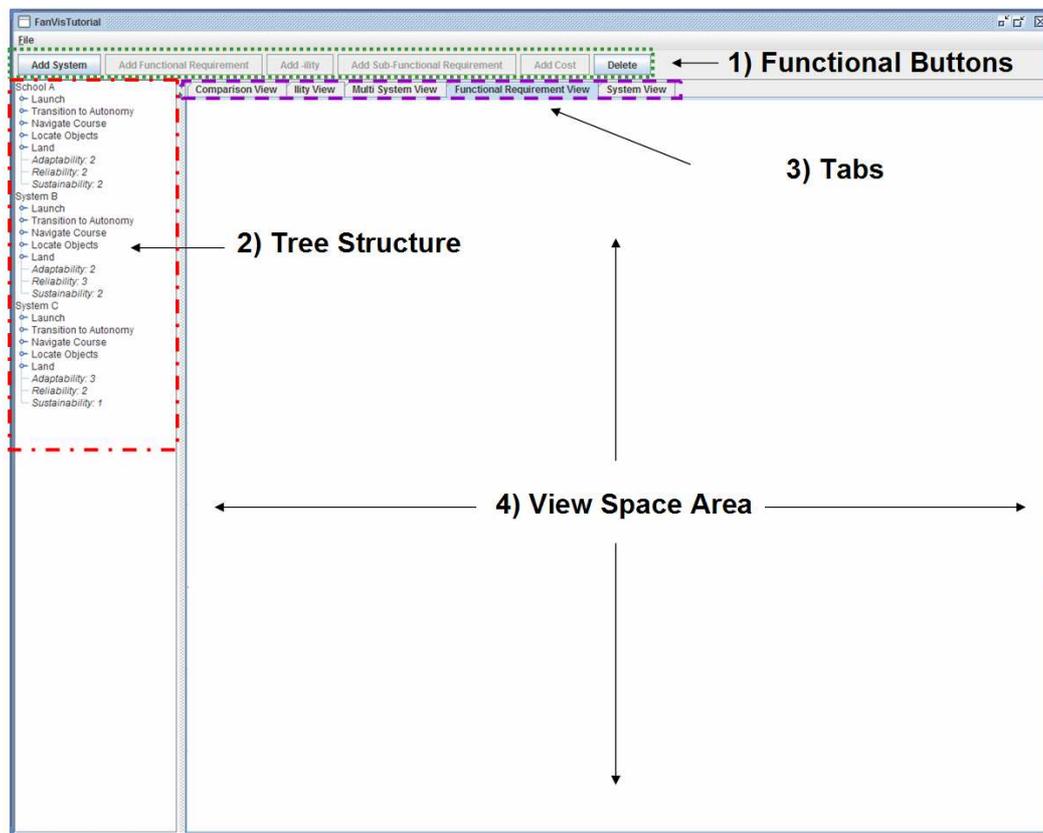
Figure 4: The overall shell of FanVis

3.3.2. The System View

The main structure of FanVis is similar to a radar chart where variables (in this case, the functional requirements of the proposed system) are represented by axes which

originate from a central point. Each system in the design space is represented by a polygon in the System View, such as in Figure 5.

The vertices of a system's polygonal representation intersect the functional requirement axes at particular points along those axes to demonstrate how well the system meets each particular functional requirement. The axes scales are a five point Likert scale [23] with the following delineations: 1) Does not Meet Requirements (closest to the central point), 2) Partially Meets Requirements, 3) Meets Requirements (middle point, shown in red), 4) Exceeds Requirements, and 5) Greatly Exceeds Requirements (furthest from the central point). Faint lines connect the axes along this five point scale to provide a visual anchor.
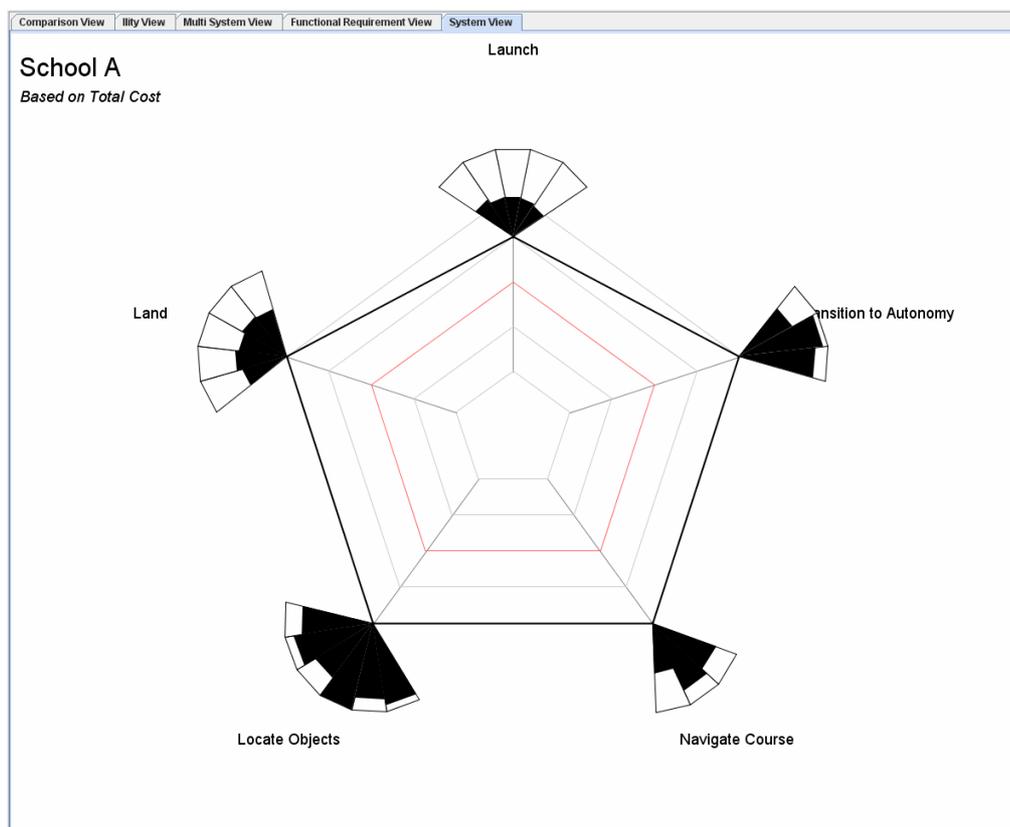
Figure 5: System View of FanVis

In all likelihood the decision maker would want the system to be on or outside the red line (center pentagon in Figure 5), which represents that the functional

requirements are being met at some minimum level. Up to ten functional requirements can be viewed at a given time, and each functional requirement can have up to fifteen sub-functional requirements due to space limitations of the visualization for a 21-inch desktop computer with a resolution of 1280 x 1024 pixels, 16 bit resolution.

Each vertex contains a fan comprised of individual blades, which represent the sub-functional requirements' within the functional requirement on that axis. These blades are shaded according to how expensive the sub-functional requirement is in relation to the most expensive sub-functional requirement for that system. The system's most expensive sub-functional requirement of the entire system will thus be completely black, while the least expensive will be primarily white (if there are significant differences in the costs). This expense could either be the total cost or one of the life cycle phase costs as chosen by the decision maker through a selection menu (Figure 6).
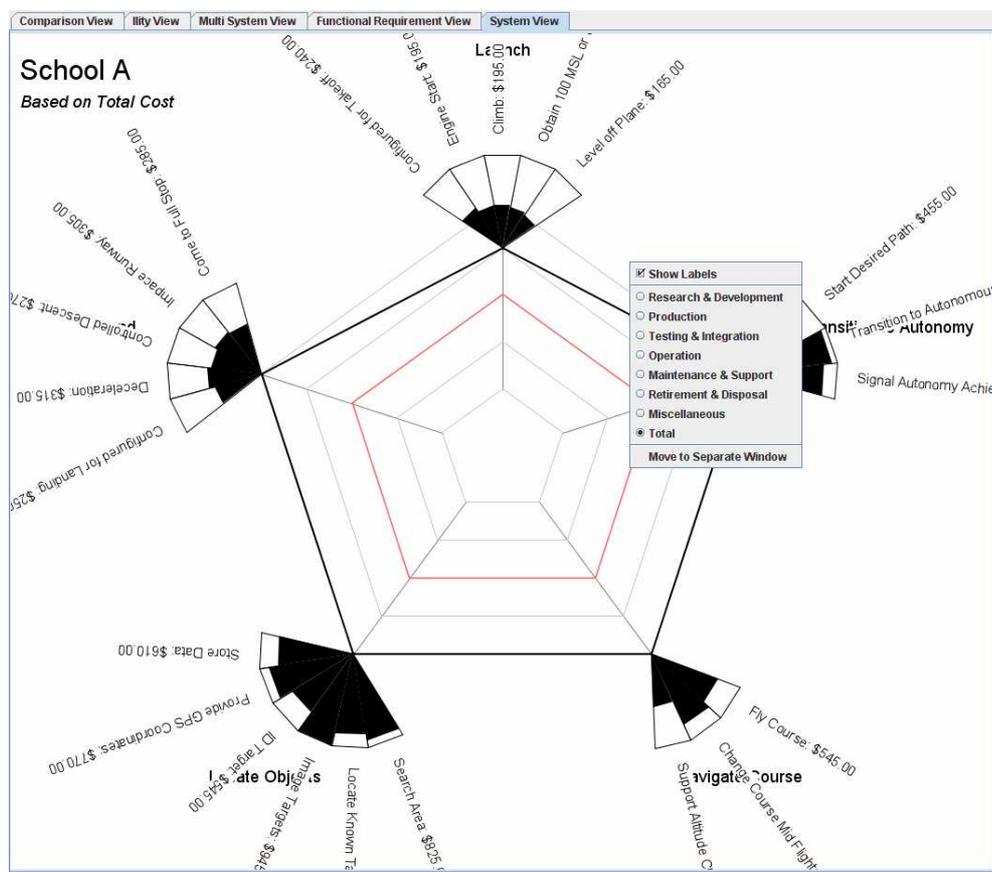
Figure 6: System View of FanVis displaying the selection menu

Additionally, the selection menu in Figure 6 allows the decision maker to show data labels as desired. These data labels provide the name of a data element along with the data value. Decision makers are able toggle these data labels on and off to avoid cluttered displays. They can also scroll over individual data elements with their mouse to obtain this information.

In addition to the options provided by the selection menu, the decision maker can easily add, delete, or modify the system data within the tool through tools in the tree structure and functional buttons (Figure 7). For instance, if the decision makers wanted to input data regarding a new functional requirement, they would select the system in the tree structure (Step 1) then click "Add Functional Requirement" in the functional buttons (Step 2). As shown in Figure 7, this creates a new functional requirement. In a similar manner sub-functional requirements can be added to new or existing functional requirement, as well as costs or new systems.
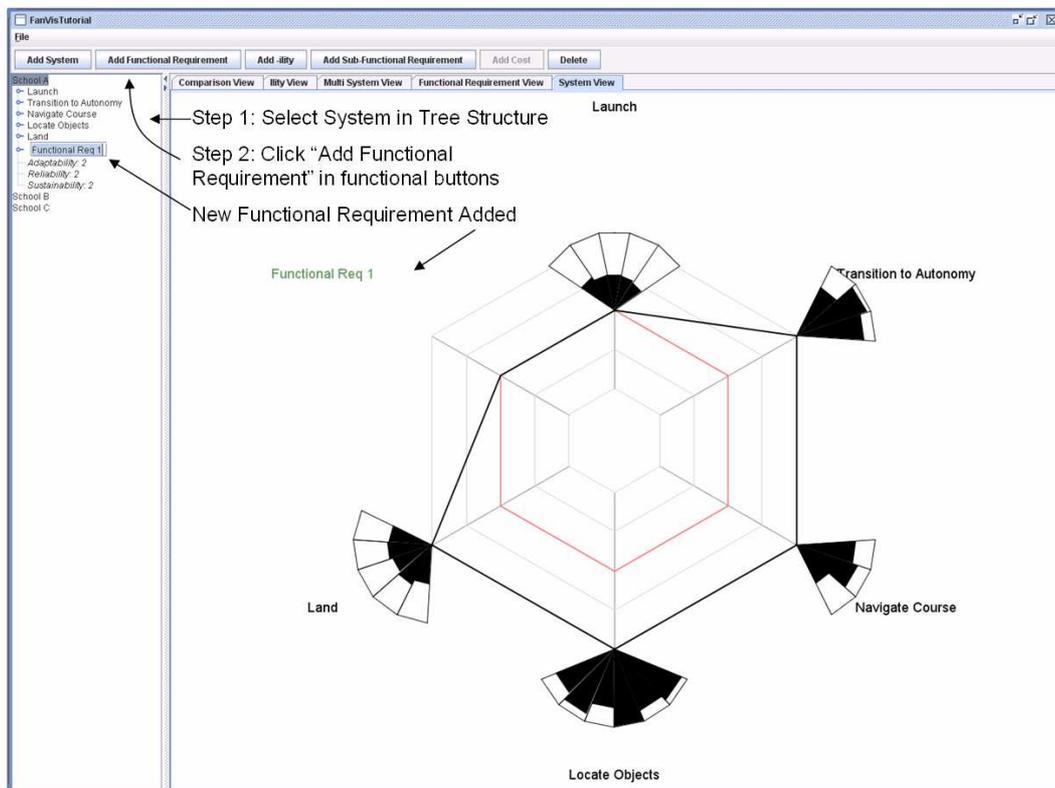
Figure 7: Example of FanVis interactivity within the System View

If the decision maker would like to delete the functional requirement (or any variable within the system trade space), he or she only has to click on the requirement or variable in the tree structure then click "Delete" in the functional buttons. Further, the decision maker can change the value of any trade space data point by double clicking on the variable in the true structure then type in the new value.

Analyzing Figure 5, there are several emergent features in this view that are important to note, the first of which is the polygon's shape and size; the area that the system encompasses is a reflection of the degree of success with which the functional requirements are met. This follows a natural mapping of bigger is better for this objective. Additionally, if a system is balanced in terms of how it meets the functional requirements, it will have a balanced shape, which follows a user's appeal towards symmetry [9]. For example, in Figure 5 the polygon is relatively large and symmetrical and thus would likely be a good system in terms of meeting functional requirements.

A second emergent feature of this view is the cost distribution. If there is a functional requirement that is driving the cost of the system, the fan representing that requirement will be mostly black, while all other fans will be mostly white. By having one fan different than all other fans, it will be more salient, thus giving the association that the difference should be noticed and potentially remedied. If the functional requirements are balanced in cost, all the fans will be mostly black. Similar to the polygon's shape, this natural mapping follows a user's appeal towards symmetry.

In terms of data elements, the primary data element is the fan representing a functional requirement. Encoded within the fan is the degree to which the functional requirement is met, the overall cost of the functional requirement, and the cost of the sub-functional requirements within the fan. In this manner a single data element is encoding three of the trade space variables outlined in section 2.2.1.

The polygonal element that encodes the high-level information of how well the system meets all functional requirements is an additional data element in this view. The

polygonal area allows decision maker to compare systems within the acquisition trade space; it is not an absolute computation. For example, if the functional requirements were rearranged, the system would have a different area. However, decision makers are not obtaining an exact figure for how well the functional requirements are being met, they are analyzing the cost-benefit trade-offs between the systems. These trade-offs can easily be completed with the System View as long as all competing systems present the functional requirements in the same order around the polygon.

3.3.3. Multi-System View

The Multi-System View displays two or more system views side by side, as shown in Figure 8. This design is able to directly promote comparisons among the systems. Because all necessary information is positioned within the user's visual scan, the decision maker benefits from uninterrupted visual reasoning [29], which allows the decision makers to focus on the differences between the systems easily as all information is positioned within their visual range. The idea is to emphasize the differences in the data, and not the manner which these changes are being displayed [29]. For instance, Figure 8 quickly reveals that the system at the right is much smaller than those on the left, but the cost distribution is very similar. This type of direct comparison could greatly help the decision makers conduct their cost-benefit analysis.

Decision makers can view up to four systems at a time in the Multi-System View. However, the decision maker can change which four systems are being analyzed by dragging that system from the tree structure into one of the four quadrants. This enables the systems to remain sufficiently large for a user to distinguish the features of each system, while displaying multiple systems at a time.
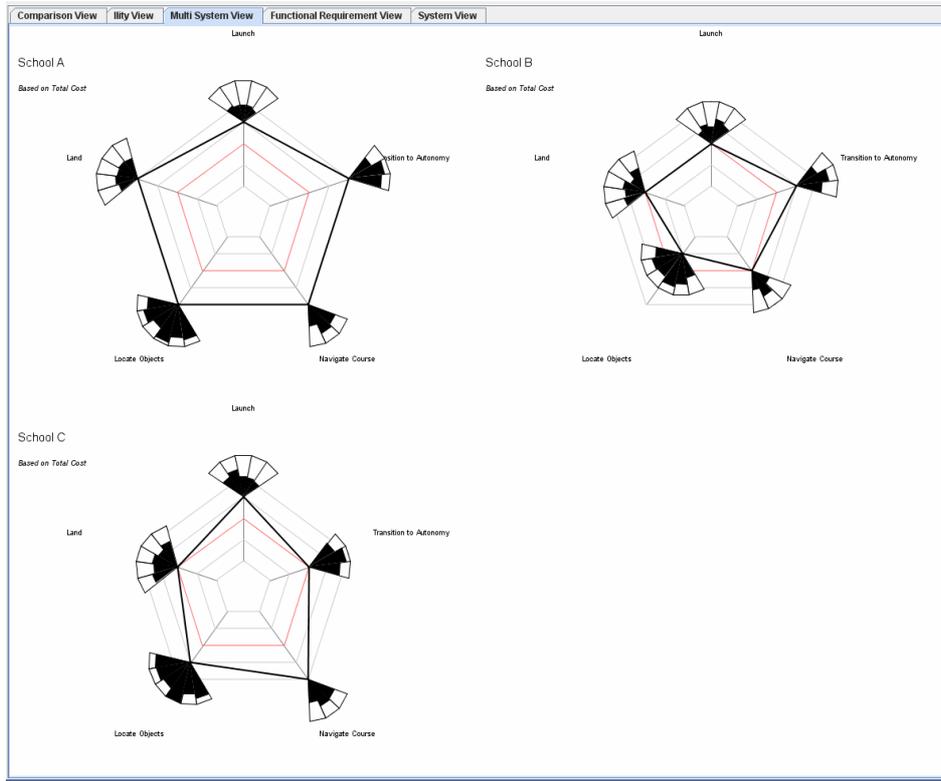
Figure 8: Multi-System View of FanVis

The emergent features of the Multi-System View are very similar in nature to those in the System View, as the same trade space criteria are displayed. The primary difference, however, is that the sub-functional requirement cost for each system is now shown relative to the most expensive sub-functional requirement for all systems being analyzed in the trade space. This allows the decision maker to perceive relative differences among the systems more readily. In this manner, decision makers can compare sub-functional requirements, functional requirements, or full systems within the trade space.

3.3.4. Functional Requirement View

The Functional Requirement View (Figure 9) displays multiple systems for a single functional requirement. This view allows decision makers to probe deeper into the potential tradeoffs within the trade space. It permits users to view multiple systems, as

in the Multi-System View, but allows a greater degree of detail. The decision makers can analyze up to four systems in this view at a time, and gain access to additional systems by dragging the view to the right or the left. This allows them to scroll through all systems within the system acquisition trade space. The decision makers can also opt to not view all systems by dragging systems out of the view back into the tree structure.

In this view, the degree to which the functional requirements are met has been modified from the polygonal structure to flat lines with the delineations: 1) Does not Meet Requirements (bottom line), 2) Partially Meets Requirements, 3) Meets Requirements (middle line, shown in red), 4) Exceeds Requirements, and 5) Greatly Exceeds Requirements (top line). For example, in Figure 9 the first system greatly exceeds the requirement, the second only partially meets the requirement, and the third exceeds the requirement.
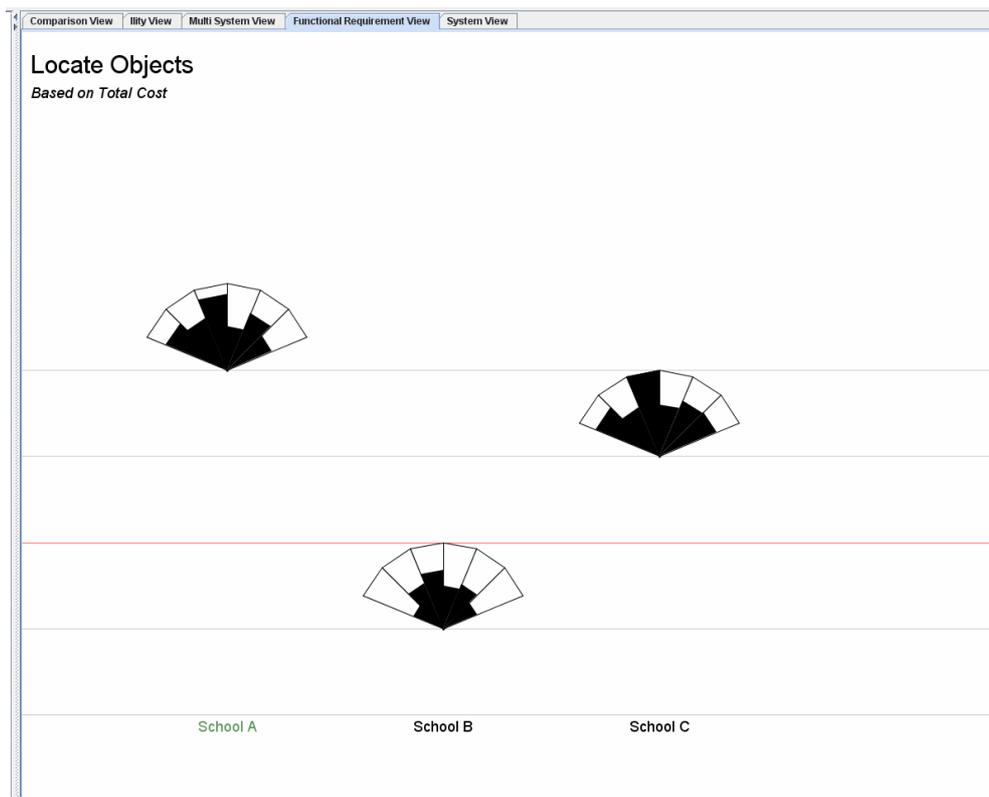
Figure 9: Functional Requirement View of FanVis

3.3.5. Comparison View

The Comparison View, as shown in Figure 10 provides a higher level of data abstraction by displaying two or more systems without the lower level sub-functional requirement cost information. This gives the user the ability to obtain a global view of the trade space. The polygonal shapes each represent a system in the same manner, as shown in the System View. The fans, however, have been removed, deleting information regarding the sub-functional requirement cost. Instead, total cost is displayed as a function of the color of the system's polygonal representation. The color of the polygon is determined by the relative cost of a particular system to the other systems in the trade space. A color legend in the lower left of Figure 10 displays both the relative placement of the systems' cost as well as a digital value for that cost. The color gradient is an interval sequence which ranges from blue for the most expensive system, to yellow for the least expensive system with all color gradations in between.
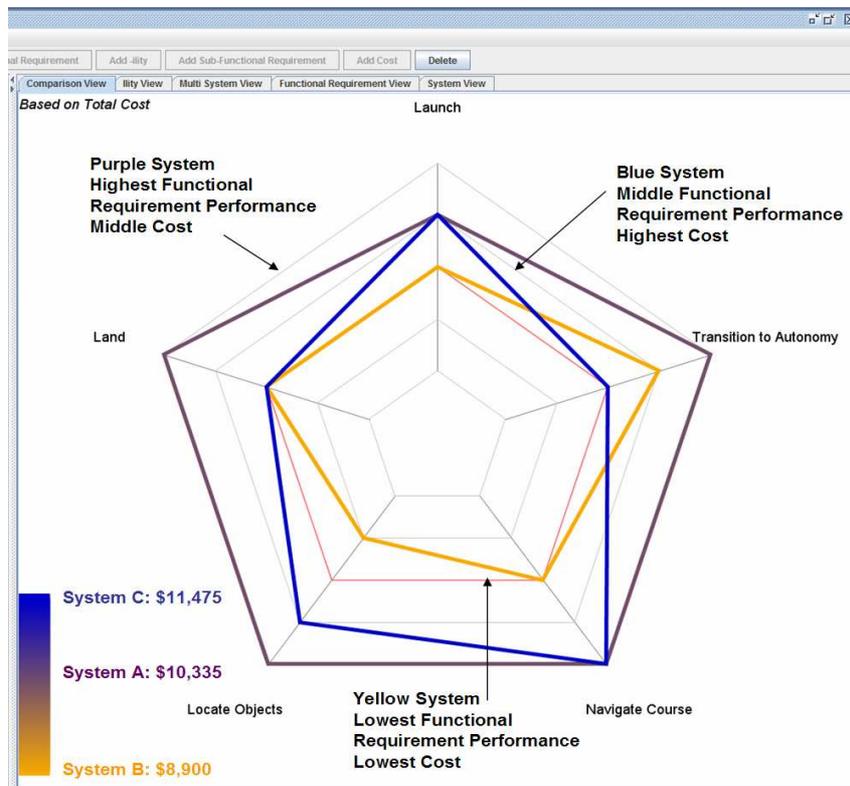
Figure 10: Comparison View of FanVis

In this example, the system with the highest cost, the blue system, is not the system that most successfully achieves the functional requirements. The system with the highest performance in terms of the functional requirements is the system with the middle cost, the purple system. The system with the worst functional requirement performance is the least expensive system. The Comparison View fosters this type of cost-benefit trade-off analysis.

As in the System View, there are several emergent features included in the Comparison view that are important to note. As in the previous views, the system that best meets requirements will have the largest polygonal shape. In Figure 10, the system that best meets requirements is the one whose polygon encompasses the other two polygons, the purple system. A second emergent property is the determination of relative cost. Since the cost scale for the trade space is coded to a color interval sequence, it can be seen which system has the most expensive cost, either in total cost or cost per life cycle phase.

3.3.6. The "-ility" View

Decision makers can obtain additional information in the "-ility" View, as shown in Figure 11. In this view, a decision maker can analyze how well "-ilities" are met in addition to analyzing the degree to which the requirements and cost are met. How well each "-ility" is met is shown by scaling the size of a system's polygonal representation. This scale is a three point Likert scale ranging from 1) Does not Meet Requirements (shrinking the polygon from its original size), 2) Meets Requirements (original size) and 3) Exceeds Requirements (expanding the polygon from its original size). A three point Likert scale is used instead of the five point Likert scale for how well functional requirements are met due to the subjective nature of "-ilities." For the most part, "-ilities" cannot be quantitatively measured as they are an evaluation of the performance

of a system. Measuring them on a finer scale could ultimately lead to data misconceptions by the decision makers [17].

In this manner, a smaller polygon represents that an "-ility" was not being met. Thus the optimal system would have a large polygons for each "-ility." The predominant emergent features in this view are the polygon's size and symmetry. Similar to the Multi-System View, the decision makers can view up to four systems at a time in the "-ility" View. To view other systems, they can drag systems in and out of the four columns and the tree structure.
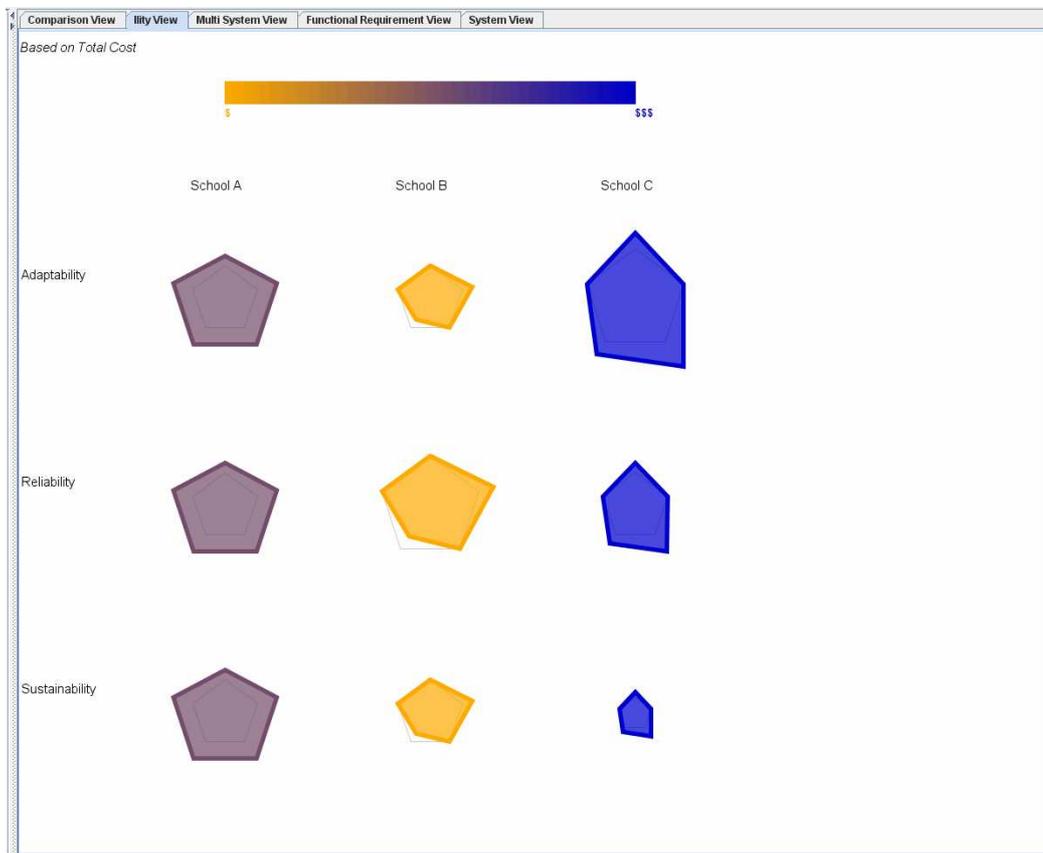
Figure 11: The "-ility" View in FanVis

Overall, each of the tabs within FanVis allows the decision maker to gain a different perspective on the system acquisition decision trade space. The Comparison and "-ility" Views allow decision makers to obtain a global view of the trade space data. The System and Muti-System Views allow decision makers to inspect the system's cost

distribution. If this level of detail is not sufficient, the decision makers can use the Functional Requirement View to review the data of a single functional requirement. Each of these perspectives allows the decision maker to assess different levels of the trade space data. This next section describes the separable display, followed by the similarities and differences of the two displays.

3.4. Separable Decision Support Tool Design

A separable decision support tool was also created to test how well the two tools supported system acquisition decisions. The separable tool was created in Excel® since it can be, and likely is, a very common application for conducting system acquisition decisions. The Excel® spreadsheet-based tool is a relatively simple decision support tool, built entirely from functions within Excel®. The tool utilizes four tabs. Three of the tabs, Requirements and "-ilities", Total Cost, and Cost Categories, are graphical displays of the data, while the last tab, Data, includes the raw numbers of the trade space. Unlike FanVis, decision makers may experience difficulty in adding or deleting system data dynamically, as well as reproducing the new charts automatically as these functions must be selected in Excel®.

3.4.1. Requirements and "-ilities" Tab

The Requirements and "-ilities" Tab displays the degree to which each requirement is met by systems in the trade space in two bar charts. Each requirement or "-ility" is represented by a different bar, while each system has a different color code (shown in Figure 12). This color code was the default Excel® color scheme for three variables in a line chart. This color scheme was retained as it gave sufficient separation among the three colors.
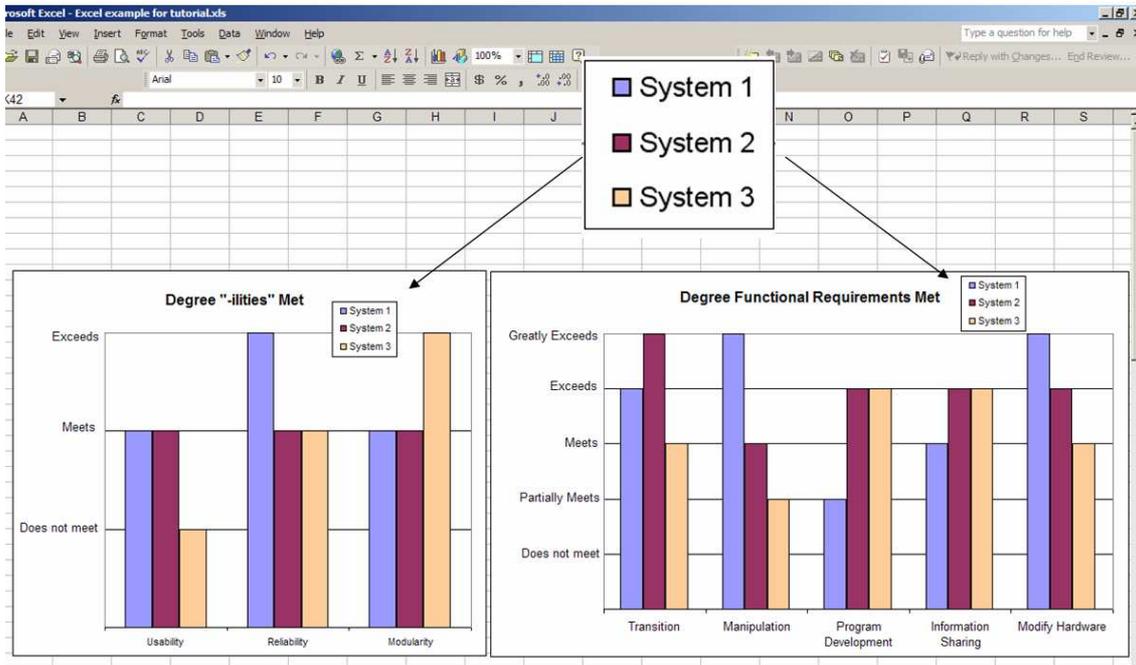
Figure 12: Requirements and "-ilities" Tab of Excel®

Unlike FanVis where data elements were often encoded with data from multiple trade space variables, each data element within the Excel® tool only represents a single trade space variable. In Figure 12, the data elements in the left bar chart each represent how a system meets an "-ility." The data elements in the right bar chart each represent how a system meets a functional requirement. There are no data elements which represent how the functional requirements as a whole are met. Instead, decision makers must integrate this information themselves.

3.4.2. Total Cost

The Total Cost Tab displays each system's total cost in a bar chart as well as the cost per sub-functional requirement in a line chart, as shown in Figure 13. A line connects the cost of the sub-functional requirements within a given functional requirement. These lines help the decision maker delineate the various functional requirements from each other in any given system.
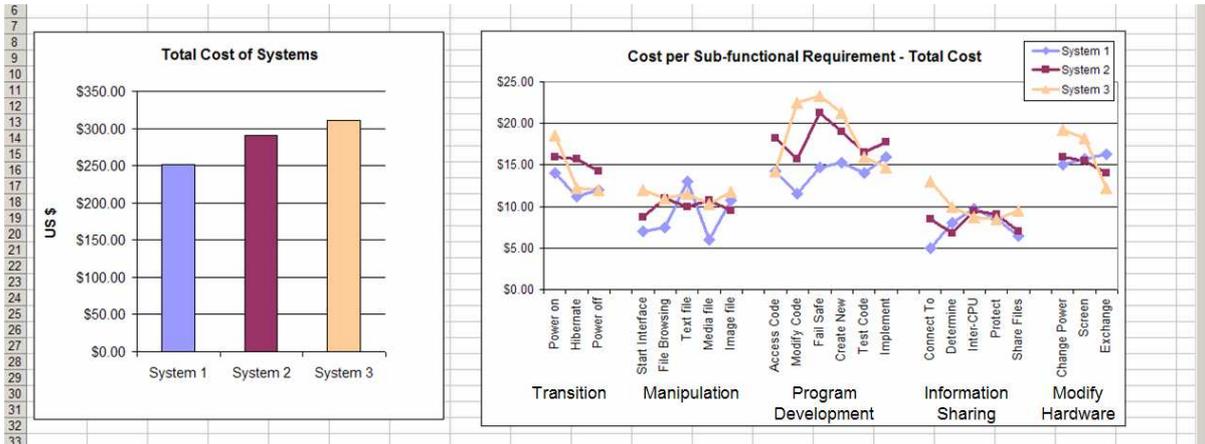
Figure 13: Total Cost Tab of Excel®

3.4.3. Cost Categories

The Cost Category Tab (Figure 14) is much like the Total Cost Tab. For each life cycle cost phase being analyzed, the total system cost appears for all systems in a bar chart. In addition, the cost per sub-functional requirement for all systems is shown in line charts by cost phase.
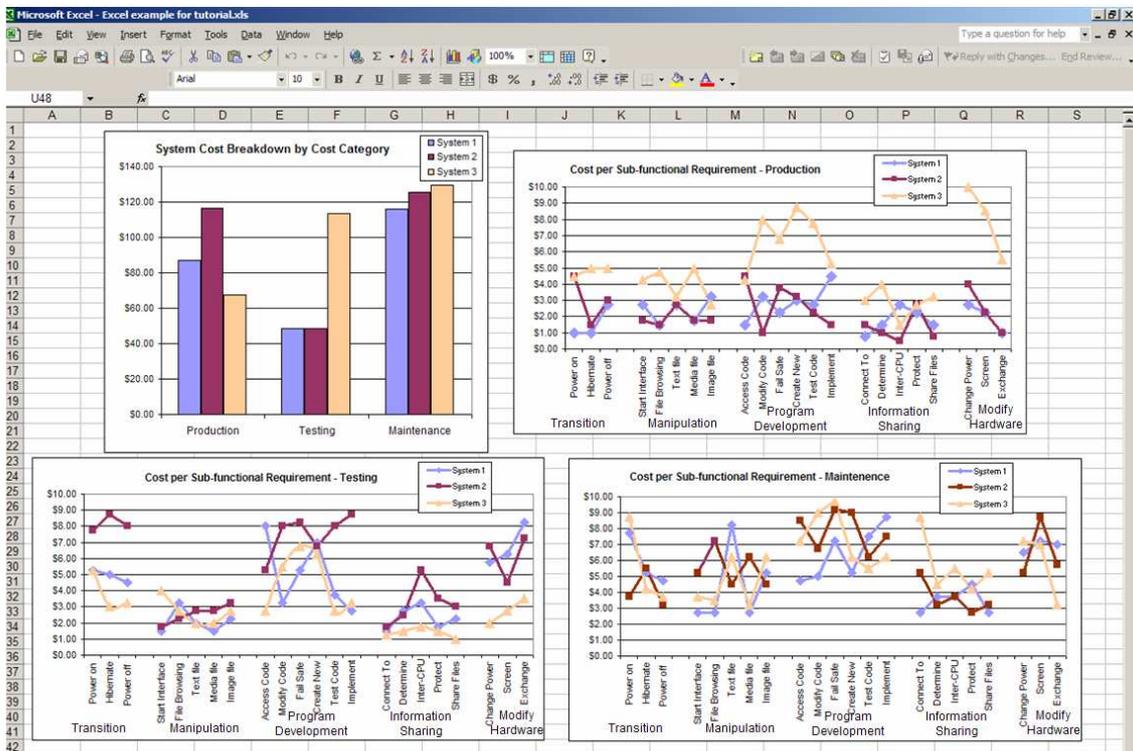
Figure 14: Cost Categories Tab of Excel®

3.4.4. Data

The Data Tab (Figure 15) is simply the raw trade space numbers, organized by system. All trade space data can be found under this tab including the degree to which a system meets the requirements and "-ilities" as well as the cost per sub-functional requirement for each of the life cycle phases being analyzed. The Data Tab is organized in such a way that a system acquisition decision maker could add additional functional or sub-functional requirements. However, the charts would not be reproduced automatically; they can only be reproduced through the Excel® functions.

Figure 15: Data Tab of Excel®

3.5. Summary

Both the configural and separable display were designed to encode the trade space variables needed for a system acquisition decision. As outlined in section 2.2.1,

these include the degree functional requirements are met, the degree "-ilities" are met, and cost. Only the manner which these trade space variables are encoded differs. In FanVis, most data elements encode two or more trade space variables, whereas in the Excel® tool, each data element only encodes one trade space variable. The fans in FanVis, for example, encode three trade space variables: the degree to which the functional requirement is being met, the overall cost of the functional requirement, and the cost of the sub-functional requirements within the fan. The functional requirement bars in Excel®, however, only encode one trade space variable: the degree to which the functional requirement is being met. This allows FanVis to encode more information in the same space, while ensuring the decision maker is still able to extract the necessary information. In addition, by utilizing emergent features, FanVis has data elements which display the higher level constraints of the trade space such as how the functional requirements as a whole are met (represented by the polygon area data element).

These differences cause the two decision support tools to have a disparate number of total number of available data elements. For example, if the trade space consisted of three systems being evaluated on five functional requirements (fifteen total for the data space) containing five sub-functional requirements each (seventy-five total sub-functional requirements) and four "-ilities" (twelve total), FanVis would have a total of 278 data elements as compared to the 171 data elements in Excel®. These elements would be distributed within each tool as illustrated in Table 1.

Table 1: Data element distribution for an example trade space

	FanVis					Excel®			
	Comparison	"-ility"	System	Multi-System	FR	Data	Requirements	Total Cost	Cost Categories
f.r. met	15		5	15	3		15		
"-ilities" met		12					12		
Total Cost	3		3	3				3	
Cost per sub f.r.			25	75	15			75	
Life Cycle Cost	3		25	75	15				75

FanVis and the Excel® tool each have their own set of advantages and disadvantages. FanVis is a series of configural displays, while Excel® is a series of separable displays. It is likely that the configural displays will allow decision makers to understand high-level information more easily than in the separable displays, as this information is being displayed through emergent properties. Thus, decision makers will be provided with more support on Knowledge Synthesis and Information Aggregation tasks while using FanVis. On the other hand, when this integration is not necessary, users may find using a separable display is easier as the individual pieces of information are not already integrated. However, FanVis was designed with the foreknowledge that both integration and non-integration tasks would be necessary, thus the low-level information is coded in a salient and easily understandable manner. With these design considerations in mind, it is believed that the configural display, FanVis, will be able to support a decision maker to a similar or better degree than a separable display. This hypothesis was tested as outlined in the next chapter, Experiment Evaluation.

4. Experimental Evaluation

Given the differences between the two tools, the next step in the research process was to determine which tool best supported a system acquisition decision and why. A human performance experiment was conducted to compare the two tools on a set of system acquisition tasks. This chapter describes the experimental method, including the setup, tasks, and design of the experiment.

4.1. Hypothesis

It was hypothesized that the configural decision support tool, FanVis, would be able to support high-level system acquisition decisions to a greater degree than the traditional separable decision support tool developed in Excel®. This hypothesis was tested in terms of participant performance on system acquisition tasks, subjective appeal of the decision support tools, and participants' cognitive strategies while using the tools.

4.1.1. Performance

It was hypothesized that the configural decision support tool, FanVis, would enable a user to achieve higher performance compared to a traditional decision support tool. Performance was measured in terms of the percentage of system acquisition trade space questions answered correctly and the speed at which they were answered. These questions were asked at the three levels of reasoning a decision maker may have to utilize while conducting a system acquisition decision including Knowledge Synthesis, Information Aggregation, and Data Processing, as defined in section 2.2.2.

The promotion of meta-analysis through the use of emergent features within FanVis made it reasonable to expect that participants would have increased accuracy for Knowledge Synthesis and Information Aggregation questions using FanVis. The

emergent features allow users to analyze the low-level information of a trade space (such as how single functional requirements are met) and display them in such a manner that higher-level interactions are conveyed (such as how the functional requirements as a whole are met). This type of meta-analysis allows users to gain more information in a shorter amount of time. It was expected that participants would achieve similar accuracy with both tools on Data Processing questions since separable displays have been shown to support these types of tasks to a greater degree than configural displays. FanVis was designed in such a way to simplify these low-level tasks by displaying the low-level information as salient and understandable as possible.

In addition, participants were expected to achieve the highest accuracy on Data Processing questions since answering these requires the lowest level of reasoning (Figure 16). Furthermore, it was expected participants would answer a higher percentage of Information Aggregation questions correctly than Knowledge Synthesis questions since the former require a lower level of reasoning than the latter. However, analyzing performance among the three reasoning levels was deemed to be of less importance than analyzing performance between the two decision support tools.
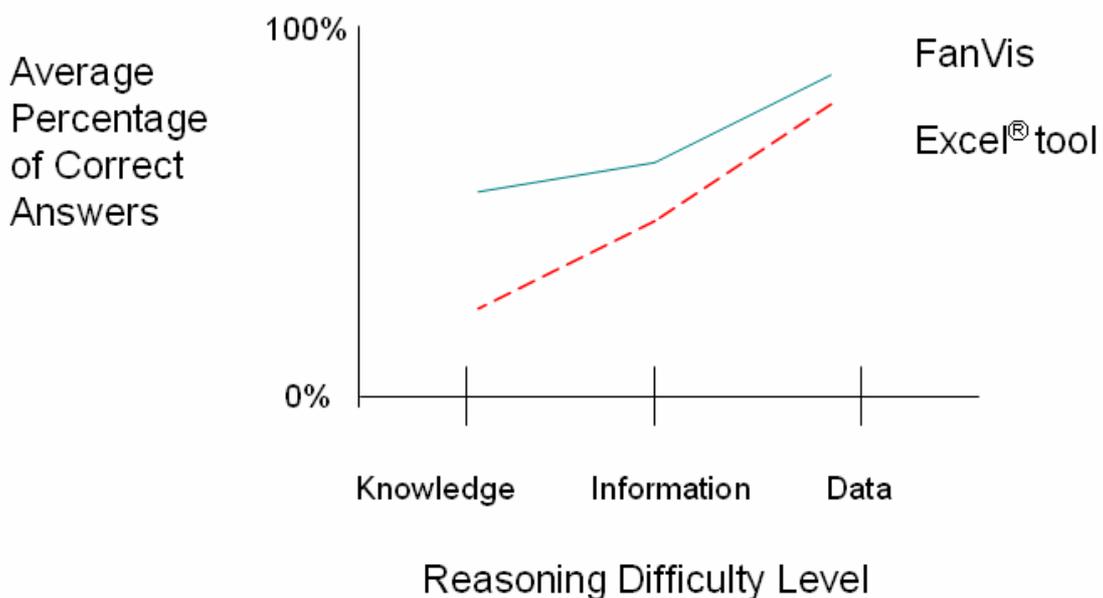
Figure 16: Hypothesized results for percentage of correct decision choices

Participants were expected to be able to analyze the trade space in a more efficient manner while answering Knowledge Synthesis and Information Aggregation questions using FanVis. As mentioned above, because FanVis allows users to conduct meta-analyses while analyzing the trade space, it was expected that the participants could be able to obtain more information in a shorter time span. While users of configural displays have been shown to have less efficient performance for low-level data extraction in some studies [30], the low-level data in FanVis has been organized in such a way to aid users extract this type of data. For this reason it was expected that participants would answer the Data Processing questions with a similar speed with FanVis as the separable Excel® tool (Figure 17). It was also expected that participants would spend a greater amount of time on questions requiring the greatest amount of reasoning, and thus would answer Data Processing questions in the shortest time frame, followed by Information Aggregation questions and Knowledge Synthesis questions.
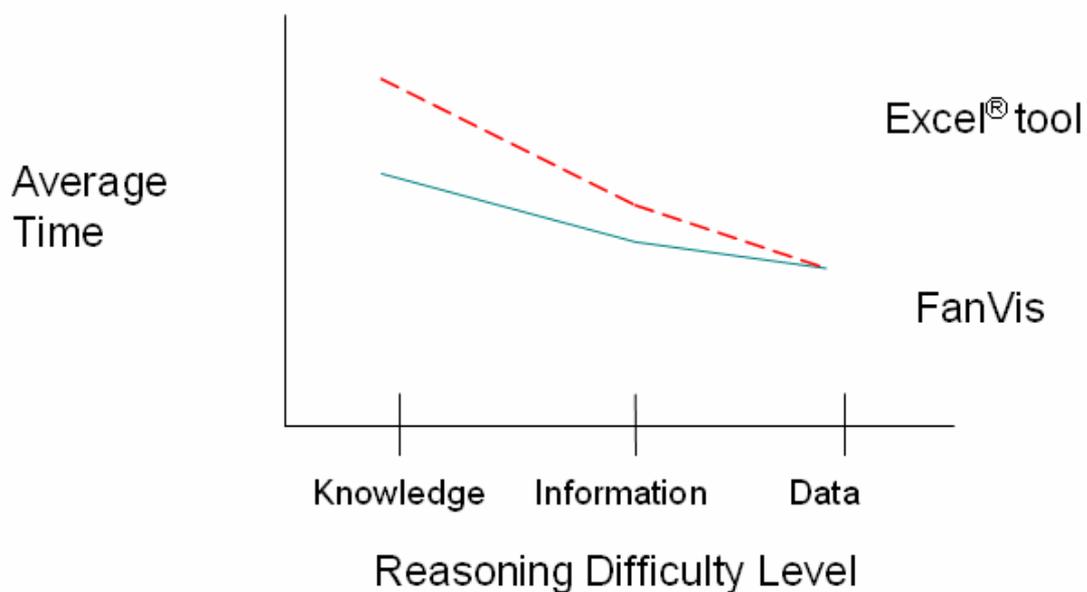
Figure 17: Hypothesized results for time to answer questions

4.1.2. Subjective Appeal

Subjectively, it was expected that users would prefer using FanVis over the Excel®-based separable tool while completing a system acquisition decision since FanVis presents the information in a clearer and more interactive manner. However, it was acknowledged that there potentially could be a bias towards the Excel® tool, as the majority of the participants were proficient with Excel® whereas FanVis was a new tool for all participants. This bias and its potential implications to this study are discussed further in the Corollary Hypothesis section. The user's subjective appeal was determined by analyzing the participants' responses to a questionnaire at the end of the experiment.

4.1.3. Cognitive Strategies

Cognitive strategies of the participants were also analyzed through the use of eye fixation patterns to help determine if the participants were accessing the relevant/necessary elements to complete their decision process, and if so, how efficiently they were accessed. An efficient eye fixation pattern is a natural fixation pattern where the shortest path is taken from one necessary element to the next. Natural fixation patterns suggest participants utilized superior cognitive strategies compared to if they were using a less efficient gaze pattern [31-33]. The fixations were obtained by gathering data from an eye tracking device (discussed in section 4.3.2). These fixations identified which elements participants were focusing on to a greater degree in each of the displays, and what fixation patterns emerged through the use of each tool. It was believed that participants would be able to access the necessary elements in a more efficient manner while using FanVis as compared to the Excel® tool since the trade space variables were encoded in a more effective manner within FanVis's data elements.

4.1.4. Corollary Hypothesis

For all research hypotheses posed, it was acknowledged that users could become confused, overloaded or even misguided because of their unfamiliarity with the FanVis tool. It should be noted that the majority of participants in this experiment were moderately to extremely proficient in Excel®, whereas none had any previous experience with FanVis. This bias could have led to improved participant performance with the Excel® tool, even if FanVis represented the trade space in a more salient manner. It was hypothesized though, that because the data in FanVis is mapped more directly to a user's cognitive model of the trade space, users would be able to readily understand the data aspects being presented in the tool.

4.2. Participants

To test these hypotheses, 30 participants between the age of 18 and 75 were recruited for this study. Further, personnel with experience in either high-level system acquisitions or high-level decisions for a team or organization were specifically recruited as both roles utilize the high-level data analysis skills required for an acquisition. Those with only high-level team decision-making experience differed in that they had not completed an actual acquisition.

The average participant age was 52.43 years with a standard deviation of 11.39 years. Half the participants had served or were currently serving in the armed forces with an average of 16.21 years of service and standard deviation of 13.03 years. All had moderate to high levels of experience completing high-level decisions for a team, project or organization, and 23 of the 30 had system acquisition experience. The average number of years of system acquisition experience of those participants was 13.95 years with a standard deviation of 13.10 years. All had experience using data manipulation tools, such as Excel®, and none indicated that they were color blind. All participants could comfortably see the information presented on the computer screens for the

duration of the experiment. The full demographic information of the participants can be found in Appendix A.

4.3. Apparatus

Two main pieces of equipment were required to complete this study; the Mobile Advanced Command and Control Station (MACCS) and an eye tracking system. This section outlines both pieces of equipment, how they were used within the context of this experiment, and how they contributed to the experiment as a whole.

4.3.1. MACCS

The Mobile Advanced Command and Control Station's an experimental test bed equipped with six 21-inch wall mounted displays, each having a resolution of 1280x1024 pixels, 16 bit color resolution. The displays are organized as shown in Figure 18. For the purposes of this experiment, only the bottom three monitors were used while the top three were not powered. The computer used to run the simulator was a Digital Tiger Stratosphere Titan with an AMD Athlon 64 X2 Duel Core Processor 4200+ and four NVIDIA Quadro NVS 285 graphics cards.

Figure 18: Inside view of the Mobile Advanced Command and Control Station

MACCS is a mobile testing platform mounted within a 2006 Dodge Sprinter shown in Figure 19. By integrating an experimental test bed into a vehicle, the experiment was able to travel to the participants, making the experimental process easier for the participant. This allowed a high number of participants to be recruited with system acquisition or high-level decision-making knowledge.

Figure 19: Outside view of the Mobile Advanced Command and Control Station

4.3.2. Eye Tracker

An eye tracker was used to collect the participants' eye fixation data as they answered the system acquisition trade space questions. As mentioned in the hypotheses section, analyzing the fixation data helped determine the cognitive strategies of the participants. The eye tracker used was a Polhemus VisionTrak® [34]. As shown in Figure 20, this is a head-mounted eye tracking system on a baseball cap with an adjustable head band. A baseball cap was chosen to minimize subject discomfort and allow full head movement.

The eye tracking system tracks the center of a participant's pupil and the reflection from the corneal surface. This tracking information is integrated with head movement data to determine the fixation point of the participant. This technology was developed

with the Polhemus VisionTrack® System by ISCAN® [35]. The head movement data is found using a magnetic source and sink. The magnetic source measures one inch square and is located approximately two feet from the participant, as can be seen in Figure 18. The magnetic sink is a small gray attachment on the brim of the baseball cap as shown in Figure 20.

Figure 20: The Polhemus VisionTrack® System

Fixation points are mapped to the computer screen to produce real-time vision tracking. This allows the participant to browse over a large area through the duration of the experiment. It also allows the participant to look down, or away from the screens of interest, and be able to return to the screen. A simple calibration routine was completed at the beginning of the experiment to accommodate for each participant's specific head and body orientation to the displays.

4.4. Experimental Procedure

The experiment consisted of seven parts: pre-experiment interactions, a baseline data handling proficiency test, two training sessions, two test sessions, and post-

experiment interactions. This section discusses the components of each of these seven parts. On average, the full experiment lasted an hour and a half.

4.4.1. Pre-Experiment Interactions

When participants arrived, they were introduced to the experiment as well as the experimental setup. The participants then read and signed the Consent to Participate Form in which they learned the purpose of the experiment, compensation conditions and the experimental aspects they were asked to complete (Appendix B). The participant then filled out a brief demographic survey (Appendix C).

4.4.2. Baseline Data Handling Proficiency Test

A baseline data handling proficiency test was administered to assess participants' Excel® familiarity and data processing skills. This test was constructed from the Educational Testing Service® practice questions for the quantitative section of the Graduate Record Examinations [36, 37]. The test consisted of quantitative multiple choice questions that were answered by interpreting Excel® charts and graphs. The questions had a varying degree of difficulty, with a definitive answer (Appendix D). The participants' baseline data handling proficiency was based upon the percentage of questions answered correctly, and how long the participants took to answer all questions.

4.4.3. Training Session

The participants were introduced to an acquisition case study and then presented with a tutorial of the decision support tool, both of which provided the participants with the information necessary to complete the system acquisition comparison test session. In FanVis, a case study regarding the selection of a student Unmanned Aerial Vehicle (UAV) system by a funding agency was presented, while in the Excel® tool, a case study regarding laptop selection by a board member of a low-income school

district was used, (Appendix E). These two case studies were built from the same trade space data in order to ensure that the two test sessions were similar in difficulty.

The trade space data was obtained from the 2007 Association for Unmanned Vehicle Systems International (AUVSI) student competition. In this competition, competing UAVs had to launch, follow a course, identify (ID) objects, track moving objects, and land successfully [38]. As part of the competition, each student team had to write a report regarding their system's design, the accuracy of the system, and other system details. Three systems were chosen for use in this experiment's case study based upon how well they performed in the competition (the two best performing, and the worst performing). The reports of these systems were then analyzed to obtain the system cost and performance information. This trade space data was presented as the system acquisition trade space data in FanVis. In the case study, the three systems were renamed School A, School B, and School C to avoid any biases to the schools. The three systems were analyzed on seven functional requirements (Launch, Transition to Autonomy, Maintain Flight, Navigate Course, ID Objects, Track Objects, and Land) and three "-ilities" (Adaptability, Reliability, and Sustainability).

For the Excel® case study, the trade space cost data was scaled by 0.035 to more accurately represent the costs of low-cost laptops and the order which the functional requirements were presented was rearranged so that it would appear as if there were two entirely different trade spaces being presented. For example, the most expensive functional requirement was presented as the fifth functional requirement in the FanVis case study and second in the Excel® case study. In this manner, the same data trade space was presented for both tools, while only the labels of this data and the manner it was presented differed. In the Excel® case study, participants evaluated System 1, System 2, and System 3 on seven functional requirements(Support State Setting, Secure Data, GUI Plat-formed, File Manipulation, Content Manipulation, Information Sharing, and Modify Hardware) and three "-ilities" (Usability, Reliability, and Modularity)

Along with the case study data, participants were given the selection criteria necessary to complete the system acquisition. The system selection criteria stated the high-level objectives that must be met by the selected system. In decreasing order of importance, they were:

- At least meet all "-ilities"
- At least meet all functional requirements
- Minimize cost
- Maximize degree "-ilities" and functional requirements met
- Balance
    - "-ilities" across system
    - Functional requirements across system
    - Cost across sub-functional requirements

The tutorial (Appendix F) gave participants an overview of the decision support tool, how data was encoded within the tool, and specific features that would likely be necessary to utilize while completing the test session. During the tutorial, the participants were able to see and interact with the tool using a practice data set and were encouraged to ask questions. Participants spent an average of ten minutes on the tutorial. For FanVis, this was the only time the participants had to interact with the tool before the experiment began. For Excel®, participants already had a moderate to high-level of experience using the tool. Participants were encouraged to practice using both tools until they felt comfortable with their use.

Following the tutorial, the eye tracker was calibrated. This calibration ensured that the correct data was collected during the actual testing phase when the participants completed the experimental questions.

4.4.4. Test Session

In each test session, the participant answered questions regarding the system acquisition trade space described in the case study. The participants were asked identical (in both format and difficulty) trade space questions in both tools. These questions began with six Knowledge Synthesis questions, followed by six Information Aggregation questions, six Data Processing questions and concluded with a repeat of the initial Knowledge Synthesis questions. The first and last question was "Which system best meets the baseline system selection criteria?" The questions were presented in this order and not randomized since system acquisition decision makers do not generally attempt to determine the best system based on a set of objective criteria randomly. Interviews with these decision makers demonstrated that they typically started with broad, more ambiguous questions, and then drilled down through hierarchical levels of information to obtain answers. Thus we attempted to emulate this strategy through the specific ordering of questions, which was held constant for each subject. The last question was repeated to determine if the exploration of the data space, held constant for everyone, changed the participants' final decisions.

All questions had a definitive correct answer. For each question, four choices were presented to the participant. The list of all questions asked, the possible choices and the correct answer are included in Appendix G. These questions were displayed on a Graphical User Interface (GUI) on the right screen of the MACCS, while the decision support tool loaded with the case study data was displayed on the center screen. The system selection criteria list was displayed on the left screen.

The first test session was completed when the participants answered all 19 experimental questions. At this point, they were offered a break before continuing with the next training and test session. Participants completed two test sessions; one with Excel® and the other with FanVis. The order of these test sessions was counterbalanced

and randomized. Each test session was preceded by the training session of the tool to be used in that particular test session. For example, participant number one completed the experiment as follows: pre-experiment interactions, baseline data handling proficiency test, training with Excel®, testing with Excel®, break, training with FanVis, testing with FanVis, and post-experiment interactions.

4.4.5. Post-experiment interactions

A brief retrospective protocol was conducted following completion of both test sessions. The intention of this portion of the experiment was to obtain information regarding why a participant manipulated the tools in a specific manner and to gain the participant's general impressions of the tools. The general questions asked during the retrospective verbal protocol are listed in Appendix H, but varied based upon participants' responses.

In addition, the participants were asked which tool they felt was more useful, which tool they felt was more pleasant to use, which tool they would prefer to use in the future, as well as which tool they felt gave them a better understanding of the system acquisition trade space (Appendix I). Finally, the participants were asked to voice any lingering questions or final thoughts on the displays or the experiment in general.

4.5. Experimental Design

The experiment was a 2x3 repeated measures design with two independent variables: Decision Support Tool (FanVis, Excel®) and Reasoning Difficulty Level (Knowledge Synthesis, Information Aggregation, Data Processing). All participants received all six treatment combinations. The order that the participants received the two levels of Decision Support Tool was counterbalanced and randomly assigned to each participant. The Reasoning Difficulty Level was presented in the same order for all participants, as previously discussed.

4.5.1. Dependent Variables

A number of dependent variables were chosen to determine if the hypotheses given in section 4.1 were correct. This section describes how each of these dependent variables was calculated. The results for each dependent variable will be described in Chapter 5.

- **Score:** Score is the percentage of correct answers over the total number of questions within a Reasoning Difficulty Level. Thus, each participant has 6 score values: Excel®-Knowledge, Excel®-Information, Excel®-Data, FanVis-Knowledge, FanVis-Information, and FanVis-Data.

- **Time to Answer:** Time to answer is the participant's cumulative time to answer all questions within a Reasoning Difficulty Level.

- **Subjective Tool Preference**: The subjective tool preference is a participant's response to the preferred tool selection questions. As there are four questions in total, there are four subjective tool preference values per participant.

- **Percent of Time Fixating on Relevant Elements:** The percent time spent fixating on relevant elements gives insight as to how accessible and understandable the trade space data is for both the tools [39]. For example, for a question regarding the functional requirements, such as "Which system meets the functional requirements to the greatest degree?", all fixations on elements containing the "functional requirement met" element would be considered relevant, while all other elements would not be considered irrelevant. Thus, for each question there is a distinct set of elements that are relevant to answering the question. The percentage of time is used as a metric as opposed to the percentage of relevant element fixations due to the disparate number of elements within the two tools.

4.5.2. Covariates

In statistical analysis, the covariate **Proficiency Time** was used. Proficiency time was the total amount of time it took the participant to answer all eight questions within the

baseline proficiency test. In this study, proficiency time was used to help predict how long it would take the participants to complete the system acquisition questions as proficiency time was both a baseline for a participant's Excel® proficiency and data handling ability.

5. Results

This chapter presents the statistical results of the experiment described in Chapter 4. For statistical analysis, a 2x3 repeated measures mixed linear model was applied to analyze the dependent variable, Time. For all other dependent variables, non-parametric tests were used since parametric assumptions were not met. An α level of 0.05 for all statistical tests was used. Additionally, though eye tracker data was gathered for all thirty participants, only five participants (3, 6, 16, 23, and 24) had tracks which were continuously accurate for the duration of both the FanVis and Excel® test sessions. Eye-track data was therefore analyzed using only these five participants.

5.1. Score

As expected, a participant's score varied depending upon the reasoning difficulty level. As shown in Figure 21, participants obtained a higher score using FanVis than with Excel® when answering Knowledge Synthesis questions (Mann-Whitney Dependent Test [40], z=1.99, p=0.046), while participants obtained a higher score using Excel® than with FanVis while answering Data Processing questions (z=2.21, p=0.027). There was no statistical difference between the two decision support tools for score on Information Aggregation questions (z=0.77, p=0.437).

In addition, there was no statistical difference given the order participants used the two tools. Analyzing score by test session using Mann-Whitney Dependent Tests [40], there was no statistical significance for score on Knowledge Synthesis questions (z=-0.62, p=0.52), Information Aggregation questions (z=-0.71, p=0.48) or Data Processing questions (z=-0.40, p=0.69). This indicates the participants' accuracy on the system acquisition questions was not affected by the order of the test sessions.
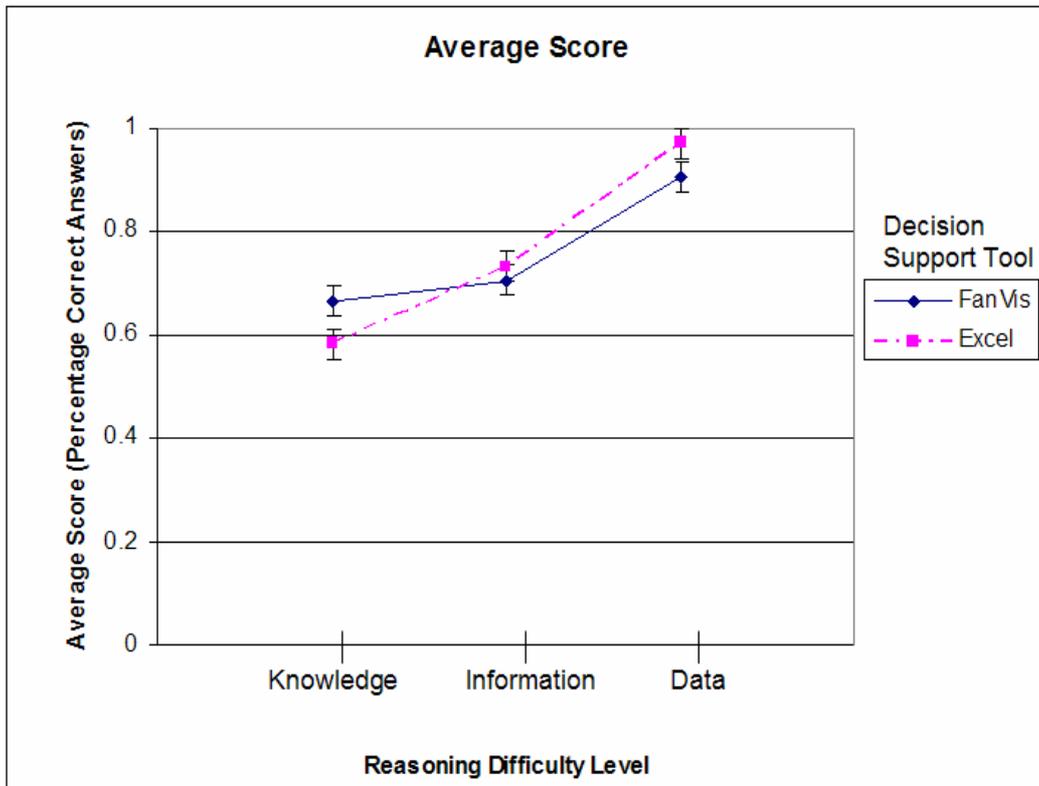
Figure 21: Average percentage of correct answers

Each participant's score performance was then analyzed on a per-question basis to determine the performance differential that arose when a participant answered a specific question correctly with one tool and incorrectly with the other. Because an identical set of questions asked for both tools, this metric indicates if a participant was only able to extract the required information out of one of the two tools. For instance, if a participant answered a question correctly while using Excel® but the same question incorrectly using FanVis, then there is a performance differential in favor of Excel®. To determine the total performance differential by question, each participant's performance differential is summed by question yielding the results shown in Figure 22. In this manner, if all thirty participants answered a question correctly in FanVis and incorrectly in Excel®, than that tool would have a thirty point performance differential in favor of FanVis. For example, five participants answered question number 2 correctly

in Excel® and incorrectly in FanVis, while eight participants answered the question correctly in FanVis and incorrectly in Excel®. Hence, there is a total performance differential of three points in favor of FanVis.

Performance Differential by Question
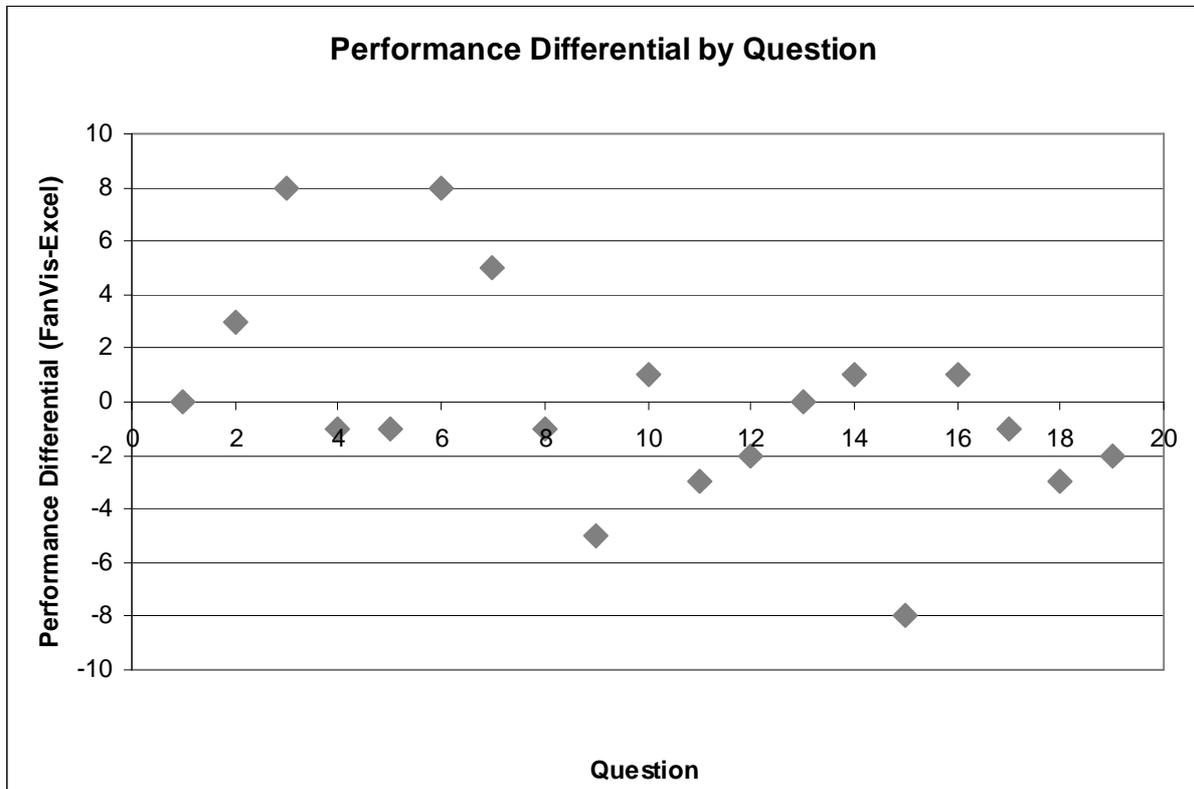
Figure 22: Total performance differential by question

The performance differential echoes the performance score results overall for the three Reasoning Difficulty Levels, as there is a total performance differential of 17 points in favor of FanVis on Knowledge Synthesis questions, a 5 point performance differential in favor of Excel® on Information Aggregation questions and a 10 point performance differential in favor of Excel® on Data Processing questions. This echoes the general trend that FanVis provided superior performance for Knowledge Synthesis tasks, the two tools provided similar performance for Information Aggregation tasks, and Excel® provided superior performance for Data Processing tasks.

What is interesting to note are those questions which have a large differential. Questions 3, 6 and 7 have particularly high performance differentials in favor of FanVis.

These questions all asked the participant to integrate the cost of the sub-functional requirements. This would indicate that FanVis allowed participants to complete this task better than in Excel®. On the other hand, questions 9 and 15 have particularly high performance differentials in favor of Excel®. These two questions asked the participants to extract the "-ility" data. This would indicate that Excel® allowed participants to complete this task better than FanVis. These findings will have important ramifications on the design of the decision support tool, as will be discussed in Chapter 6.

Furthermore, the participants' performance differential on the question "Which system best meets the baseline system selection criteria?" was analyzed to determine if exploring the data space changed the participants' decisions as per which system best met these criteria. This particular question was both the first and last question answered by the participants. In FanVis, 2 participants answered the question incorrectly both times, 1 initially answered correct but answered incorrectly the second time the question was asked, 6 initially answered incorrectly but then answered correctly the second time, and 21 answered correctly both times. In all, a marginally statistically significant[1] portion of the participants changed their answers (z=-1.890, p=0.059), suggesting interaction with FanVis allowed the participants to obtain a clearer picture of the system acquisition trade space over the time frame of the experiment.

Within Excel®, 1 participant answered correct but answered incorrectly the second time the question was asked, 4 initially answered incorrectly but then answered correctly the second time, and 25 correctly answered the question both times. In all, a non-significant portion of the participants changed their answers (z=-1.342, p=0.180). Further, participants did not have a statistically significant difference in their change strategy when completing their first test session compared to their second test session (z=-0.513, p=0.608). As the test session order (FanVis presented first or Excel® presented

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[1] An α value between 0.05 and 0.10

first) was counterbalanced and randomly assigned, this indicates participants answered these questions based upon the case study being analyzed for that test session and were not affected by fact that the case study questions were asked in the same manner for both test sessions.

5.2. Time to Answer

A logarithmic transformation (natural log) of the dependent variable time to answer was utilized to satisfy normality and homogeneity assumptions [40]. A Levene test indicated the homogeneity assumption was not met ($F(5,172)=15.347$, $p<0.001$) before the logarithmic transformation was applied, but that the homogeneity assumption was met after the transformation was applied ($F(5,172)=0.568$, $p=0.724$). In addition, two outliers (greater than 3.29 standard deviations from the mean) were deleted from the data set. With the filtered data set, a 2x3 mixed linear model, $\alpha=0.05$, was used to determine if Reasoning Difficulty Level or Decision Support Tool had a significant effect on time to answer (Appendix J). It was found that the proficiency time metric had a positive correlation to the log of time to answer through the Spearman Rank Correlation ($\rho=0.271$, $p<0.001$). Proficiency time, as described in Section 4.5.2, was the time it took the participants to answer a set of baseline data processing questions based on Excel® charts and graphs. Thus, proficiency time was included as a covariate. The resultant model is shown Equation (1).

$$Y_{ijkl} = \mu.... + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + (\rho\alpha)_{ij} + (\rho\beta)_{ik} + \gamma(X_{ijkl}) + \varepsilon_{ijkl} \tag{1}$$

In this equation μ is a constant, ρ_i are the participants, α_j are the Decision Support Tools, β_k are the Reasoning Difficulty Levels, $(\alpha\beta)_{jk}$ are the interaction effects between Decision Support Tools and Reasoning Difficulty Levels, $(\rho\alpha)_{ij}$ are interaction effects between the participants and the Decision Support Tools, $(\rho\beta)_{ik}$ are the

interaction effects between the participants and the Reasoning Difficulty Levels, $\gamma(X_{ijkl})$ are the effects adjustments from the covariate and ε_{ijkl} are the residual errors.

Using this model, proficiency time was found to be significant (F(1,56)=21.81, p<0.001). In addition, a significant difference was found for Decision Support Tool (F(1,29)= 12.17, p=0.0016) and Reasoning Difficulty Level (F(1,29)=216.71, p<0.001). Most of the differences among the six treatments were statistically significant when analyzed as pair wise comparisons, shown in Table 2. However, three points were not statistically significant: Excel®-Information/FanVis-Data (p=0.251), Excel®-Information/FanVis-Information (p=0.032), and Excel®-Knowledge/FanVis-Knowledge (p=0.471). It is the two latter pairs which are most interesting, as this indicates there was no statistical difference in time between the two tools to complete Knowledge Synthesis and Information Aggregation questions, as can be seen in Figure 23.

Table 2: Pair wise comparisons with significant differences in highlighted cells

		Excel®			FanVis		
		Knowledge	Information	Data	Knowledge	Information	Data
Excel®	Knowledge		<0.001	<0.001	0.471	<0.001	<0.001
	Information			<0.001	<0.001	0.032	0.251
	Data				<0.001	0.002	<0.001
FanVis	Knowledge					<0.001	<0.001
	Information						<0.001
	Data						

Figure 23 yields insight into the actual average time participants spent to answer the system acquisition decision support questions. The greatest time difference between the two decision support tools on a given reasoning difficulty level occurred on Data Processing questions. Here, participants spent an average of 60.8 seconds more in FanVis than Excel®. Though this comparison was found to be statistically significant, it is a little more than one minute, altogether a small amount of time. Further, time is not as important as accuracy for system acquisition decisions. While it is important to note the statistical significance, for an actual decision, this minute would likely not matter. In

addition, participants may have spent a greater amount of time answering the system acquisition decision support questions in FanVis simply due to the greater number of data elements within the tool. As mentioned in section 3.5, FanVis contains a total of 278 data elements whereas Excel® contains 171 data elements. Accessing these additional hundred elements could have certainly caused this time disparity. Future research could analyze if this hypothesis is correct, or if there are different motivating factors.
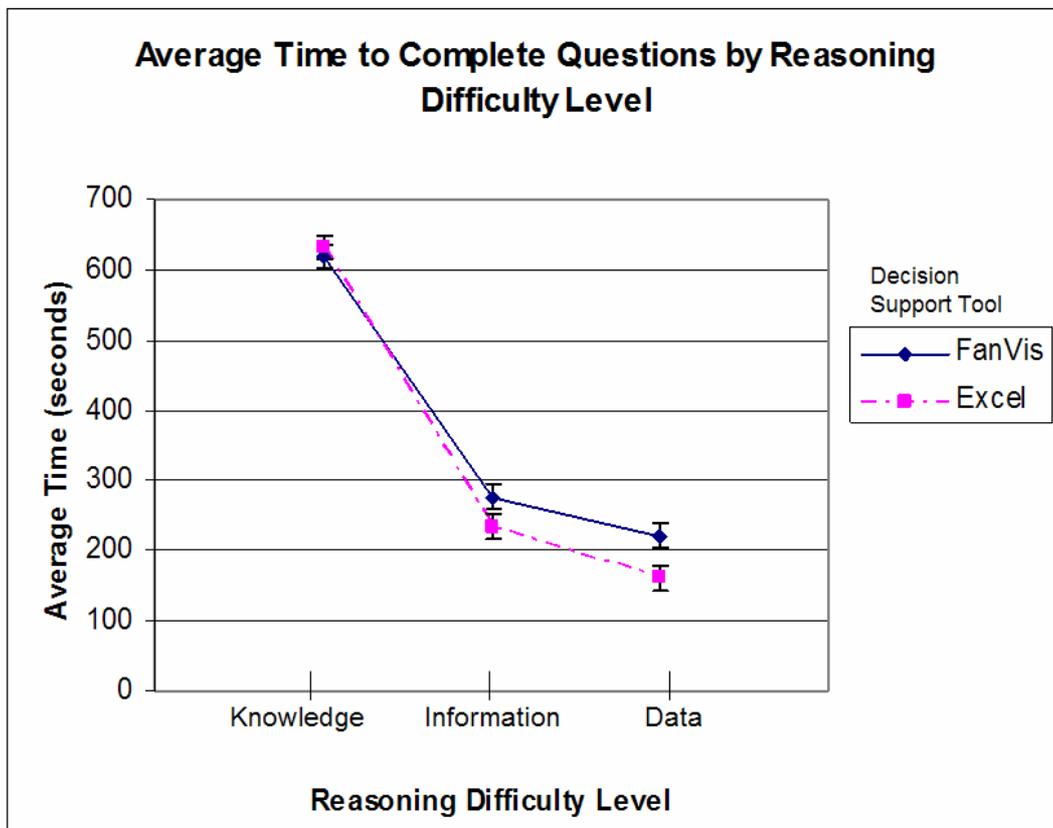
Figure 23: Average time to answer questions

Similar to score, there was no statistical difference given the order participants used the two tools. Analyzing time by test session and Reasoning Difficulty level using a 2X2 Analysis of Variance (Appendix J), test session was not statistically significant ($F(1,172)=0.79$, $p=0.373$). This indicates the participants' response times to the system acquisition questions were not effected by the order of the test session.

5.3. Subjective Tool Preference

Subjective tool preference was found by analyzing the participants responses to a set of subjective questions using a Mann-Whitney Dependent Test [40]. A statistically significant portion of the participants felt FanVis was a more useful tool than Excel® (z=2.01, p=0.04), felt that FanVis was able to give them a better understanding of the trade space than Excel® (z=3.10, p=0.002), and would choose to use FanVis over Excel® given the opportunity during their next system acquisition decision (z=2.01, p=0.04). A marginally statistically significant portion of the participants felt FanVis was a more pleasant tool to use than Excel® (z=1.64, p=0.1).

Responses from the retrospective protocol varied for both FanVis and the Excel® tool. Participants were asked a range of questions including their impressions of the tools, the aspects of the tools that they liked the most, the information they felt was most useful in completing their decision and other related questions. The most frequent response, in these interviews was participants' comments that they were used to Excel®. Forty percent of the participants made this comment. Overall, twenty-six percent of the participants felt that given time they would be able to find data more effectively in FanVis. This could be due to the fact that participants felt the views in FanVis conveyed more information, a comment made by twenty-six percent of the participants. Thirteen percent of the participants commented that FanVis was more intuitive, thirteen percent commented they enjoyed being able to dig deeper into the data in FanVis, and thirteen percent commented FanVis was more visually appealing. On the other hand twenty percent of the participants commented it was easier for them to view the bar charts in Excel® and determine how the requirements were being met versus using FanVis.

In terms of the decision support tool designs, participants gave praise and critiques for both FanVis and Excel®. Thirty percent of the participants commented that the center red line in FanVis, which represents a baseline requirements constraint

helped them determine the baseline in FanVis, and would have liked to see a similar line in Excel®. Thirty-three percent of the participants commented they were not able to discern the "-ility" view in FanVis, thirty-three percent commented they had difficulty determining total cost, and twenty-six percent commented they had difficulty integrating the sub-functional requirement cost.

In addition, thirteen percent of the participants did not like how "cost" and "the degree functional requirements were met" could not be decoupled. In FanVis, data elements contained information regarding multiple trade space variables (the fans) encoded both cost information and the degree the functional requirement was being met. This coupling allowed participants to quickly gather information, but the participants who commented on this coupling would have also liked to see this information presented separately.

In terms of other FanVis usability issues, sixteen percent of the participants had difficulty connecting the system legend in the cost scale with the displayed systems in the comparison view. Further, twenty-three percent had difficulty navigating within FanVis. These participants commented they were uncertain as to which tab contained the information necessary to answer each question. Of the views in FanVis, participants liked to use the Multi-System View most, as it "provided an overview of all information." They liked Comparison View best next, and the Functional Requirement View the least.

Participants spent less time analyzing Excel® because, as one participant stated, "it is ordinary." However, participants commented that they did not like the line charts in Excel®, especially the cost categories tabs. Forty percent of the participants commented they liked using the bar charts, while only thirteen percent commented they liked utilizing the data tab, as it allowed them to access the functional requirement total cost. Sixteen percent of the participants commented that they would have liked to

have the information presented on the Requirements and "-ilities" Tab and the Total Cost Tab combined.

Overall, participants felt both tools allowed them to complete the necessary tasks, and many commented either tool was a vast improvement on how they currently complete acquisitions (they mentioned currently sifting through reams of paper). Twenty-three percent of the participants commented they would have liked to have the total functional requirement cost in both the tools. This metric was not shown for the purposes of this test to determine how well the participants could integrate information with both of the tools. Thirteen percent felt automation could have answered the system acquisition trade space questions better than they could, as absolute differences were being judged in many instances. Additionally, participants would have liked to see more interactivity within the tools. In FanVis, this could include the ability to switch from the Multi-System View to the System View by double clicking on one of the systems. In Excel®, this interactivity could include the ability to query for actual values, or highlight specific system data.

5.4. Cognitive Strategies

Analyzing the fixation pattern of the participants between the two tools can yield insight into the participant's cognitive strategies [41, 42]. This section describes some participants' fixation patterns that were common within the two tools, and postulates the similarities and differences caused by the two different tools among these pattern types, as well as their implications.

There was a considerable amount of noise present in the eye tracker data. It is possible that the structure of the van interfered with the signal from the magnetic sink during all or portions of the experiments. Additionally, though participants had free range of head motion, the software was not robust enough to support changes in posture, as a posture change affected the overall position of the participant relative to

the screens and the magnetic source. Thus, if participants moved too much, their eye track was lost. For this reason, only five participants (3, 6, 16, 23, and 24) had eye tracks which were continuously accurate for the duration of both the FanVis and Excel® test sessions. Even for these participants, there were instances of data noise. In these instances, only the overall pattern was analyzed.

5.4.1. Patterns in FanVis

In FanVis, participants primarily demonstrated fixation patterns which allowed them to obtain information in the fastest and easiest manner possible. For instance, when viewing the Comparison View, the System View or the Multi-System View, participants utilized near-circular fixation patterns. In these three tabs, the data elements are arranged around a polygonal structure. The near-circular fixations patterns are therefore quite intuitive. This type of pattern allowed the participants to scan from one element to the next in the shortest distance. Additionally, participants could maintain a continuous scan, repeating around the polygon until all necessary information was gathered. Further, the close proximity of the labels to the data elements aided the manner which participants gathered information. For those tasks where labels were required, primarily those questions regarding individual functional requirements or "-ilities", the participants did not have to modify their fixation patterns within a given view but could quickly and easily obtain the necessary information in the same manner for all task types.

For instance, Figure 24 depicts one of participant 6's fixation patterns while answering the question "Which system meets the functional requirements to the greatest degree?" In the figure, the thin line designates the participant's fixation track. The circles represent the participant's fixation location, with the duration of this fixation indicated by the size of the circle. The bold arrows indicate the direction of these fixation patterns. In this example, more than 50 individual fixations are displayed. It can

be seen that the participant moved from the tree structure to the ID Objects fan, up through the Track and Land fans, to the tabs and the Launch fan and then back down between the Autonomy and Cruise fans.
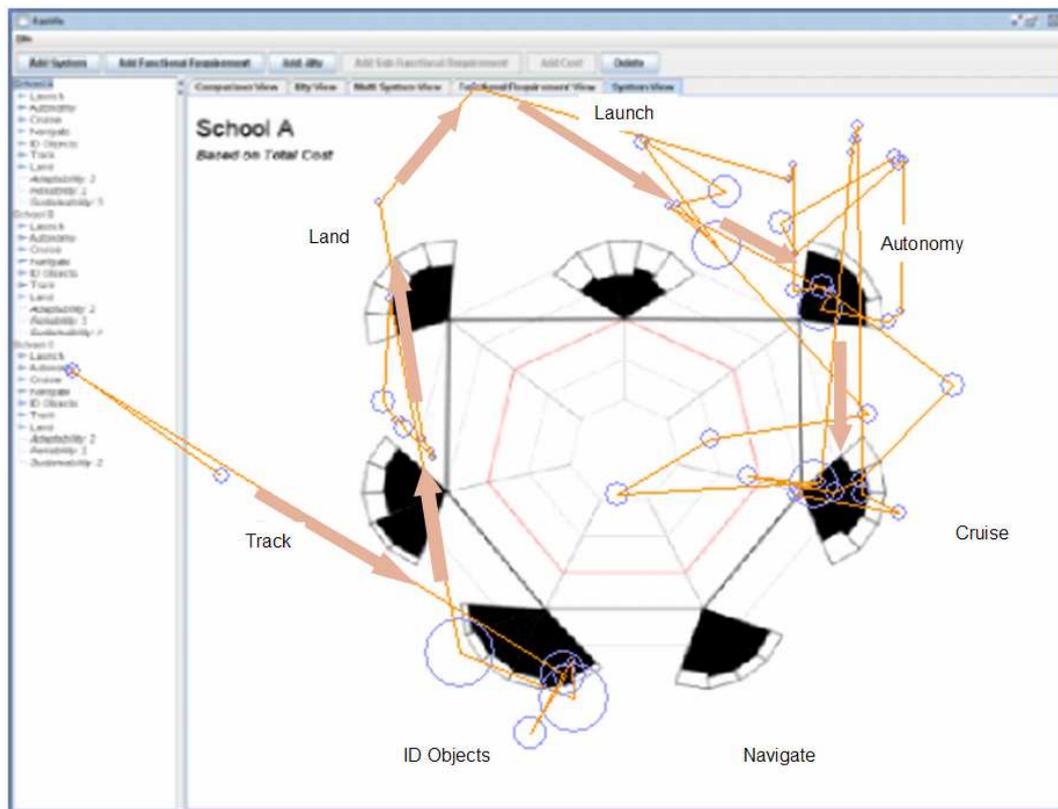
Figure 24: Participant 6's fixation pattern within the System View

Typically, participants fixated upon each of the elements within the "-ility" View from side to side in a horizontal pattern. This fixation pattern again allowed the participants to travel the shortest distance from one data element to the next. For instance, Figure 25 shows that participant 16 first fixated between School A and School B Adaptability, moved on towards School C Adaptability, where the fixation then shifted down to School C Reliability through School B Reliability to School A Reliability. At this point the participant either went directly back up to the views to select the next view or through the school labels.
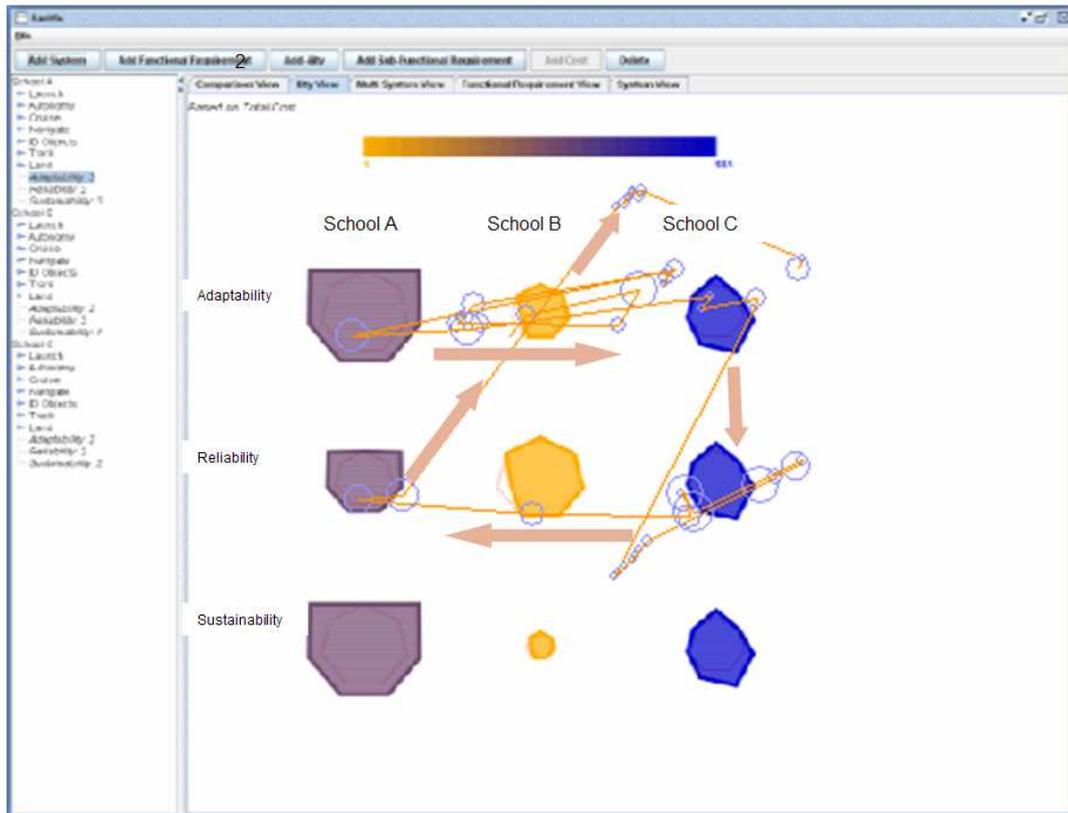
Figure 25: Participant 16's fixation pattern within the "-ility" View

Though this gaze pattern looks different from that in the other views within FanVis, it is based upon the same principle. For the most part, participants adopted a scanning pattern that allowed them to view data elements in a continuous manner where the shortest path is taken from data element to data element. This type of gaze pattern is efficient and simple. Hence for the "-ility" view this is a horizontal pattern, and for the Comparison, System and Multi-System Views this is a near-circular pattern.

5.4.2. Patterns in Excel®

In Excel®, participants also utilized scanning patterns which allowed them to obtain information in the fastest and easiest manner possible. However, because the data labels were placed further from the data elements they describe, the scanning pattern varied dependent upon the task type. For tasks which did not require the labels, primarily those questions on how the system generally met the system acquisition metrics, the

participants generally had a horizontal fixation pattern. Figure 26 depicts participant 23's eye fixation track while answering the question, "Which system is most balanced in terms of meeting the "-ilities"?" Here the participant focused on the "-ility" legend seen in the upper right corner of the left graph. He or she then fixated on each of the three "-ilities" in turn going from left to right much in the same way one would read a sentence. The far right fixation is likely a transient fixation when the participant shifted his or her gaze back to the questions on the right screen in order to correctly identify the answer as System A.
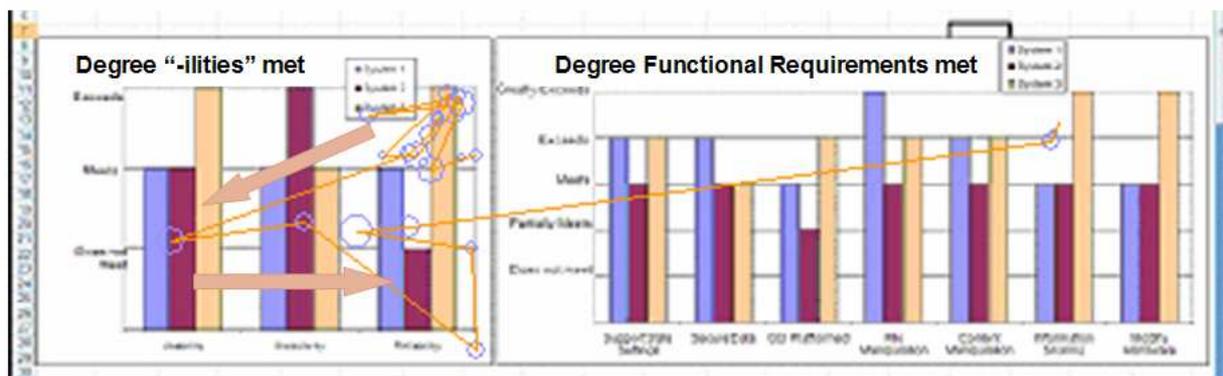
Figure 26: Participant 23's fixation pattern within the Requirements and "-ilities" Tab

When obtaining information from the data element labels was required, participants exhibited a box fixation pattern. As shown in Figure 27, this box pattern allowed the participant to view the labels of the functional requirements; followed directly by the degree each requirement was met. In this example, participant 16 answered the question "Which of the following functional requirements is overall met to the least degree while maintaining the highest cost?" This question required the participant to understand the name of the functional requirements along with the degree they were being met. In the previous example, participant 23 only had to analyze the how the overall "-ilities" were being met, as compared to determining how individual "-ilities" were met. The box pattern was therefore unnecessary. The horizontal fixation pattern is a faster pattern, as the participant's gaze does not travel as

far within the figure. Thus, the box fixation pattern was only used when the participant needed to know the names of the functional requirements or "-ilities." This only occurred when information pertaining to individual functional requirements or "-ilities" was necessary.
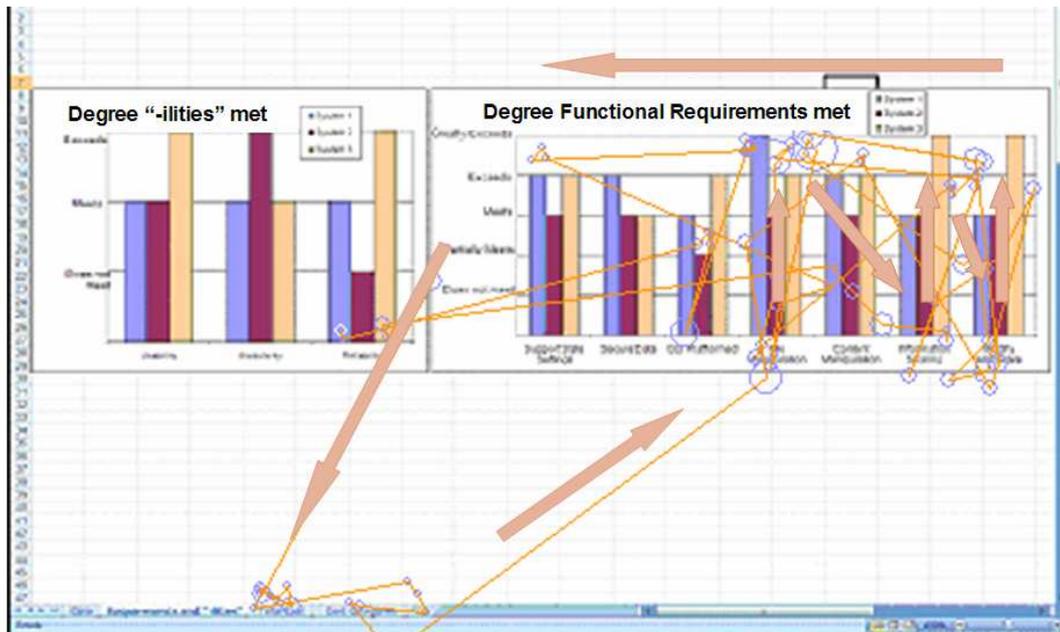
Figure 27: Participant 16's fixation pattern within the Requirements and "-ilities" Tab

5.4.3. Comparison of Eye Fixation Patterns

In both FanVis and Excel®, participants elected to use eye fixation patterns which would allow them to obtain information in the fastest and easiest way possible. For data elements arranged in a row, this typically meant a horizontal fixation pattern which would begin at the right, go towards the left, and on most occasions repeat back to the left. For data elements arranged in a near-circular fashion, the eye fixation pattern typically was near-circular matching the pattern of the elements. This pattern was exhibited for all five participants on questions of all three levels of reasoning difficulty. More importantly, participants were able to use the same fixation pattern within a single view for all types of tasks while using FanVis, as the data labels were placed in close proximity to the data elements they were describing. When these data label were

necessary while using Excel®, participants were required to modify their fixation patterns. In these instances, the participants utilized less efficient fixation patterns as the distances between fixations were larger. This shift in the participants' fixation patterns could indicate the participants also had to change their cognitive strategy.

In some instances the fixation patterns became more erratic. These erratic fixations were observed most frequently on questions the participants did not answer correctly. While erratic patterns have been shown as an indication of poorly designed interfaces [42], non-erratic patterns were exhibited by the same participants on questions answered correctly. From this observation, it can be concluded that the participant's cognitive strategy changed between the instances where the participant displayed normal eye fixation patterns and erratic patterns. However, it cannot conclusively be stated if a participant's uncertainty on the question caused him or her to have more erratic eye fixations or if a lack of focused fixations caused the participant to answer the question incorrectly. This is a complex relationship, which could be analyzed further in future work. Two examples are illustrated to highlight these eye fixation changes.

One of the most difficult questions for participants to answer was question 5, "Which system is most balanced overall?" Only 9 participants out of 30 responded correctly using either of the two tools, and no participant responded correctly using both tools. Participant 6 responded incorrectly to this question with both tools, spending 31.29 seconds in Excel® and 25.20 seconds in FanVis to try to answer the question. What is interesting to note is participant 6's eye fixation patterns in both FanVis and Excel® are much more erratic than those seen in his or her eye fixation patterns on questions that were correctly answered. As shown in Figure 28, participant 6 has no readily apparent track in either FanVis or Excel®. This same lack of pattern can be seen in other participants on questions that were answered incorrectly.
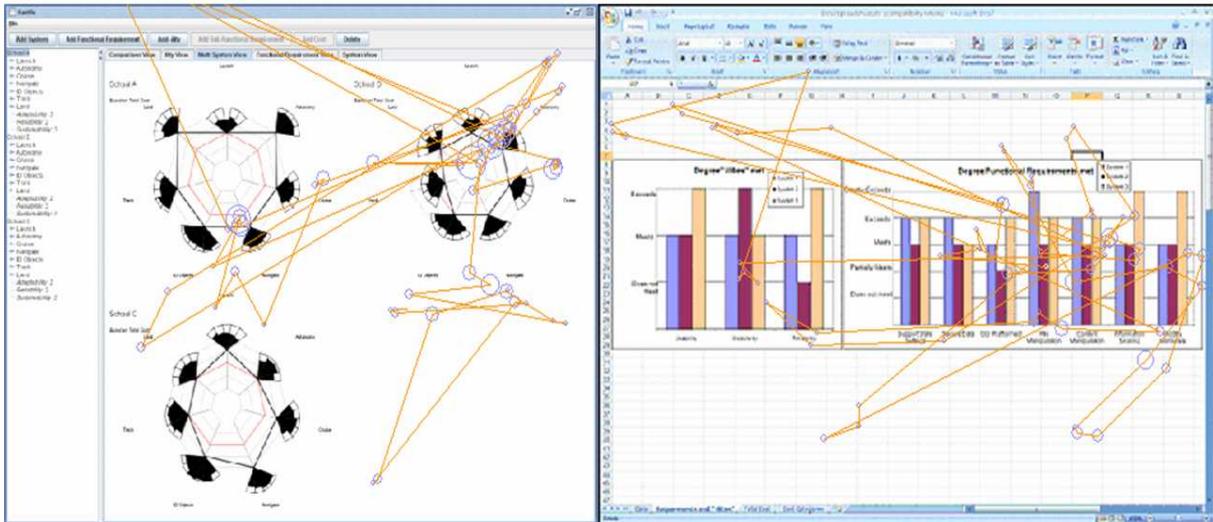
Figure 28: Participant 6's fixation pattern within FanVis(left) and Excel® (right) on question 5

A second example examines the fixation patterns of participant 23 while answering the question "Which system is most balanced in terms of meeting the functional requirements?" (Figure 29). In FanVis this question was answered correctly in 42.25 seconds, while in Excel® it was answered incorrectly after 15.03 seconds. In FanVis, a normal pattern is exhibited, whereas in Excel® the participant has an erratic eye pattern.
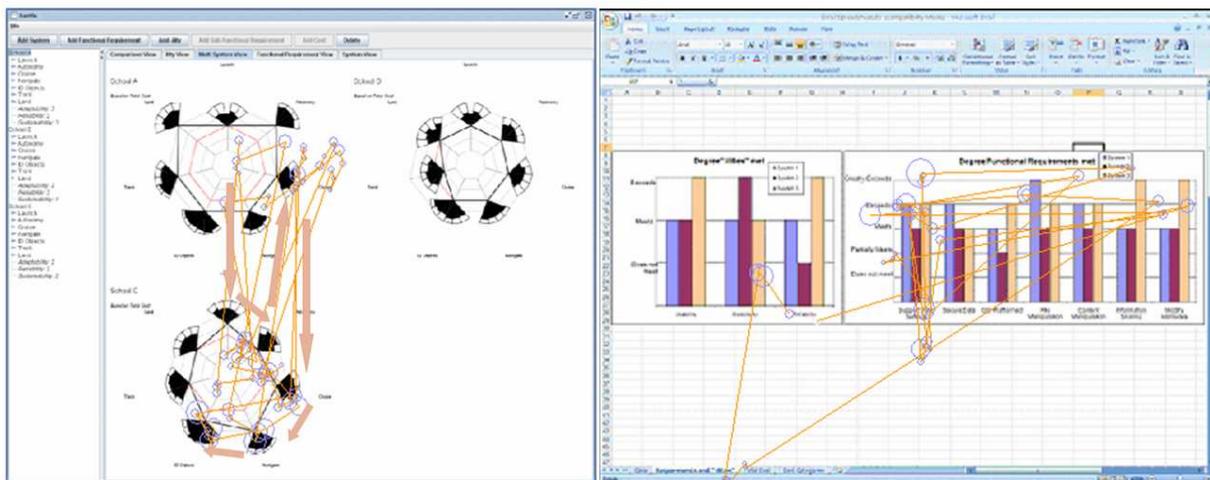
Figure 29: Participant 23's fixation pattern in FanVis (right) and Excel® (left) on question 11

5.4.4. Implications of Eye Fixation Patterns

It has been found that humans generally exhibit fixation patterns which are tightly linked to the task. These patterns are developed over time, and fall on elements which help promote the completion of the task [32]. This suggests that users of any display develop a fixation pattern most natural to interacting with that display. Natural fixation patterns consist of small incremental movements between necessary elements and is the quickest scanning pattern that could exist for that task [32]. Natural fixation patterns were exhibited by participants in both FanVis and Excel® for most of the experiment. However, participants generally had more erratic fixation patterns on questions that were answered incorrectly, potentially indicating the participant did not understand how to access the data required to answer that question.

To determine recommendations for a display design so that the quickest gaze pattern can be obtained, Fitts' law should be considered. Fitts' law is a model of human movement and is used to predict the time it would take a user to point to an area as a function of distance to target and target size [43]. It has been shown that Fitts' law holds for selection tasks using an eye tracking device [44]. Though many function variations have been established, the main relationship is given by the equation $Time \propto \log_2(D/S)$ where D is the distance to the target and S is the target size. Hence, large targets placed close to each other could be accessed faster than smaller targets spaced further apart. Thus, relevant data elements should be placed in close proximity to foster faster acquisition of information. In addition, data elements and their labels should be placed close to each other if users need to correlate names with data elements. As was shown in this research, such proximity could allow users to utilize a single fixation pattern regardless of the task. Participants had to shift from a natural fixation pattern to a less efficient pattern for a number of tasks while using Excel®. Though system acquisition decisions are not time-sensitive tasks, it is likely that the display which allows users to

utilize the most natural and therefore efficient pattern could also improve the users' performance [42]. Additionally, a display which promotes natural fixation patterns regardless of task could also allow users to maintain a single type of cognitive strategy.

5.5. Element Analysis

To further analyze how participants interacted with the data elements, it is important to determine what time was spent fixating on elements relevant to the system acquisition trade space questions. Overall, participant spent an average of 66.18% of the time fixating on relevant elements in FanVis compared to 66.58% in Excel®. Hence, participants spent essentially the same amount of time spent fixating on relevant elements between the two tools. However, analyzing the percent time fixating on relevant elements by Reasoning Difficulty Level yields some interesting trends. As shown in Table 3, participants have a statistically significant higher percentage of time fixating on relevant elements in FanVis for Knowledge Synthesis questions compared to Excel® using a Wilcoxon-Signed Rank Test ($z=-2.023$, $p=0.043$). This trend is reversed for Data Processing questions where participants have a slightly higher percentage time fixating on relevant elements in Excel® compared to FanVis, though this pair was not statistically significant ($z=-0.730$, $p=0.465$). This trend is very similar to the performance trends. Overall, one would want to observe a higher percentage of time spent fixating on relevant elements, as this would indicate the participants spent a greater amount of time fixating on data elements useful to answering the question at hand [45].

Table 3: Average percent time fixating on relevant elements

	FanVis	**Excel®**	**Significance**
Knowledge	75.81%	65.80%	Yes (p = 0.043)
Information	66.65%	65.26%	No (p = 0.500)
Data	64.75%	64.59%	No (p = 0.465)

5.6. Summary of Experimental Findings

Results from the human-performance experiment led to a range of results. Each dependent variable provided insight into how well the human participants were able to interact with the two decision support tools as they completed a system acquisition decision. Results indicated that both tools had strengths and weaknesses in terms of how well they supported the human participant as illustrated by Table 4. These strengths and weaknesses can help guide how future decision support tools are built in the future.

Table 4: Summary of experimental findings

	Knowledge Synthesis	Information Aggregation	Data Processing
Score	FanVis (p=0.046)	Indistinguishable (p=0.437)	Excel® (p=0.027)
Time	Indistinguishable (p=0.471)	Indistinguishable (p=0.032)	Excel® (p<0.001)
% Time Fixating on Relevant Elements	FanVis (p=0.043)	Indistinguishable (p=0.50)	Indistinguishable (p=0.46)
Cognitive Strategy	FanVis (no statistical test)		
Subjective Opinion	FanVis (p=0.040)		

For example, it was observed that using FanVis over Excel® statistically influenced how accurately participants answered the system acquisition questions. Participants obtained higher accuracies in FanVis on Knowledge Synthesis questions and higher accuracies with the Excel® tool on Data Processing questions. Though time was not as important as accuracy, participants had similar response times answering Knowledge Synthesis and Information Aggregation questions in FanVis and Excel®, but faster speeds in Excel® on Data Processing questions. In addition, participants spent a greater percentage of time fixating on relevant elements while completing Knowledge

Synthesis questions in FanVis. Results also suggest that FanVis better supported natural gaze patterns, thus FanVis potentially allowed participants to maintain their cognitive strategies. Possibly these more efficient patterns could lead to improved performance, especially when users become more familiar to using the tool. Finally, participants subjectively believed FanVis was a better tool.

Chapter 6 will discuss the implications these results have on the initial research question and the design of future related decision support tools.

6. Conclusions and Future Work

The goal of this research was to determine the type of decision support system which could best aid system acquisition decision makers as they utilize multiple levels of reasoning. This research question was addressed through the following methods:

- The investigation of the scope of system acquisitions and current acquisition practices to determine the design requirements for a system acquisition decision support tool (Chapter 2).

- The design of a system acquisition decision support tool which encompasses the identified design requirements and best supports an acquisition decision, based upon previous research (Chapter 3).

- The use of human-performance experimentation to evaluate the effectiveness of this tool versus a more traditional tool which represents current state-of-the-art decision tools (Chapters 4 & 5)

This research sought to determine if a configural decision support tool, FanVis, is able to support high-level system acquisition decisions better than a traditional separable decision support tool, Excel®. The answer to this question was determined through analysis of participants' performance in the experiment outlined in Chapter 4. Chapter 4 also examined subjective appeal to the tools, and the participants' cognitive strategies used to complete their goals.

6.1. Performance

In general, both decision support tools supported participants as they answered questions pertaining to a system acquisition decision trade space on all levels of reasoning difficulty tested. In terms of terms of speed, Excel® allowed participants to answer Data Processing questions more quickly, though the actual average improvement was only 60.8 seconds (essentially ten seconds per question). However, it

is likely that acquisition decision makers value accuracy over speed. In this respect, FanVis allowed the participants to answer Knowledge Synthesis questions more accurately than Excel®. On the other hand, Excel® allowed participants to answer Data Processing questions more accurately than FanVis, while participants answered Information Aggregation questions similarly with the two tools.

While making an acquisition decision, decision makers will ultimately be answering Knowledge Synthesis questions. Thus, it appears that FanVis could be the superior acquisition decision support tool in terms performance. As mentioned, the participants all had experience using Excel®, and as several participants mentioned, it was "ordinary" tool to use, while none had ever seen or used FanVis.

By further examining performance at the categorical question level, it was determined which decision support tools best supported users as they extracted specific system acquisition trade space variables. FanVis best supported the extraction of sub-functional requirement cost and the Excel® tool best supported the extraction of "-ility" data. This information can help guide the development of new system acquisition decision support tools.

6.2. Subjective Appeal

Participants preferred to use the configural decision support tool FanVis over the traditional separable decision support tool Excel® while completing a system acquisition decision. This conclusion is supported by the fact that statistically, participants felt FanVis was a more useful tool, gave them a better understanding of the trade space, and would choose to use it in their next acquisition decision. This trend was present even though participants may have preferred Excel® due to the fact that all had substantial experience using Excel® and had never seen FanVis.

While participants preferred FanVis, there were portions of both decision support tools that participants did not understand or did not enjoy using. In FanVis,

some participants mentioned they had difficulty with the "-ility" View, integrating the sub-functional requirement costs, and determining the total cost of the system. With the Excel® tool, participants would have liked a "meets requirements" reference line similar to that in FanVis. They also believed the Cost Categories Tab was too cluttered, and would have liked to see the requirements, "-ilities," and total cost plots displayed on the same tab. For both tools, participants would have liked to see the total functional requirement cost, and have more interactivity within the tools.

6.3. Cognitive Strategies

The participants' cognitive strategies were analyzed primarily from eye tracker data collected during the experiment. As is typical in eye tracking studies, the data obtained was often noisy, unreliable in some instances, and nonexistent in others. Thus, using the eye tracker for this experiment did not yield a complete data set for analysis. However a baseline for the participants' cognitive strategies was established from the five consistent and reliable tracks obtained.

In terms of fixation patterns, participants demonstrated similar fixation pattern behaviors with both FanVis and the Excel® tool. When participants understood the question, and how to access the data required to answer a question, they primarily utilized a fixation pattern that allowed them to gather information in the fastest and easiest manner. When participants did not understand the question, and/or how to access the data they required to answer that question, the fixation patterns were much more erratic.

Additionally, due to the design of the Excel® tool, participants had to change their fixation pattern dependent upon the type of task being completed. For those tasks where data element names were required, such as questions pertaining to individual functional requirements, participants used a box fixation pattern. This pattern is a less efficient pattern than the natural horizontal fixation pattern used for tasks where data

element names were not required. FanVis allowed the participants to maintain more natural fixation patterns regardless of task, which suggests FanVis supported a more organized cognitive strategy as compared to Excel®, although more data should be collected to support these observations. This preliminary analysis indicates FanVis could promote better performance as more efficient eye fixation patterns have been linked to improved performance [42].

The general trend in the percentage of time participants spent fixating on relevant elements when analyzed by Reasoning Difficulty Level matched that of the trends observed in performance. Participants spent a larger percentage of time fixating on relevant elements in FanVis while answering Knowledge Synthesis questions, while they spent a larger percentage of time in Excel® while answering Data Processing questions. This trend suggests that performance is increased in both tools when users spend a larger potion of time fixating on elements that are relevant to the task at hand compared to irrelevant data elements or non-data elements.

6.4. Design Recommendations

Design recommendations for a future system acquisition decision support tool were developed from these findings. These design recommendations stem from the performance, subjective, and cognitive strategy results of the experiment. These recommendations include design modifications to the current designs, the inclusion of additional metrics, the expansion of the use of the element of time, and the modification of the designs into a hybrid configural-separable display.

6.4.1. Design Modifications to FanVis

Design modifications should be made if FanVis were utilized as an actual system acquisition decision support tool. Each of these changes would likely increase the usability of the tool, thus increasing the user's understanding of the system acquisition

trade space. Within FanVis, the greatest necessary design change is the "-ility" View in its entirety. Participants did not understand this view, and were thus not able to accurately understand the "-ility" trade space data. Additionally, more view connectivity should be enabled. The user should be able to click on a system in the Multi System View to access that system in the System View, or click on a functional requirement to access it in the Functional Requirement View. Such interactivity could help the user understand where necessary information is located. Additionally, the manner in which cost is displayed should be reconsidered. Participants had difficulty integrating the sub-functional requirement costs as well as determining the total cost. Furthermore, some participants had difficulty discerning systems from each other in the color scheme.

6.4.2. Inclusion of Additional Metrics

Some acquisitions require additional metrics to those currently presented within the current designs. First, there is often uncertainty in the data of a candidate system. The decision maker must determine to what degree the data provided is accurate. For instance, in the recent Air Force Tanker acquisition, the acquisition team estimated Boeing's engineering costs, as they felt Boeing's figures did not accurately reflect what these costs would be. However, these estimates were later deemed unreasonable. This unreasonable estimation was one of the causes cited for why the Government Accountability office upheld Boeing's protest to the Air Force's acquisition decision [46]. It is likely that if the acquisition team understood the uncertainty held in this metric to a greater extent, the resulting circumstances would have been different.

A second metric used in some current acquisition decisions is risk. Though risk may initially seem similar to uncertainty, they are quite different [47]. Risk is generally measured as the probability of an event occurring multiplied by the impact of that event occurring [48-50]. For example, if the system were a rocket, one risk to be considered

would be a valve not opening, perhaps causing the rocket not to fire. Here the impact would be the rocket not firing and the probability would be found by determining how often the valve would malfunction. For an acquisition, a system's risks encompass these individual engineering risks, but could also include risks from cost, schedule, and uncertainty to name a few [51]. In this manner, there can be hundreds of risk data points, each symbolizing one of the different types of risk.

A third metric that could be included in FanVis is the explicit cost of a functional requirement. The total cost of a system and the cost of sub-functional requirement were both presented. Participants could integrate the sub-functional requirement cost to obtain the functional requirement cost, but many mentioned they did not believe they integrated this information correctly and would have liked the functional requirement cost presented.

6.4.3. Expansion of the Element of Time

An important consideration of displaying the acquisition trade space is that of time or schedule. Currently in FanVis, cost is separated by the system's life cycle phases. Breaking down the cost or risk of the system for a proposed schedule would aid decision makers in understanding the temporal aspects of the project. Additionally, decision makers must determine if the system can be delivered on time. This is a critical consideration as there may be a finite amount of time when the organization needs the system. Once this time passes, the system is no longer useful.

6.4.4. Hybrid Configural-Separable Display

Two decision support tools were built to test if a configural or a separable decision support tool would best support a system acquisition decision to a greater degree. Both tools were able to support this type of decision, and each was able to support aspects of the decision to a varying degrees. However, in order to provide the best support, it might be most beneficial to design a decision support tool that is a

hybrid of a configural and separable display. In this manner, high-level system information could be displayed in a configural manner so that the larger constraints and interactions can be easily pinpointed. The decision maker can then query for lower level information where it is necessary, which would be then shown as a separable display. In this manner, the decision maker's display would be dependent upon the task he or she was performing.

6.5. Future Experiment Recommendations

In addition to a set of design recommendations, a set of recommendations for future experiments is provided. The future experiment recommendations stem from the difficulties faced during the experiment. They include modifications to information presented in the system acquisition case study, and how the eye tracking system was used.

6.5.1. System Acquisition Case Study

The first recommendation would be to obtain a more robust set of system acquisition trade space data. The case study used in this experiment was from the AUVSI UAV student competition in 2007. The functional requirements, cost figures, and performance metrics for this case study were obtained by analyzing the papers the submitted by students. However, the metrics that could not be found in this manner were estimated. While this provided a sufficient amount of data for the purposes of the experiment, participants may be able to connect to the case study to a greater extent if the numbers were more realistic. In this experiment, some participants commented that they did not understand some of the functional requirements and "-ilities" presented in the case studies. Additionally, an experiment could be designed where the participants would conduct system trades. In this experiment, participants could analyze different

system outcomes if funding for a proposed system was uncertain. This would be a much more realistic experiment, as there is often leeway in the design of systems.

6.5.2. Eye Tracker System

There was little benefit from using an eye tracking system in this experiment. While the results found were interesting, they were either common knowledge (organized gaze patterns promote performance) or mirrored results found through other metrics (percentage of time participants spent fixating on relevant elements mirrored the score performance differential). If an eye tracking system is used in the future, three suggestions to improve the quality of the results include:

1) To not use a head tracking system with a magnetic sink if the experiment takes place inside a small metallic enclosure. Even though the manufacturer stated no problems should be encountered, it is likely the experimental setup hampered the ability to collect a greater amount of reliable eye tracker data.

2) To shorten the time period of the experiment, or make the experiment environment more comfortable so that the participants does not move to a great of a degree. Even though movements of the head are allowed through the means of head-tracking, the measurements may be more precise if head movement is limited.

3) To limit the screens the participant needs to view to one screen. By limiting the number of places the participant must look, head movement can further be limited.

6.6. Future Work

The system acquisition community could greatly benefit from the introduction of an organized and interactive system acquisition decision support tool. However, before this can be accomplished, the design and test of a more robust system acquisition

decision support tool needs to be conducted. The design recommendations for FanVis should be further investigated and addressed. In order to enable FanVis to support a wider range of system acquisitions, the metrics risk and uncertainty should be included, and the element of time should be expanded.

Additionally, to truly be useful to the system acquisition community, the decision support tool must be formally linked with the current acquisition process. For both government and commercial use, the decision support tool could be linked to e-procurement. E-procurement allows organizations to communicate requirements, resources, cost structures, and other data vital to an acquisition decision through the Internet. It also allows organizations to search for buyers or sellers of systems. It has been identified that the key to using this technology is to not simply automate the process, but allow the decision maker to address regulations, as described in the FAR, in a more consistent and timely manner [52]. In this manner, data provided by the candidate organization to the soliciting organization can be automatically filtered into the tool. This linkage is critical for all acquisitions, as it will seamlessly allow the soliciting organization to acquire and review all data necessary for the acquisition decision.

Most importantly, the findings in this study and others need to be acted upon. There is no benefit knowing the acquisition process is broken if no positive steps are taken to improve the process. As Secretary Gates mentioned in his Defense Budget Recommendation Statement for 2010, "There is broad agreement on the need for acquisition and contracting reform in the Department of Defense. There have been enough studies, Enough hand-wringing. Enough rhetoric. Now is the time for action [53]."

Appendix A : Demographic Descriptive Statistics

Category	N	Min	Max	Mean	Std. Dev.
Age (years)	30	29	74	52.43	11.39
Service in Armed Forces (years)	14	4	42	16.21	13.03
Acquisition Experience (years)	23	1	39	13.95	13.1
High-level Decision Experience (Y/N)	30/0	-	-	-	-
Excel® Experience (Y/N)	30/0	-	-	-	-
Gender (M/F)	5/25	-	-	-	-

Appendix B : Consent to Participate Form

CONSENT TO PARTICIPATE IN
NON-BIOMEDICAL RESEARCH

FanVis: Visualization Tool for System Acquisition Decision Support

Government Personnel

You are asked to participate in a research study conducted by Professor Mary Cummings Ph.D, from the Aeronautics and Astronautics Department at the Massachusetts Institute of Technology (M.I.T.). The results of this study may be published in a student thesis or scientific journal. You were selected as a possible participant in this study because the expected population this research will influence is expected to contain men and women between the ages of 18 and 65 with an interest in making high-level decisions. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

This study is designed to evaluate if FanVis, a visualization tool for system acquisition decision support, is an effective tool for completing system acquisition decisions. To evaluate the tool's effectiveness, the decisions and conclusions subjects make while using FanVis will be compared to the decisions and conclusions that they make while using a more traditional set of decision tools, mainly that of bar charts, line graphs, and pie charts. Factors that will be taken into consideration while measuring the effectiveness of the tool, will include your overall acquisition choices, and comprehension of the information being displayed, which functionalities you used during the process, as well as your fixation points on key visualization elements, visual scanning duration and location, and finally your subjective appeal to the decision tools. Secondary goals of the study are to determine additional tools that the future decision

makers could potentially require while using FanVis, and to asses the general responses to emergent features by comparing your eye focus location and scan pattern to other subjects in this study.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:
- ♦ Be equipped with an adjustable head-mounted eye tracker. The eye tracker will be explained and calibrated.
- ♦ Complete a baseline data proficiency test consisting of a series of general questions and tasks (estimated time 20 minutes).
- ♦ Complete two comparison tasks. One task will be completed with FanVis, and the other with an excel tool. Prior to the comparison task, a brief tutorial will be administered explaining the tool and its features. Following this, a case study will be given to you and explained. This case study will have all the information needed to complete the comparison task.
- ♦ The comparison task will ask you to determine which system presented in the case study best fits the specific scenario outlined. Once you have you're your decision choice, you will be prompted to answer a series of supporting questions regarding the visualizations you have just seen. Some of these questions will also ask if your final decision choice would change if various portions of the scenario of the system data were slightly modified. In addition a small set of questions will be asked regarding how well you liked using the tool and if it was understandable. You will be able to view and respond to all comparison task questions through the tool's interface. Finally, you will be asked to review your comparison decision and the steps made in your determination by completing a review of the decision steps along the way using a retrospective verbal protocol tool (estimated time 30 min to 1 hour for each task).
- ♦ Testing will either occur at MIT in room 37-301 if you are on or near the MIT campus, or near your facility using HAL's Mobile Advanced Command and Control Station (MACCS).
- ♦ Total time: approximately 2 hours.

- **POTENTIAL RISKS AND DISCOMFORTS**

There are no anticipated physical or psychological risks in this study. There is a slight possibility that you will have mild discomfort from the head-mounted eye-tracker. You may adjust the eye-tracker at any point in the experiment if you desire. A brief calibration will follow any adjustments to ensure proper tracking of your eye. You may

also withdraw from the experiment at any time for any reason without penalty or consequences of any kind.

- **POTENTIAL BENEFITS**

While there is no immediate foreseeable benefit to you as a participant in this study, your efforts will provide critical insight into the effectiveness of this new decision support tool. Conclusions from this study will yield better interfaces for high-level decision makers who are facing system acquisition decisions.

- **PAYMENT FOR PARTICIPATION**

This is a voluntary study. You will not receive payment for your time. The highest performing individual will be awarded an Ipod Nano. You are eligible to receive this award. Performance will be based upon the number of correct responses to questions asked during the experiment. In case two or more individuals obtain the same number of correct responses, the tie will be resolved by awarding the prize to the individual with the fastest response time.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You will be assigned a subject number which will be used on all related documents to include databases, summaries of results, etc. Only one master list of subject names and numbers will exist that will remain only in the custody of Professor Cummings.

Your eye will be videotaped during this experiment for purposes of eye position data extraction. By signing this form you agree to have your eye videotaped throughout the duration of the experiment. You have the right to review the video tape. If you wish to do so, please notify the experimenter. All interaction with the computer system will be recorded via tracking software for reproducibility purposes. All video, tracking and other data will be stored in electronic files under your subject number, and will only accessible by the experimenter and the principal investigator. At no point will your personal data be released unless required by law. At no point will the experimental data and research analysis be released in a manner that allows for your identification. If further use of your experimental data is needed, you will be contacted for consent.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact the Principal Investigator, Mary L. Cummings, at (617) 252-1512, e-mail, missyc@mit.edu, and her address is 77 Massachusetts Avenue, Room 33-305, Cambridge, MA 02139.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, neither the offer to provide medical assistance nor the actual provision of medical services shall be construed as an admission of negligence or acceptance of liability. Questions regarding this policy may be directed to M.I.T's Insurance Office, (617) 253-2823.

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

Appendix C : Demographic Survey

1. Age: _____

2. Gender: □ Male □ Female

3. Native Language: _____

If native language is not English:
English Proficiency:
   □ Low
   □ Moderate
   □ High

4. Occupation: _____

   If student:
   a)   *Class Standing:* □ Undergraduate □ Graduate
   b)   *Major:* _____

   If currently or formerly associated with any country's armed forces:
   a)   *Country/State:* _____
   b)   *Status:* □ Active Duty □ Reserve □ Retired □ DOD Civilian □ Other_____
   c)   *Service:* □ Army □ Navy □ Air Force □ Other _____
   d)   *Rank:* _____
   e)   *Years of Service:* _____

   5. Have you had experience making high-level decisions for a team, project, or organization?
   □ Yes
   □ No

   If yes, extent of experience:
   □ Low
   □ Medium
   □ High

6. Have you had system acquisition experience?
   □ Yes
   □ No

   If yes:
   a)   *Type of system(s) acquired:* _____
   b)   *Reason system(s) acquired:* _____
   c)   *Duration (years or hours):* _____

7. Have you had experience using data manipulation tools (such as Microsoft Excel, MATLAB, Mathematica, Maple, Statistical analysis software, etc…) ?

□ Yes
□ No

If yes:

a) *Types or names of products used:* _____

b) *Extent of experience:*

□ Low
□ Moderate
□ High

c) *Extent of usage on a daily basis:*

□ Low
□ Moderate
□ High

8. Are you color blind?

□ Yes
□ No

If yes:

Which type of color blindness (if known)_____

Appendix D : Baseline Data Handling Proficiency Test

1) Which year had the largest increase in exports from the previous year?
   a) 1972
   b) 1977 – correct
   c) 1975
   d) 1973

FOREIGN TRADE OF COUNTRY X, 1968-1980
(in United States dollars)

2) In 1965, private school expenditures were approximately what percentage of total expenditures?
   a) 15%
   b) 20%
   c) 25% - correct
   d) 30%

PUBLIC AND PRIVATE SCHOOL EXPENDITURES
1965 – 1979
(in billions of dollars)
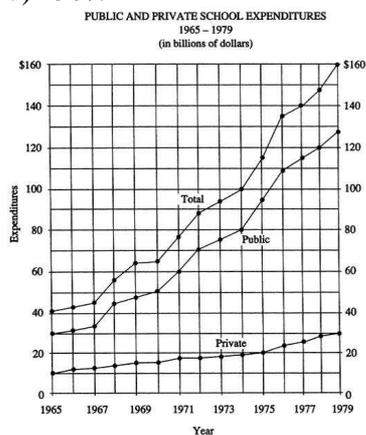
3) Which of the following categories has the greatest increase in workers between 1981 and 1995?
   a) Blue Collar
   b) Service
   c) Farm
   d) Professional – correct

Workforce Distribution 1981

Farm 1%
Sevice 15%
Blue Collar 28%
Professional 18%
Celical 20%
Managerial 10%
Sales 8%

Workforce Distribution 1995

Farm 2%
Sevice 16%
Blue Collar 20%
Professional 24%
Celical 18%
Managerial 13%
Sales 7%
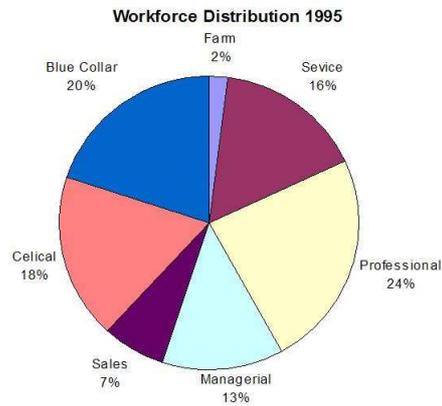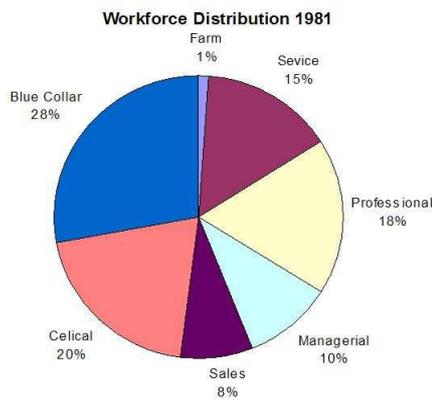
4) In which year did the number of applications increase the most from the previous year?
   a) 1984
   b) 1985
   c) 1986 – correct
   d) 1987

Number of Graduate Student Applicants at University X, 1982–1991
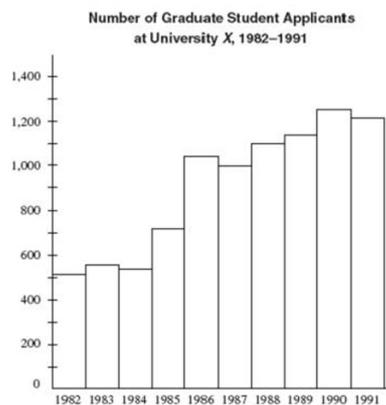
5) The difference between the profits for product A and B is greatest in which year?
   a) 1996
   b) 1997 – correct
   c) 1998
   d) 1999

Profits for the AB Company, 1995 - 1999
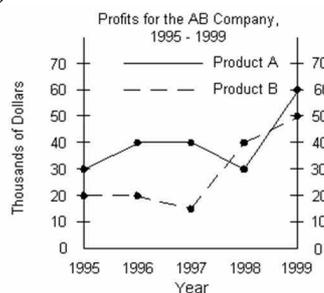
6) In how many years was the average number of pages per newspaper at least twice as much as the average in 1940?
   a) One
   b) Two

110

c) Three – correct
d) Four

AVERAGE NUMBER OF PAGES PER NEWSPAPER FOR NEWSPAPAER X
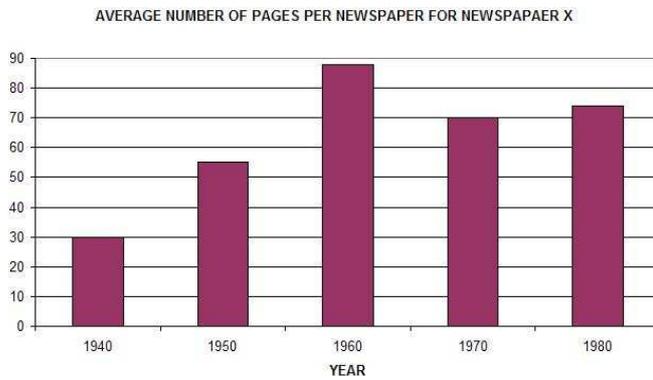
7) How many boys attended the 1995 convention?
   a) 716
   b) 540
   c) 358 – correct
   d) 225
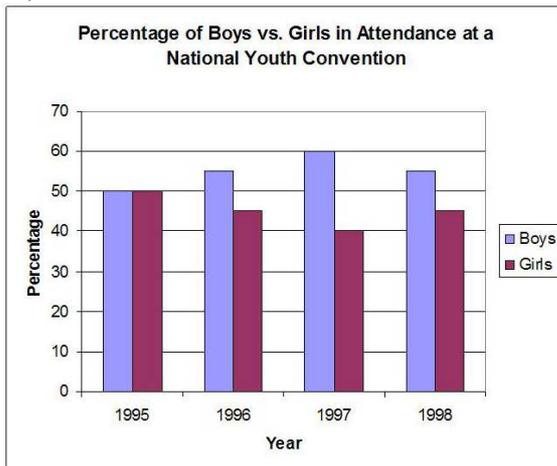
Total number in attendance

Year	Number
1995	716
1996	1108
1997	1520
1998	2244

8) Which two years did the least number of boys attend the convention?
   a) 1995 & 1996 – correct
   b) 1995 & 1998
   c) 1996 & 1998
   d) 1997 & 1998

Percentage of Boys vs. Girls in Attendance at a National Youth Convention
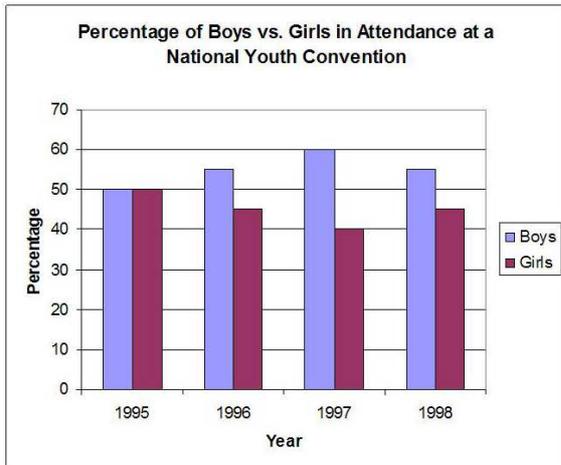
Total number in attendance

Year	Number
1995	716
1996	1108
1997	1520
1998	2244

Appendix E : Case Studies for Test Sessions

FanVis Case Study

Your Mission

- You are an executive at AMI Funding, where you find projects worthy of your company's financial support
- You would like to invest in a student group that is developing an Unmanned Aerial Vehicles (or UAV for short)
  - Future commercial endeavors would more than likely profit the company
- All the information you will need is already loaded in a tool for you to use, this brief simply will give you an overview

2

UAV Overview I

- The UAV need to have three system characteristics, or "-ilities"
  - Adaptability – adapt to changes in the types of missions it performs
  - Reliability – perform desired functions when requested for a time span of at least 3 years
  - Sustainability – have the ability to be repaired, or upgraded as necessary during its lifespan

3

UAV Overview II

- In addition, they need to fulfill 7 basic functional requirements:
  - *Launch*
  - *Transition to Autonomy*
  - *Maintain Flight*
  - *Navigate Course*
  - *Locate Objects*
  - *Track Objects*
  - *Land*

4

UAV Performance

- You have selected 3 UAVs named here as School A, School B and School C
- You have determined how well each system fulfills the system "-ilities" and requirements
  - This information has been entered into a tool for you to evaluate
- You have created a scale to represent how well systems meet these requirements:

Requirement Categories:	
Does not meet:	1
Partially meets:	2
Meets:	3
Exceeds:	4
Exceeds Greatly:	5

"-ilities" Categories:	
Does not meet:	1
Meets:	2
Exceeds:	3

5

Sub-functional Requirements

- The sub-functional requirements allow the larger functional requirement to be achieved
- For example the functional requirement Land requires the following sub-functional requirements:
  - Plane configured for landing
  - Deceleration
  - Controlled descent
  - Impact with runway
  - Come to full stop

6

Cost of UAV

- You are concerned with how much it will cost to develop the system
- You also want to make sure that one functional requirement does not dominate the total cost of the UAV
- You have asked each UAV company to report how much it costs to develop its system broken down over the sub-functional requirements of the system by three cost phases of its development
  - Research and Development (R&D)
  - Production
  - Operations

7

Cost breakdown example

- The systems took the functional and associated sub-functional requirements you gave them, and provided you with a cost breakdown such as the one below for School A:

Land Functional Requirement

Sub-functional Name	R&D	Production	Operations	Total
Plane configured for landing	$50	$150	$50	$250
Deceleration	$65	$205	$45	$315
Controlled descent	$95	$125	$50	$270
Impact with runway	$75	$180	$50	$305
Come to full stop	$80	$130	$75	$285

8

System Selection Criteria

When making your system decisions please use the following baseline criteria. This will be provided for you on your screen along with other criteria scenarios which you may need during your decision.

- Meet or exceed "ilities"
- Meet or exceed Functional Requirements
- Minimize Cost
- Balance
  - "ility" across system
  - Functional Requirement across system
  - Cost across sub-functional requirement
- Maximize degree "ilities" and requirements met

9

Your task

- Now that you have all the information you need to determine a system to choose
- All the information you need has already been loaded into the comparison tool named FanVis you will be using
- Once you have determined that choice on the questionnaire panel, a series of questions will follow to solidify your answer

10

Excel Case Study

Your Mission

- You are head of the Mika District Education Board, a district with 50% of its population below the poverty line
- You would like to improve the district by purchasing hundreds of new low cost educational laptops
  - Enable students to explore and learn better with their teachers and peers
- All the information you will need is already loaded in a tool for you to use, this brief simply will give you an overview

---

Laptop Overview I

- The laptops need to have three system characteristics, or "-ilities"
  - Usability – be easy to use by a variety of people, some of which have never used a computer before
  - Reliability – perform desired functions when requested for a time span of at least 3 years
  - Modularity – consist of small subsets that can be combined, replaced, or upgraded when desired

---

Laptop Overview II

- In addition, they also need to fulfill 7 basic functional requirements:
  - *Support State Settings*
  - *Secure Data*
  - *GUI Platformed*
  - *File Manipulation*
  - *Content Manipulation*
  - *Information Sharing*
  - *Modify Hardware*

Laptop Performance

- You have selected 3 laptops named here as System 1, System 2, and System 3
- You have determined how well each system fulfills the system "-ilities" and requirements
  - This information has been entered into a tool for you to evaluate
- You have created a scale to represent how well systems meet these requirements:

Requirement Categories:	
Does not meet:	1
Partially meets:	2
Meets:	3
Exceeds:	4
Exceeds Greatly:	5

"-ilities" Categories:	
Does not meet:	1
Meets:	2
Exceeds:	3

Sub-functional Requirements

- The sub-functional requirements allow the larger functional requirement to be achieved
- For example Secure Data requires the following sub-functional requirements:
  - Log-in protection
  - Support Updates
  - Embedded Software
  - Automatic Backups
  - Data Recovery

Cost of Laptop

- Beyond how well the systems meet requirements, you are concerned with how much all these laptops will cost
- You want to make certain that neither a single sub-functional nor a functional requirement dominate the total cost of the laptop
- You have asked each laptop company to report how much it costs to develop its system broken down over the sub-functional requirements of the system by three cost phases of its development
  - Production
  - Testing
  - Maintenance

Cost breakdown example

- The systems took the functional and associated sub-functional requirements you gave them, and provided you with a cost breakdown such as the one below for System 1:

Secure Data

Sub-functional Name	Production	Testing	Maintenance	Total
Log-in protection	$1.25	$3.00	$8.75	$13.00
Support Updates	$1.50	$4.00	$4.50	$10.00
Embedded Software	$0.75	$3.25	$5.25	$9.25
Automatic Backups	$1.75	$1.50	$5.50	$8.75
Data Recovery	$1.50	$2.75	$4.25	$8.50

System Selection Criteria

When making your system decisions please use the following baseline criteria. This will be provided for you on your screen along with other criteria scenarios which you may need during your decision.

- Meet or exceed "ilities"
- Meet or exceed Functional Requirements
- Minimize Cost
- Balance
  - "ility" across system
  - Functional Requirement across system
  - Cost across sub-functional requirement
- Maximize degree "ilities" and requirements met

9

Your task

- Now that you have all the information you need to determine a system to choose
- All the information you need has already been loaded into the an Excel® spreadsheet you will be using
- Once you have determined that choice on the questionnaire panel, a series of questions will follow to solidify your answer

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Appendix F : Tutorials for Test Sessions

FanVis Tutorial

FanVis Tutorial

- FanVis tool is a new decision support visualization tool intended to be used while making system acquisition decisions

- As you are going through the tutorial, interact with the interface, try to answer the questions in these slides and ask any questions you might have

- The interface has a modified case study for you to use. You will get a different set of data for your decision task.

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Anatomy of FanVis Interface
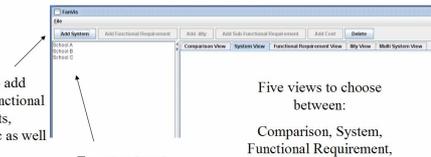
Input bar to add systems, functional requirements, "ilities", etc as well as to delete components

Tree structure to manipulate and/or change components

Five views to choose between:

Comparison, System, Functional Requirement, Ility and Multi-System View

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Comparison View I

The comparison view shows how the systems are performing on the requirements and cost

Each axis represents a different functional requirement

Distance from center circle is degree to which requirement is met: A red line delineates between what meets, and what doesn't meet requirements. You want to be at least on or outside that line

Is there a system that is not meeting all the requirements?

System Legend

Each polygon represents a different system

The polygon color is coded to its total relative cost as shown in the System Legend

Which system is most expensive?

Comparison View II
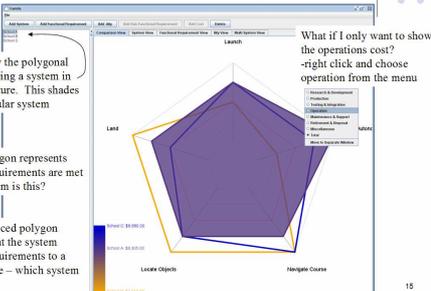
You can view the polygonal area by selecting a system in the tree structure. This shades in that particular system

A larger polygon represents that more requirements are met – which system is this?

A more balanced polygon represents that the system meets the requirements to a similar degree – which system is this?

What if I only want to show the operations cost? -right click and choose operation from the menu

15

Ility View

The Ility view shows you how well the systems are performing on the ilities, as well as on the requirements and cost

Each system's shape comes from how the requirements are met. This shape is then made larger or smaller based upon how well an ility is met. The larger the shape, the more an ility is met…the smaller the less it is met.

Which ility is School C performing the best on?

The worst?
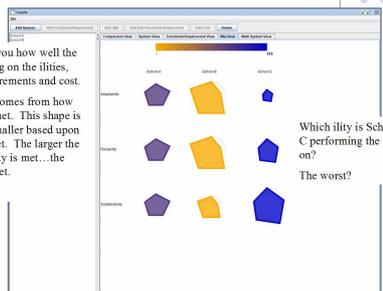
FanVis System View I

Each vertex has a fan consisting of triangles, which are the sub-functional requirements.

Percentage each fan is shaded indicates the sub-functional requirement cost compared to most expensive sub-functional requirement of the system being viewed

Most expensive = all black

Least expensive = most white space
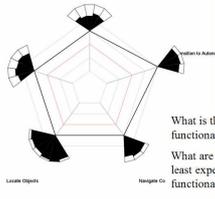
What is the most expensive functional requirement?

What are the most and least expensive sub-functional requirements?

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FanVis System View II

What if I want to see the sub-functional requirement names?
– right click and select show labels

Also try: left clicking and dragging – the polygon will spin so you can read the sub-functional requirement names better
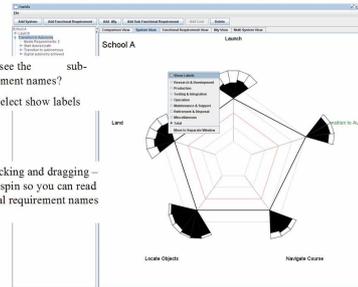
18

FanVis Multi System View I

The multi-system view shows several system views on one screen.

Now the percentage each fan is shaded indicates the sub-functional requirement cost compared to the most expensive sub-functional requirement of *all* the systems as all systems are shown

Do you see any trends between the systems?

Which system is most balanced over how each functional requirement costs?

Most expensive sub-functional requirement of their individual systems = blackest of that system
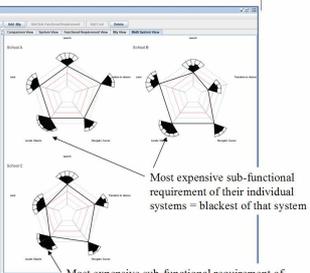
Most expensive sub-functional requirement of all systems = completely black

FanVis Multi System View II

Do you see any trends between the systems?

Which system is most balanced over how each functional requirement costs?

Try spinning these system representations, changing the cost phase and showing the sub-functional requirement labels.
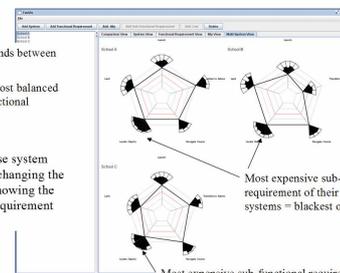
Most expensive sub-functional requirement of their individual systems = blackest of that system

Most expensive sub-functional requirement of all systems = completely black

Functional Requirement View

The functional requirement view gives you a detailed look at one of the functional requirements.

The percentage of each fan is shaded indicates the sub-functional requirement cost compared to most expensive sub-functional requirement shown in this view.

Which system looks like they spent the least on this functional requirement? The most?
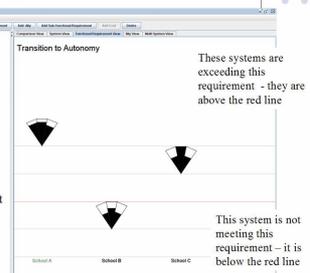
These systems are exceeding this requirement - they are above the red line

This system is not meeting this requirement – it is below the red line

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End of Tutorial

- You have now reached the end of the tutorial

- You may take some time now to review any portion of this tutorial if you wish. Once you are done your decision process will begin.

- Again, feel free to ask any questions and good luck with your decision making process!

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Excel Spreadsheet Tutorial

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Excel Spreadsheet Tutorial

- This tutorial will show you the different features that are included in the Excel spreadsheet you will be using

- As you are going through the tutorial, interact with the interface, try to answer the questions in these slides and ask any questions you might have

- The interface has a modified case study for you to use. You will get a different set of data for your decision task.

12

Spreadsheet Anatomy

- There are four different sheets in the spreadsheet; Data, Requirements and "-ilities", Total Cost and Cost Categories
- Requirements and "-ilities", total Cost and Cost Categories each shows you a different set of charts
- You can select one of the sheets to view by clicking on its tab at the bottom left corner.

13
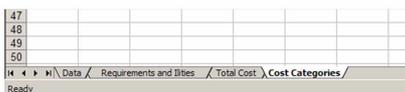
Requirements and "-ilities"

The Requirements and "-ilities" page shows how well the systems are performing on meeting "-ilities" and functional requirements

The larger the bar is, the more that requirement is being met.

Is there a system that is not meeting all the "-ilities" ?

Is there a system that is not meeting all the requirements?

Which system is most balanced on the "-ilities"? Functional Requirements?

14
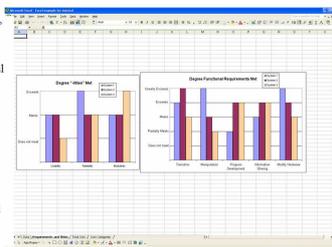
Total Cost

Total Cost shows the total system cost per system as well as the cost per sub-functional requirement

The more even the line chart is for cost per sub-functional requirement, the more balanced that system is its cost distribution

Which system costs the most? The least?

Which system is most balanced on cost distribution here?

15
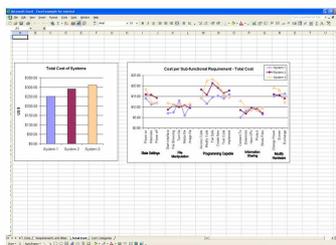
Cost Categories

Cost categories shows the total cost per each cost category as well as the cost breakdown per sub-functional requirement for each of the categories

Which system has the highest cost for each of the cost phases?

16
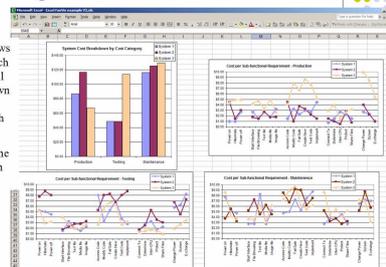
Data Sheet Overview

- You will not need to change any information in the data sheet
- The data sheet comprises of two sections in case you would like to reference this sheet:
  - System Information Section - Add or remove systems, functional requirements, sub-functional requirements, "-ilities", and cost categories
  - System Data Section - Change the degree to which systems meet functional requirements and "-ilities", and change how much each sub-functional requirement costs

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End of Tutorial

- You have now reached the end of the tutorial

- You may take some time now to review any portion of this tutorial if you wish. Once you are done your decision process will begin.

- Again, feel free to ask any questions and good luck with your decision making process!

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Appendix G : System Acquisition Trade Space Questions

Questions while testing within FanVis:

Knowledge Synthesis Questions
1) Which system best meets the baseline system selection criteria?
>   a) School A – correct
>   b) School B
>   c) School C
>   d) Uncertain

2) What system best meets the system selection criteria #2? This criteria asks to maximize how the functional requirements Cruise and Navigate are met before completing the baseline criteria.
>   a) Schools A
>   b) School B
>   c) School C – correct
>   d) Uncertain

3) Which of the following functional requirements for School C best meets the following set of criteria: Maximize degree met, and minimize total cost.
>   a) Launch – correct
>   b) Cruise
>   c) Track
>   d) Land

4) Which system meets the functional requirements and the "-ilities" to the greatest degree?
>   a) Schools A– correct
>   b) School B
>   c) School C
>   d) Uncertain

5) Which system is most balanced overall? This balance is in terms of meeting the functional requirements and "-ilities" as well as total cost per sub-functional requirement?
>   a) Schools A
>   b) School B– correct
>   c) School C
>   d) Uncertain

6) Which of the following functional requirements is overall met to the least degree while maintaining the highest cost?

a) Launch
b) Cruise
c) Track – correct
d) Land

Information Aggregation Questions

7) Which system balances the cost per sub-functional requirement to the greatest degree?
a) Schools A
b) School B– correct
c) School C
d) Uncertain

8) Which system meets the functional requirements to the greatest degree?
a) Schools A– correct
b) School B
c) School C
d) Uncertain

9) Which system is most balanced in terms of meeting the "-ilities"?
a) Schools A
b) School B
c) School C– correct
d) Uncertain

10) Which of the following functional requirements is most expensive for School A?
a) Launch
b) Cruise
c) Track – correct
d) Land

11) Which system is most balanced in terms of meeting the functional requirements?
a) Schools A
b) School B– correct
c) School C
d) Uncertain

12) Which system meets the "-ilities" to the greatest extent?
a) Schools A– correct
b) School B
c) School C
d) Uncertain

Data Processing Questions

13) Which system has the greatest total cost?

      a) Schools A

      b) School B

      c) School C– correct

      d) Uncertain

14) Which system meets the functional requirement Launch to the greatest degree?

      a) Schools A

      b) School B

      c) School C– correct

      d) Uncertain

15) Which "-ility" does School B meet to the greatest extent?

      a) Adaptability

      b) Reliability– correct

      c) Sustainability

      d) Uncertain

16) The most expensive sub-functional requirement for School A is under which functional requirement?

      a) Autonomy

      b) Navigate

      c) ID Objects– correct

      d) Land

17) Which of the following functional requirements does School C meet to the least degree?

      a) Launch

      b) Cruise

      c) ID Objects

      d) Track– correct

18) Which system meets the "-ility" Sustainability to the greatest degree?

      a) Schools A– correct

      b) School B

      c) School C

      d) Uncertain

Repeated Knowledge Synthesis Question

19) After answering these questions, which system do you now believe meets the baseline system selection criteria?

      a) Schools A– correct

      b) School B

      c) School C

      d) Uncertain

Questions while testing within the Excel® Tool:

Knowledge Synthesis Questions
1) Which system best meets the baseline system selection criteria?
  a) System 1
  b) System 2
  c) System 3– correct
  d) Uncertain
2) What system best meets the system selection criteria #2? This criteria asks to maximize how the functional requirements File Manipulation and Content Manipulation are met before completing the baseline criteria.
  a) System 1– correct
  b) System 2
  c) System 3
  d) Uncertain
3) Which of the following functional requirements for School C best meets the following set of criteria: Maximize degree met, and minimize total cost.
  a) Secure Data– correct
  b) GUI Plat-formed
  c) Content Manipulation
  d) Information Sharing
4) Which system meets the functional requirements and the "-ilities" to the greatest degree?
  a) System 1
  b) System 2
  c) System 3– correct
  d) Uncertain
5) Which system is most balanced overall? This balance is in terms of meeting the functional requirements and "-ilities" as well as total cost per sub-functional requirement?
  a) System 1
  b) System 2– correct
  c) System 3
  d) Uncertain
6) Which of the following functional requirements is overall met to the least degree while maintaining the highest cost?
  a) Secure Data– correct
  b) GUI Plat-formed
  c) Content Manipulation
  d) Information Sharing

Information Aggregation Questions

7) Which system balances the cost per sub-functional requirement to the greatest degree?

      a) System 1

      b) System 2– correct

      c) System 3

      d) Uncertain

8) Which system meets the functional requirements to the greatest degree?

      a) System 1

      b) System 2

      c) System 3– correct

      d) Uncertain

9) Which system is most balanced in terms of meeting the "-ilities"?

      a) System 1

      b) System 2– correct

      c) System 3

      d) Uncertain

10) Which of the following functional requirements is most expensive for System 3?

      a) Secure Data

      b) GUI Plat-formed– correct

      c) Content Manipulation

      d) Information Sharing

11) Which system is most balanced in terms of meeting the functional requirements?

      a) System 1

      b) System 2– correct

      c) System 3

      d) Uncertain

12) Which system meets the "-ilities" to the greatest extent?

      a) System 1

      b) System 2

      c) System 3– correct

      d) Uncertain

Data Processing Questions

13) Which system has the greatest total cost?

      a) System 1– correct

      b) System 2

      c) System 3

      d) Uncertain

14) Which system meets the functional requirement Modify Hardware to the greatest degree?

    a) System 1

    b) System 2

    c) System 3– correct

    d) Uncertain

15) Which "-ility" does System 2 meet to the greatest extent?

    a) Usability

    b) Modularity– correct

    c) Reliability

    d) Uncertain

16) The most expensive sub-functional requirement for System 3 is under which functional requirement?

    a) Support State Setting– correct

    b) File Manipulation

    c) Information Sharing

    d) Modify Hardware

17) Which of the following functional requirements does School C meet to the least degree?

    a) Support State Setting

    b) Secure Data

    c) GUI Plat-formed– correct

    d) Content Manipulation

18) Which system meets the "-ility" Reliability to the greatest degree?

    a) System 1

    b) System 2

    c) System 3– correct

    d) Uncertain

Repeated Knowledge Synthesis Question

After answering these questions, which system do you now believe meets the baseline system selection criteria?

    a) System 1

    b) System 2

    c) System 3– correct

    d) Uncertain

Appendix H : Retrospective Protocol

1) What was your first impression of the tools?

_____
_____
_____
_____

2) What was your impression of the systems with regards to the tools?

_____
_____
_____
_____

3) Was there information that you felt you needed and couldn't find, or had difficulty finding?

_____
_____
_____
_____

4) What information helped you determine which system was best in each tool?

_____
_____
_____
_____

5) Were there aspects of the tools that you felt was distracting?

_____
_____
_____
_____

6) Was there a portion of the tool (a graph or a page) that you liked the most? If so what was it?

_____
_____
_____
_____

7) Was there a portion of the tool (a graph or a page) that you liked the least? If so what was it?

_____
_____
_____
_____

Appendix I : Preferred Tool Selection Questionnaire

I felt that _____ was more useful as a decision support tool.
    □ FanVis   □ Excel[®]

I felt that _____ was a more pleasant tool to use.
    □ FanVis   □ Excel[®]

Overall I felt _____left me with a better understanding of the system acquisition trade space.
    □ FanVis   □ Excel[®]

Given the opportunity, I would choose _____ to complete my next system acquisition decision.
    □ FanVis   □ Excel[®]

Please provide any last thoughts or comments on either the tools, or the experiment itself.
Thank you!

Appendix J : Statistics for Time

Solution for Fixed Effects							
Effect	Decision	Reason	Estimate	Std. Error	DF	t value	Pr>ItI
Intercept			5.7632	0.1367	28	42.14	<.0001
Proficiency Time			0.00204	0.00043	56	4.67	<.0001
Decision Support Tool	Excel®		0.0493	0.0681	29	0.73	0.4741
Decision Support Tool	FanVis		…	…	…	…	…
Reasoning Difficulty Level		Data Processing	-1.0198	0.0759	58	-13.43	<.0001
Reasoning Difficulty Level		Information Aggregation	-0.7816	0.0759	58	-10.30	<.0001
Reasoning Difficulty Level		Knowledge Synthesis	…	…	…	…	…
Decision*Reasoning	Excel®	Data Processing	-0.3954	0.0920	56	-4.28	<.0001
Decision*Reasoning	Excel®	Information Aggregation	-0.1974	0.0916	56	-2.16	0.0352
Decision*Reasoning	Excel®	Knowledge Synthesis	…	…	…	…	…
Decision*Reasoning	FanVis	Data Processing	…	…	…	…	…
Decision*Reasoning	FanVis	Information Aggregation	…	…	…	…	…
Decision*Reasoning	FanVis	Knowledge Synthesis	…	…	…	…	…

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr>F
Proficiency Time	1	56	21.81	<.0001
Decision Support Tool	1	29	12.17	0.0016
Reasoning Difficulty Level	2	58	217.71	<.0001
Decision*Reasoning	2	56	9.18	0.0004

Tests of Between-Subjects Effects

Dependent Variable: Time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6378001.438[a]	5	1275600.288	54.972	.000
Intercept	22153966.661	1	22153966.661	954.730	.000
Reasoning_Difficulty_Level	6353097.075	2	3176548.538	136.894	.000
Test_Number	18519.590	1	18519.590	.798	.373
Reasoning_Difficulty_Level * Test_Number	6384.901	2	3192.451	.138	.872
Error	3991164.166	172	23204.443		
Total	32451639.362	178			
Corrected Total	10369165.604	177			

a. R^2 = 0.615 (Adjusted R^2 = 0.604)

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