NASA/TM-2002-211414

Vertex Movement for Mission Status Graphics: A Polar-Star Display

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January 2002

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Abstract

Humans are traditionally bad monitors, especially over long periods of time on reliable systems, and they are being called upon to do this more and more as systems become further automated. Because of this, there is a need to find a way to display the monitoring information to the human operator in such a way that he can notice pertinent deviations in a timely manner. One possible solution is to use polar-star displays that will show deviations from normal in a more salient manner. A polar-star display uses a polygon's vertices to report values. An important question arises, though, of how the vertices should move. This experiment investigated two particular issues of how the vertices should move: (1) whether the movement of the vertices should be continuous or discrete and (2) whether the parameters that made up each vertex should always move in one direction regardless of parameter sign or move in both directions indicating parameter sign. The results indicate that relative movement direction is best. Subjects performed better with this movement type and they subjectively preferred it to the absolute movement direction. As for movement type, no strong preferences were shown.

Introduction

Humans are traditionally bad monitors, especially over long periods of time on reliable systems (ref. 1), and they are being called upon to do this more and more as systems become further automated. Because of this, there is a need to find a way to display the monitoring information in such a way that the operator can notice pertinent deviations in a timely manner. Research has shown that an automated monitor can aid humans in recognizing and dealing with failures (refs. 2 and 3). One possible solution to this is to use polar-star displays (ref. 4) that will show deviations from normal in a more salient manner. A polar-star display uses a polygon's vertices to report values.

A polar-star display was chosen for its emergent features. Buttigieg and Sanderson reported that these "emergent features can be effectively used in displays to support global failure detection if they clearly carry information about important system states" (ref. 5). Furthermore, Cooper reported that the "identification of single lines in coherent, object-like contexts can be superior to identification of the lines when presented alone" (ref. 6).

With a polar-star type of display, a different grouping of information may be beneficial rather than just one parameter per vertex, as is traditionally displayed. In the aviation domain, these groupings must reflect the parameters pilots feel are necessary to safely complete a flight (refs. 7 and 8).

An important question arises, though, once the groupings are determined: *How should the vertices move?* Since there is no longer a one to one mapping of one parameter to one vertex, combination methods of several parameters to one vertex needs to be established. These combination methods will thus partially determine how the vertices of the polar star display move. However, since this movement is key to the operator monitoring and diagnosing mission health, operator preferences on movement were deemed important enough to resolve before various parameter combination methods were studied.

Experiment Objectives

This experiment investigated two particular issues with how the vertices of a polar-star display should move. The particular issues studied were (1) whether the movement of the vertices should be continuous or discrete and (2) whether the parameters that made up each vertex should always move in one direction regardless of parameter sign or move in both directions indicating parameter sign. The tasks that addressed these issues were (1) a simple desktop simulation of a polar star and (2) a survey asking for preferences on movement.

Experimental Variables

The two primary experimental variables for this experiment were the (1) movement type and (2) movement direction of the vertices. Both of these variables were within subject. A between subject variable that was considered in the analysis was whether the subject was a certificated pilot.

Movement Type

The two movement types were selected for a couple of reasons. One school of thought was that continuous movement would aid in the gathering of trend information. On the other hand, there were thoughts that discrete movement would be more "eye catching." Another aspect supporting discrete movement was that "the total movement required for motion detection increases with increased exposure duration" (ref. 9). Discrete movement was thought to be helpful in this case since, theoretically, pilots would be looking at this display often to check the general status of the aircraft and mission and a sudden jump would be more obvious than a slow deviation.

Continuous. Continuous movement (c) was updated constantly. Occasionally, a small jump occurred due to the parameter combining method used to determine movement direction.

Discrete. Discrete movement (d) had particular jump points. These jump points were (1) zero, (2) half-way between zero and the beginning of an alert range, (3) the beginning of an alert range, (4) half-way from the beginning of an alert range to the end of an alert range, and (5) end of an alert range (fig. 1).

Movement Direction

Movement direction was considered for a couple of reasons. It has been reported that "direction of movement makes little difference" in detection (ref. 10); but, this display is also supposed to aid in making a preliminary diagnosis. Therefore, movement direction was included to see if it did aid in realizing the nature of the non-normal situation.

Absolute. The absolute method (a) of combining the parameter values at each vertex was basically the average of the absolute values of each parameter at a particular index (eq. 1). Since the average value was always positive, the vertices always moved out.

let n = number of parameters at a vertex

$$\begin{aligned} &\text{if } \underset{i=1}{\overset{n}{x_i}} = \text{warning} \Rightarrow \text{absolute} = |x_i| \\ &\text{else if } \underset{i=1}{\overset{n}{x_i}} = \text{caution} \Rightarrow \text{absolute} = |x_i| \\ &\text{else if } \underset{i=1}{\overset{n}{x_i}} = \text{advisory} \Rightarrow \text{absolute} = |x_i| \\ &\text{else absolute} = \frac{\sum_{i=1}^{n} |x_i|}{n} \end{aligned} \tag{1}$$

In this experiment, color bands for each parameter signified the alert ranges (fig. 2). A red band indicated a warning. An amber band signified a caution. Finally, a cyan band signified an advisory.

Relative. The relative method (r) of combining the parameters basically took the largest magnitude of the parameters at a particular vertex and then applied the sign of that value to the number (eq. 2). Therefore, the vertices could move both in and out.

$$\text{relative} = \text{sgn}\{y\} * |y| \tag{2}$$

where

let n = number of parameters at a vertex (3)

$$\text{if } \bigcup_{i=1}^{n} x_i = \text{warning} \Rightarrow y = x_i$$

$$\text{else if } \bigcup_{i=1}^{n} x_i = \text{caution} \Rightarrow y = x_i$$

$$\text{else if } \bigcup_{i=1}^{n} x_i = \text{advisory} \Rightarrow y = x_i$$

$$\text{else } y = \max\left(|x_1|, |x_2| \ldots |x_n|\right)$$

Pilot Status

Pilot status was determined by whether the subject was a certificated pilot. Pilot status was considered because a previous experiment determined that there were differences between pilots and non-pilots in the way they handled non-normal system events (refs. 11 and 12).

Experiment Design

Subjects

Eleven people participated in this experiment as subjects. Ten were male and one was female. The average age was 43.7 years old. Six of the subjects were certificated pilots.

Polar-Star Display

The polar-star display each subject saw is shown in figure 3. The dotted circle indicated the normal or expected value. The dotted circle was included because other research indicated that it was easier to detect abnormalities when a standard was provided (ref. 6). For this experiment, the expected value was zero. If a parameter reported by a particular vertex reached an alert range, the vertex number and a small dot placed at the vertex changed to the alert level color. Movement outside of the circle indicated positive or absolute values while movement to the interior of the circle indicated a negative value.

Accuracy Question Screen

After one of the vertices reached an alert level, subjects had to answer questions about the non-normal situation they just saw. These questions were (1) which vertex had the problem, (2) which parameter had the problem, (3) was the alert in the alert range above zero or below zero, and (4) what was the alert level (fig. 4). In some instances, the subject would not be able to resolve which parameter had the problem and/or if the alert was in the alert range above or below zero. In these cases, the subject was instructed to answer "Could Not Tell." If the subject forgot or just did not know the answer, he was instructed to answer with "Don't Know."

Display Questionnaire

After the subject completed all the runs for a particular display, he filled out a questionnaire asking how easy or difficult it was to use the display (appendix A). He also completed a NASA-TLX worksheet asking for his workload on using the display (appendix B and ref. 13).

Final Questionnaire

At the end of all the data runs, each subject rank ordered their preferences for the four displays they just saw (appendix C). An area was also provided for general comments.

Procedure

When a subject first arrived, he received a verbal briefing on the purpose of this experiment (appendix D). He was then shown the polar-star display and its characteristics were explained to him. The parameters that made up each vertex were described to him (fig. 2). The movement type of the vertices and the movement direction were also detailed. The questions he would be answering after each run were shown to him (fig. 4) plus the questionnaire and NASA-TLX were shown and explained to the subject (appendix A and B).

After this initial briefing, the subject moved to the computer where he would be performing the experiment. The polar-star display was programmed on an Octane Silicon Graphics Computer using VAPS (ref. 14). The movement type and movement direction that he would see for the first display type were explained to him.

At this point the experiment began with three practice runs using the first display. These practice runs behaved exactly like the six data runs that followed the practice runs except that no data were recorded.

During each run, only one parameter would reach an alert condition and once it did, it would remain in that alert condition. Once the subject saw this and was fairly sure he could answer questions about what he just saw, he used the mouse to click on the "STOP" button (fig. 3). The question screen then replaced the polar-star display screen (fig. 4).

The subject could answer the questions in any order he wanted. He could also use and was encouraged to use the figure detailing the parameters that made up each vertex in order to help him answer the questions (fig. 2). The parameter sheet was provided for a couple of reasons. First, it was not expected that the subject had the time to memorize each parameter's alert ranges. Second, the polar-star display is to be used with the available systems displays, which include parameter displays. Therefore, the parameter sheet acted as the actual parameter display. The subject's answers were not recorded until he clicked on the "NEXT" button. Once he selected the "NEXT" button, the next practice or data run began.

After six data runs with a particular display configuration were finished, a screen telling the subject to complete the display preferences questionnaire and the NASA-TLX appeared. It also told the subject the next display combination he would see.

When the subject completed the two question sheets, the next display combination was described to him. He then clicked on the "NEXT" button to start the three practice runs with that display combination.

At the end of all the data runs, each subject filled out the final questionnaire.

Dependent Measures

Several dependent measures were recorded. The objective data measures: time looking at the polar-star display and time to answer questions were recorded by the computer. Also recorded by the computer were the subject's responses to the accuracy questions after each data run. The rankings that the subjects gave during the display questionnaire, NASA-TLX, and the final questionnaire were the subjective dependent measures.

Hypothesis

When considering the three experimental variables and the objectives of this study, the following were hypothesized. For the factor of movement type, subjects would prefer continuous movement but movement would not affect objective performance because subjects would be only attending to this display. This lack of secondary tasks precluded the need for increased motion to detect a change (ref. 9). For movement direction, subjects would perform better and prefer the relative condition because it would be easier to determine which parameter had the problem and whether the parameter value was high or low. The last experimental variable, whether the subject was a certificated pilot, would affect subject workload and the ability of the subjects to determine what the non-normal situation was (ref. 12).

Data Analysis

SPSS® was used for all data analyses (ref. 15). The display factor was the combination of movement type and movement direction.

Time and Subjective Questionnaires

For the time subjects watched the display, the time it took them to answer questions, and the total combined time, data was analyzed using a repeated measures design with trial as the repeated measure. The independent variables were display and pilot status.

The subjective questionnaires were analyzed using a one-way ANOVA. This was possible since subjects were directed to mark anywhere on a continuous scale. Again, the independent variables were display and pilot status.

Accuracy Questions

The accuracy questions that subjects answered after each data run were analyzed. In particular, a Mann-Whitney U statistic was used for pilot status and a Kruskal-Wallis H statistic was used for the display factor.

Results

Display Effects

Display was significant for the accuracy of determining if the non-normal parameter value was greater or less than zero ($X^2(3)=24.07$, $p<0.01$). As can be seen in figure 5, the parameter combination that included relative movement direction resulted in the most accuracy when determining if the non-normal parameter value was high or low. Subjects also reported that it was easier to determine if the parameter was high or low using the relative movement direction ($Z=4.63$, $p<0.01$) (fig. 5). In fact, a Tukey HSD post-hoc test indicated that relative movement direction grouped together and absolute movement direction was a separate group.

Display was also significant for the subjective measure of how difficult it was to determine which parameter had the alert ($F(3,36)=3.15$, $p<0.04$) but was not significant for the objective measure of how accurate subjects were in determining which parameter had the alert ($X^2(3)=1.52$, $p<0.70$). The subjective rating essentially indicated that the relative movement direction was preferred over the absolute movement direction (fig. 6). A Dunnett's T3 post-hoc test was not significant but the trends indicated suggest the above groupings.

When considering the display as a whole, there were significant differences for movement acceptability and the ease of determining the status as a whole. Subjects rated the relative movement type displays higher than the absolute movement type displays ($F(3,36)=4.10$, $p<0.02$) for movement acceptability (fig. 7). The same also held true when determining the overall status of the display ($F(3,36)=3.26$, $p<0.04$) (fig. 7). Once again, relative movement ranked higher than absolute movement. Movement acceptability results also indicated a near-significant interaction of display by pilot status ($F(3,36)=2.76$, $p<0.06$). As can be seen in table 1, pilot ratings were much less extreme than the non-pilot ratings.

Table 1 – Display by Pilot Status Ratings for Movement Acceptability

Display	Pilot Status Ratings (0-1)	
	Non-Pilot	Pilot
continuous-relative	0.94	0.75
continuous-absolute	0.50	0.72
discrete-relative	0.89	0.77
discrete-absolute	0.60	0.73

Note: 0=low, 1=high

Whether the subject was a certificated pilot was only significant for how long they viewed the display. There were no significant results with pilot status for diagnosis accuracy although as seen in table 2, the same trends do seem to be present as reported in reference 12.

Table 2 – Diagnosis Accuracy

	Pilot Status	
	Non-Pilot	Pilot
Diagnosis Accuracy (%)	86	87
Previous Experiment Diagnosis Accuracy (%) (ref. 12)	34	62

Lastly, when rank ordering the displays, subjects preferred relative movement to absolute movement ($F(3,36)=44.03$, $p<0.01$) (fig. 8). Although not significant, workload ratings also show the same trend ($f(3,36)=0.54$, $p<0.70$) (fig. 8).

Times

The time that subjects viewed the polar-star display was significant ($F(1,36)=9.09$, $p<0.01$). As seen in table 3, pilots viewed the display longer than non-pilots did. The time that subjects took to answer the questions was not significant ($F(1,36)=0.16$, $p<0.13$) but here pilots answered the questions faster than non-pilots (table 3).

Table 3 – Time Viewing Polar-Star Display and Time To Answer Questions

	Pilot Status Time (sec)	
	Non-Pilot	**Pilot**
View Display	11.72	14.36
Questions	14.68	12.54

Discussion

For determining how the vertices should move on a polar-star display, the results indicate that relative movement direction is best. Subjects performed better with this movement type and they subjectively preferred it to the absolute movement direction. As for movement type, no strong preferences were shown.

Overall, the results indicate that relative movement direction is best with either continuous or discrete movement type. Since this display will be used for monitoring purposes and a reference normal will be shown at all times, the follow-on experiment to see whether the polar-star display aids in monitoring mission and aircraft health and in making a preliminary diagnosis will use continuous-relative movement.

Conclusions

Since humans are traditionally bad monitors, and since they are being called upon to perform this function more and more as systems become further automated, there is a need to find a way to display the monitoring information to the human operator in such a way that he can notice pertinent deviations in a timely manner. One possible solution to this problem is to use polar-star displays that will show deviations from normal in a more salient manner.

In the experiment just described, subjects did best and preferred relative movement direction over absolute movement direction. Subjects did not show a strong preference for movement type.

The next experiment will employ the polar-star display in a more full-mission simulation to see if the display does, in fact, aid in monitoring mission and aircraft health and in making a preliminary diagnosis. The polar-star vertices will show relative direction with continuous movement. But since the results from this experiment did not definitively find that continuous movement was best, subjects will be asked for their preferences after the simulation in the next experiment. Their reported preferences after using the display in a more realistic situation will be taken into consideration in the further refinement of the polar-star display used for these purposes.

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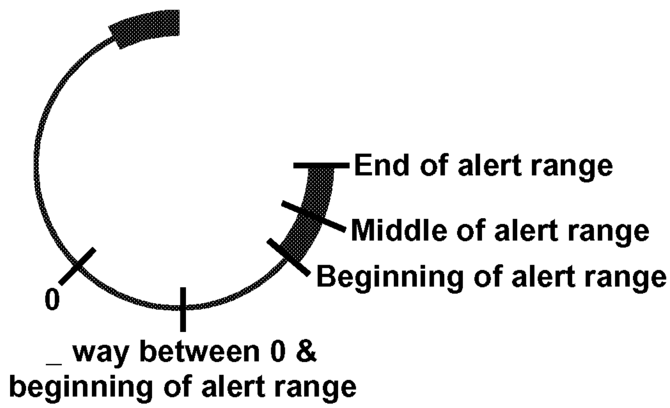

Figure 1 – Discrete Jump Points

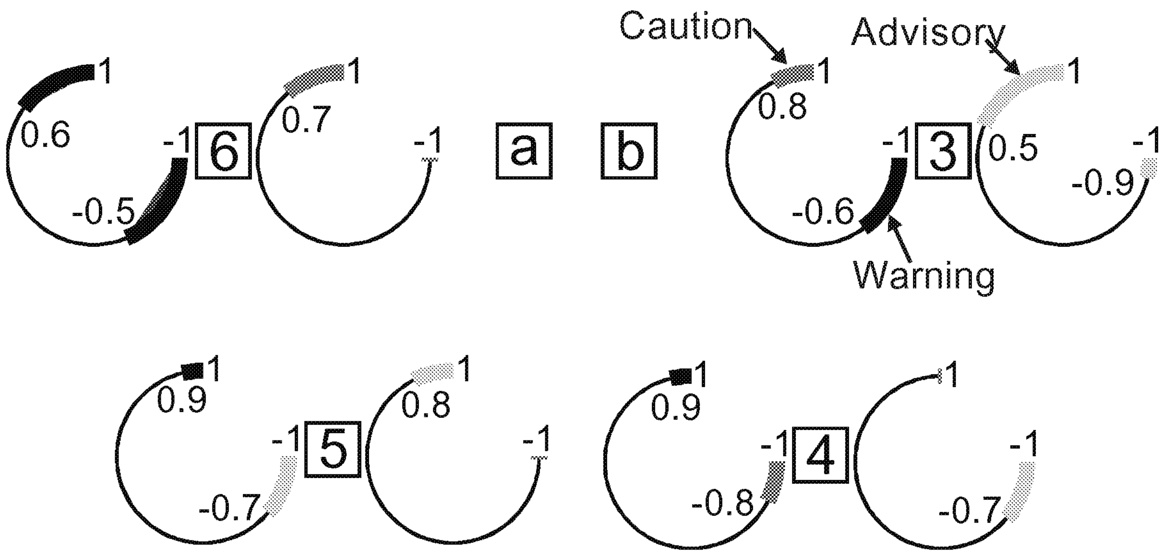

Figure 2 – Parameter Alert Ranges

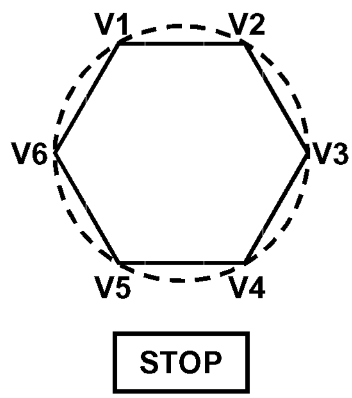

Figure 3 – Polar-Star Display

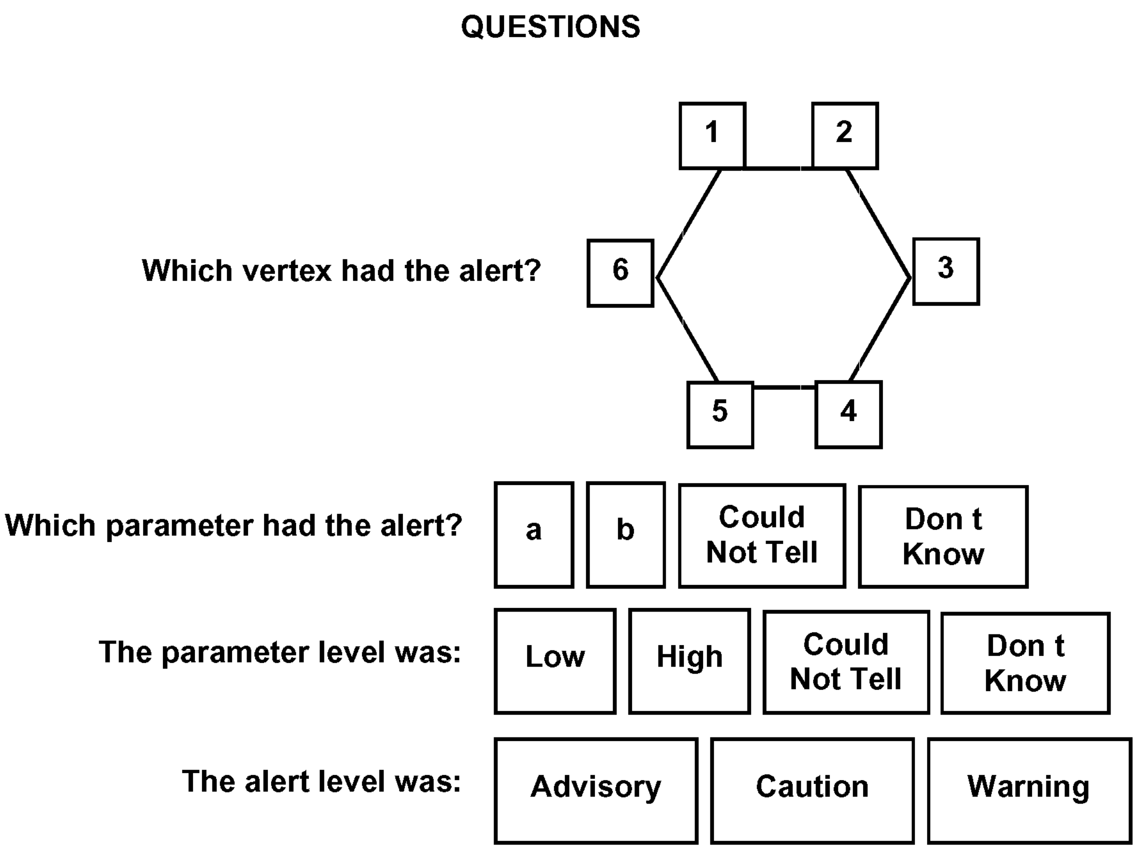

Figure 4 – Question Screen

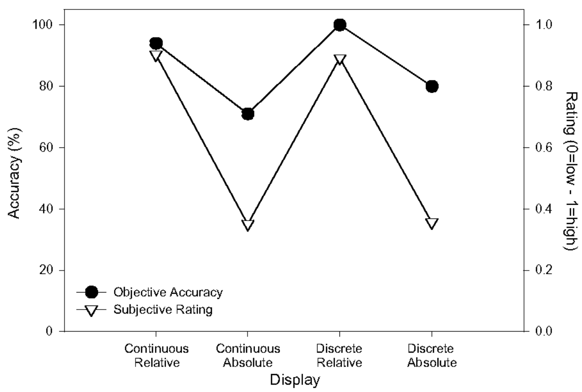

Figure 5 – Ability and Ease of Determining Whether Alert was a Above or Below Zero

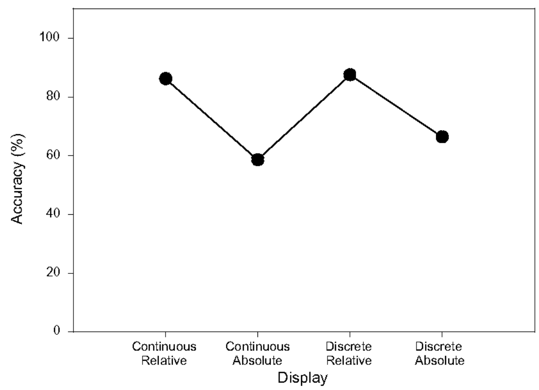

Figure 6 – Accuracy of Determining Which Parameter Had an Alert

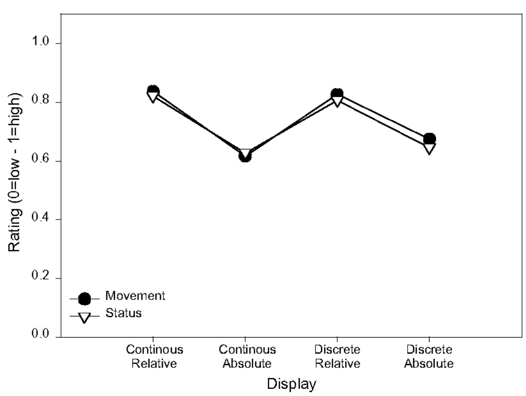

Figure 7 – Movement Preferences and Ease of Determining Status Ratings

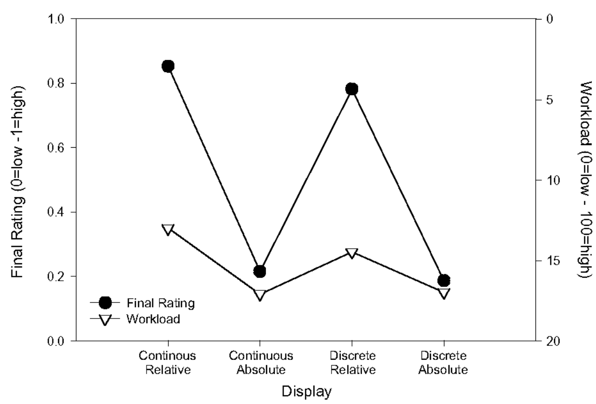

Figure 8 – Final and Workload Ratings

Subj: Date:

Appendix A — Display Questionnaire

Directions: Please place a mark **anywhere** along the horizontal line of the rating scale when answering each question.

1. For the this MSG display,

   a. determining which parameter had the problem was — very difficult / very easy

   b. determining if the non-normal parameter value was above or below normal was — very difficult / very easy

   c. determining the alert level of the non-normal parameter value was — very difficult / very easy

   d. the movement of the display was — very unacceptable / very acceptable

   e. determining the status of the parameters was — very difficult / very easy

Comments: ____

PreMSG Exp

Display	C-H	C-S	D-H	D-S
Order	1	2	3	4

Subj:
Date:

Appendix B — NASA TLX

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Place a mark at the desired point on each scale:

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

PreMSG Exp

Appendix C — Final Questionnaire

Directions: Please place a mark **anywhere** along the horizontal line of the rating scale when answering the question.

Rank order the displays on the scale below:

worst best

where 1=Continuous-Highest
2=Continuous-Summation
3=Discrete-Highest
4=Discrete-Summation

Comments:

Thank you

Appendix D — MSG Pre-Test Experiment

(Directions / Script for PI)

Background

- This experiment is looking at a new display for overall mission monitoring and preliminary diagnosis that combines several parameters.
- The display is a polar star where each vertex represents a parameter or a combination of parameters.
- Need to determine how the vertices should move.

Purpose

This experiment will compare 4 different combinations of ways to move the vertices.

Procedure

- This is a 1 hr experiment.
- You will have several scenarios where one of the vertices will move out of the green normal range.
- After you determine which parameter is not normal, you will have to answer some questions about the alert you saw.
- After using a particular display, you will fill-out the NASA—TLX and a questionnaire on your likes and dislikes of the display.
- After the data runs, you will complete a final questionnaire asking you for your preferences on the displays you just saw.

<u>Displays</u>

- The general layout of the display is seen in figure 1. The dotted circle indicates the normal expected value. Each vertex is a combination of 2 parameters (see figure 2). This sheet will be available to you during the data runs.
- Each vertex will move either continuously or discretely.
  - Continuous movement is self-explanatory.
  - For discrete movement, each vertex will jump to either on the dotted line, _ the distance to the bottom of an alert range, the bottom of an alert range, _ the distance into the alert range, or the top of the alert range.
- The vertices will show either the highest absolute value of the lumped parameters or a summation of the parameters.

- For the highest absolute value, the vertex will display the actual value of the highest absolute value of the parameters associated with that vertex (*i.e.*, $\max(|x_1|,|x_2| \ldots |x_n|)$) unless a parameter is in an alert range. In that case, the value of the parameter in the highest alert range (warnings will be shown before cautions which will be shown before advisories) will be displayed. A value less than 0 will be in and a value greater than 0 will be out.
- For summations, the vertex will display the value $\frac{\sum_{i=1}^{n}|x_i|}{n}$ where *x* is the parameter and *n* is the total number of parameters lumped into that vertex. However, if a parameter is in an alert range, the vertex text and dot will be the same color as the highest alert reached. Movement will always be out (values are always positive).

* Therefore, the 4 display combinations are Continuous-Highest, Continuous-Summation, Discrete-Highest, and Discrete-Summation.

<u>Alerts</u>

* You will see 3 alert levels: advisories, which are cyan; cautions, which are amber; and warnings, which are red (see figure 3).
* You will only see 1 alert per data run.

<u>Questions After Each Data Run</u>

* After each data run, you will answer some questions about what just happened.
* The questions are which vertex was not normal, which parameter was in the alert range, whether the alert was a high or low alert, and the alert level (advisory, caution, or warning) (see figure 4).
* In some instances, you may not be able to answer a question because there is not enough information. In that case, please hit Could Not Tell.
* If you do not know an answer to a particular question, hit Don t Know.

<u>NASA TLX Workload Rating Form</u>

* After completing all the data runs for a particular display combination, you will fill-out a NASA-TLX workload rating form and Display Questionnaire sheet (see sheets 1 and 2).

<u>Runs</u>

* There are 24 data runs.
* Before the data runs, you will be given 3 practice runs that behave similarly to the data runs (see figure 5).

- After the practice runs for a particular display, you will have 6 data runs (see figure 1).
- Once you know what parameter is out of bounds, hit the Stop button (see figure 1) to answer the questions (see figure 4).
- Once you have answered the questions for that particular data run, hit the Next button to go on to the next trial (see figures 4 and 1).
- After the 6 data runs for a particular display, you will fill out the NASA—TLX and Display Preferences sheets (see sheets 1 and 2 and figure 6).
- You will then have 3 more practice runs with the new display before continuing on to the data runs.
- At the end, you will fill out 1 last question about your display preferences (see sheet 3).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 2002

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Vertex Movement for Mission Status Graphics: A Polar-Star Display

5. FUNDING NUMBERS
WU 706-21-71-02

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
L-18138

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2002-211414

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 03 Distribution: Nonstandard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Humans are traditionally bad monitors, especially over long periods of time on reliable systems, and they are being called upon to do this more and more as systems become further automated. Because of this, there is a need to find a way to display the monitoring information to the human operator in such a way that he can notice pertinent deviations in a timely manner. One possible solution is to use polar-star displays that will show deviations from normal in a more salient manner. A polar-star display uses a polygon's vertices to report values. An important question arises, though, of how the vertices should move. This experiment investigated two particular issues of how the vertices should move: (1) whether the movement of the vertices should be continuous or discrete and (2) whether the parameters that made up each vertex should always move in one direction regardless of parameter sign or move in both directions indicating parameter sign. The results indicate that relative movement direction is best. Subjects performed better with this movement type and they subjectively preferred it to the absolute movement direction. As for movement type, no strong preferences were shown.

14. SUBJECT TERMS
polar-star display, vertex movement, deviations

15. NUMBER OF PAGES
23

16. PRICE CODE
A03

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