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In order to facilitate a single operator controlling multiple unmanned vehicles, numerous autonomous support tools are being considered. One such candidate tool monitors the situation and alerts the operator when a deviation from the vehicle's plan has occurred. The goal of this research was to develop an effective visualization method for conveying plan deviations. Two interface formats were developed based on a review of the literature: a pie chart and a bar chart. Each format allows an operator to compare values for parameters that have different units, value ranges, and relative priority. Twelve participants were tested using a 2 (chart format) X 3 (number of parameters) X 4 (question type) repeated measures within-participants design. Both objective and subjective data were collected. Participants both preferred and were faster at retrieving parameter state and priority information from the bar chart versus the pie chart.

Intelligent autonomy capabilities are being developed to enable a single operator to control multiple heterogeneous unmanned vehicles (UVs). For example, cooperative control algorithms are being designed that rapidly calculate the most efficient route for a vehicle to take to a specific point while taking into account no fly zones, unpassable terrain, and environmental conditions (Kingston, Rasmussen, & Mears, 2009). Additionally, an intelligent agent is under development (Douglass, 2013) that recommends which vehicle(s) to assign to a specific task based on the UV's probability of success (e.g., detecting the target that the UV is searching for), the UV's estimated time enroute (ETE) to the task location, the time the UV can dwell at the task location once it has arrived, the amount of fuel needed to get to the task location, and the impact assigning the UV to the task will have on other existing tasks. Finally, capabilities are being added to the Rainbow autonomics framework (Verbancsics & Lange, 2013) that monitor the ongoing situation and alert the operator when a deviation from the plan occurs (e.g., a wind shift delays the UV's ETE). Such technologies will allow the human operator to offload manual control of the UVs to the automated system, allowing more time to focus on assigning high-level tasks, monitoring the situation, and adjusting to unexpected events (Draper, 2007).

One of the key challenges facing system developers is designing a human-autonomy interface that allows an operator to monitor the status of assigned high-level tasks and alerts the operator when a deviation from the plan has occurred. A review of the literature provided several potential solutions. One of the most promising was Findler's (2011) Visual Thinking Sprocket. This design was adapted to communicate a given plan's status using the pie chart shown in Figure 1a. This format conveys several types of information to the operator. The size of each pie slice represents the priority weightings that each parameter was given (e.g., ETE was the highest priority, followed by probability of detection [PoD]). The parameters were ordered based on their priority in a clockwise fashion, with the highest priority parameter located at the twelve o'clock position. Color is used to represent a plan's status. If everything is on track for a specific parameter (e.g., the UV is still expected to arrive at task location on time) the middle circular segment of that parameter's pie slice is green and indicates a "normal/ideal" state (see Impact parameter in Figure 1a.). A warning state is represented with three yellow segments and indicates a "slight" deviation from the ideal state. An error state is represented with five red segments and indicates a "severe" deviation from the ideal state. The specific location of the segment with the brighter, more saturated color indicates whether the value exceeds or is less than the desired operating range for that parameter. For example, in Figure 1a the UV is now expected to arrive slightly ahead of the scheduled ETE time (bright yellow segment near pie's center) and with a greatly reduced probability of detection (PoD) than expected (bright red segment near pie's center). This could notify the operator that the UV could possibly get closer to the target for increased sensor quality (since PoD is critically lower than nominal) or could possibly be re-planned to image another target while enroute.

The present study evaluated performance on retrieving UV plan status with this prototype pie chart visualization. The study also evaluated an alternative visualization that encoded the relative priority of each parameter into the width of their respective bars (in contrast to the angle of the wedge used in the pic chart; see Figure 1b). This "bar chart" approach is based on the findings of Cleveland & McGill's (1985) graphical perception task study in which participants were much better at detecting differences in length (e.g., the width of a bar) than differences in angle or area (e.g., the angle/size of the pie wedge).

In the bar chart, the parameters were ordered from left to right based on their priority, with the highest priority parameter at the far left. Otherwise, the coding of the color of each segment of the bars was similar to that employed in each segment of the slices in the pie chart. To summarize, this study compared the effectiveness of the pie chart versus the bar chart at conveying UV plan status information. Additionally, since display clutter can impact information retrieval, the number of parameters presented in the pie and bar charts was varied as well.

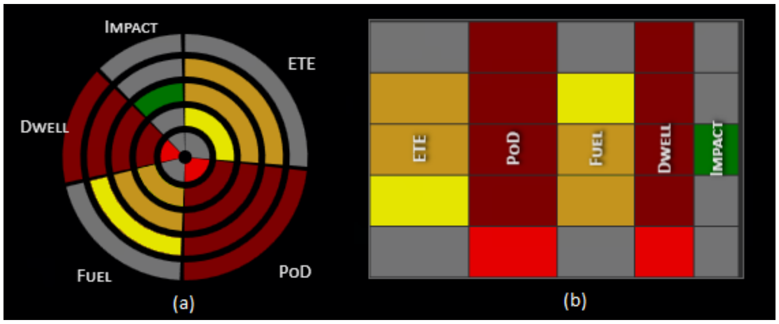

Figure 1. Sample pie chart (a) and bar chart (b) visualizations evaluated to determine effectiveness in conveying the status of parameters related to unmanned vehicle plans.

Method

Participants

A total of twelve volunteer Wright-Patterson Air Force Base employees (8 males, 4 females) between the ages of 22 - 46 (M = 29, SD = 9) participated in this study. All participants reported normal/normal corrected vision and normal color vision.

Experimental Design

Trials were blocked by Chart Format, such that participants completed trials with one Chart Format (pie or bar) before trials with the alternate format. The order of the two Chart Format trial blocks was counterbalanced across participants. Within each of these two blocks, participants completed 96 trials consisting of three 32-trial sets, one with each of three different Number of Parameters conditions tested (3, 5, and 7 parameters), with the order of the sets counterbalanced across participants. Each trial required participants to answer one of four types of questions by retrieving information from a static chart format. Question types included: (1) "What is the state of *parameter X*?" (2) "Which parameter has state of *X*?" (3) "How many parameter(s) have an error or a warning?" and (4) "In comparison to *parameter X*, is *parameter Y* less important, more important, or equally important?" The order in which each question type was posed was randomized with the constraint that each type occurred eight times in each trial set. This resulted in a 2 (Chart Format) X 3 (Number of Parameters) X 4 (Question Type) X 8 (Replication) within-participant factorial design, with each participant completing 192 trials.

Apparatus

Test Stimuli. To generate the Chart Formats (samples shown in Figure 2), 24 data sets were generated, eight for each of the three Number of Parameters (3, 5, and 7) conditions. Each data set specified the priority and operating state (e.g., normal, warning, or error) for each parameter. This step involved defining a unique combination of variables with the goal of representing a range of priorities and operating states, both within each chart and across charts within the trial sets and blocks. Parameter error states had a 50% chance to be nominal, a 15% chance to have a lower warning, a 15% chance to have an upper warning, a 10% chance to have a lower error, and a 10% chance to have an upper error. For the last step, parameter names were randomly assigned (e.g., for dataset 1, parameter 1 was fuel, for dataset 2, parameter 1 was dwell, etc.).

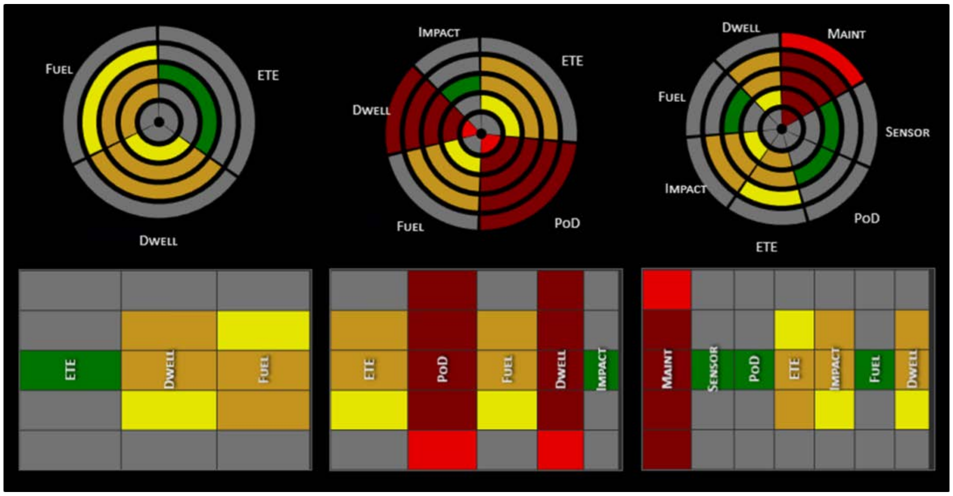

Figure 2. Sample Pie and Bar Chart Formats depicting three, five, and seven parameters of unmanned vehicle plan status. Each chart was approximately 2 X 3 in.

Trial Procedure. The methodology was similar to that employed by Spriggs, Warfield, Calhoun, & Ruff (2010). For each trial, a question was presented along with one chart on a 1920 X 1200 resolution 24 in. widescreen monitor. Participants were trained to click a button labeled "SHOW ANSWERS" when he or she was ready to respond with an answer. Upon button selection, the chart disappeared and candidate responses to the question were presented, as well as the question itself. The Chart Format was removed during the response selection step to prevent the participant from using a process of elimination to answer the question. The participant's task was to select the correct answer as quickly and accurately as possible. Selection of a response blanked the display, except for the presentation of a "NEXT" button; selection of this button initiated the next trial. Thus, progression through the blocks of trials was self-paced with participants selecting buttons via a mouse. Participants could only control progress forward within and across trials; for instance, participants could not return to a previous screen to view the chart again before answering the question. Participants did not receive feedback on their performance during the experimental trials.

Test Sessions

Upon arrival, participants read and signed the informed consent document, filled out a short demographics questionnaire, and were given an overview of the study. Participants were next trained on the specific trial block (Chart Format) they were assigned to complete first. Training consisted of twelve questions (three examples of the four types of questions) using a non-UV scenario in which the state of parameters influencing the success of a hypothetical party were depicted in the charts. Participants were allowed to repeat the training questions until they felt confident in their ability to retrieve information from the chart. Also, participants had to accurate on the training questions before beginning the experimental trials. Participants were briefed to answer questions as quickly and accurately as possible, and that both speed and accuracy would be recorded.

At the completion of the first trial block, participants were given a Post-Block Questionnaire asking their opinion on the specific Chart Format they just saw. These questions included items asking about their perceived speed, accuracy and general ability to retrieve information, as well as whether the number of parameters made a difference in their ability to answer the questions. Next, the procedures were repeated for the alternate Chart Format. After completion of the training and trial block with the alternate Chart Format, participants were administered another Post-Block Questionnaire. This was followed by a Final Debriefing Questionnaire that included items for participants to compare the two chart formats, indicate their preference, and provide additional feedback. Total session time, per participant, was approximately one hour, with each trial lasting about 5 s.

Results

Data were collapsed across replications. Performance data (response accuracy and time) were analyzed with a repeated measures Analysis of Variance (ANOVA) model. Questionnaire responses were analyzed using paired t-tests and the Kolomogorov-Smirnov nonparametric test of significance.

Response Accuracy. The percent of questions answered correctly was 97% overall. Therefore, data analysis concentrated on mean response time for questions answered correctly.

Response Time. To better reflect the time required to retrieve information to answer the question correctly, response time was calculated from the time that the chart/question was presented until the participant selected the "SHOW ANSWERS" button. The results showed that mean response time to correctly retrieve information was significantly faster with the Bar Chart compared to the Pie Chart Format ($F(1,11) = 5.14$, $p = 0.04$, Figure 3).

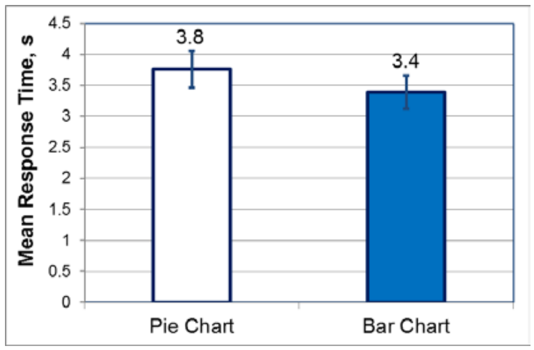

Figure 3. Mean time to retrieve information to answer questions correctly for both the Pie and Bar Chart visualizations. Error bars are the standard errors of the means.

The results also showed significant main effects for Question Type ($F(3,33) = 57.10$, $p < 0.001$) and Number of Parameters ($F(2,22) = 26.20$, $p < 0.001$). These results should be interpreted in light of a significant interaction. Participants' mean response time significantly differed between Question Type as a function of the Number of Parameters ($F(6,66) = 3.18$, $p = 0.045$; Figure 4). Post-hoc Bonferroni t-test results indicated that response time was significantly longer for Question Type #4 (comparison of parameter priorities) than that for the other three question types (all $p < 0.01$). Also, for all question types, mean response time was faster when there were only three parameters depicted in the chart, compared to the seven parameter condition. This result was significant ($p < 0.020$) for three of the four question types (for Question Type #3, count of parameters with errors/warning, $p = 0.080$). There were no significant mean response time differences for tests comparing trials with 3 parameters and 5 parameters, as well as 5 parameters and 7 parameters (all $p > .10$).

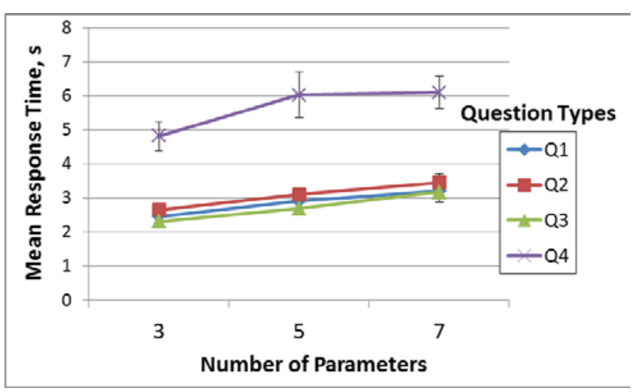

Figure 4. Mean response time for each question type as a function of the number of parameters depicted in the charts. Error bars are the standard errors of the means.

Subjective Data. The results for two items in the Post-Block Questionnaire were aligned with the performance data. Participants' responses on these 5-point rating scales indicated that it was easier to determine the state of a particular parameter as well as the type of warning/error state with the Bar Chart compared to the Pie Chart (respectively, $t(11) = 3.02$, $p = 0.01$ and $t(11) = 2.69$, $p = 0.02$). In contrast, responses to most questions in the Final Debriefing Questionnaire did not significantly differ between the two chart formats: neither format was rated significantly better than the other in terms of speed, accuracy, and general ability in retrieving information to answer the test questions. The only statistically significant finding was in an item addressing information retrieval as a function of the number of parameters. Participants rated the two formats as equal when there were only 3 parameters ($D(12)=.4$, $p<.05$). In contrast, their ratings indicated a slight preference for the Bar Chart format over the Pie Chart when there were 5 or 7 parameters.

Discussion

The results provide empirical support that participants performed better when using the Bar Chart as compared to the Pie Chart. These results are consistent with the results of Cleveland and McGill's (1985) study on basic graphical perception tasks. Though accuracy was extremely high for both chart formats, participants were able to respond more quickly with the Bar Chart. The high level of accuracy might suggest that the questions participants were tasked with answering were relatively easy. Despite this ceiling effect, the fact that there was still a statistically significant difference in participants' mean response time between the Pie and Bar Charts suggests that this difference would likely increase with more difficult questions.

In addition to performing better with the Bar Chart, participants also preferred this visualization method over the Pie Chart for retrieving data when there were five or seven parameters. (Questions were easier to answer in the three parameter condition, explaining why there was no significant difference in response preference). A review of the participants' comments suggests, though, that each chart format had specific advantages. Some participants liked that the Pie Chart was condensed and found the format more intuitive and aesthetically pleasing. Other comments indicated that the Bar Chart format provided a consistent orientation and position of each parameter as well as more separation between parameters. This may explain why some participants said the Bar Chart made it easier to locate parameters and gather a mental picture of parameter state. Another advantage was that comparing parameters was easier since "low" was always on the bottom. Also, the Bar Chart was better to view parameters that were small in value, compared to small Pie Chart slices. One participant summarized the advantages of both chart formats, stating "Pie seemed more aesthetically pleasing than the bar, but the bar seemed ultimately more effective."

The visualization methods examined in this study were designed to enable future UV operations to benefit from automatic monitoring technologies under development, providing the operator near real-time status of a UV plan in progress. It has also been proposed that a similar format be used for autonomy systems to convey one or more *proposed* UV mission plans that the operator should consider. In this manner, the autonomy can illustrate several plans, showing their tradeoffs with respect to different plan parameters. However, employing a Bar Chart similar to that used in the present experiment for each proposed plan would require considerable display space and complicate information retrieval.

For comparison of multiple autonomy-generated plans, the Air Force Research Laboratory has designed a candidate visualization that provides a more concise summary of multiple parameters for multiple plans. With this new Plan Comparison Chart (illustrated in Figure 5; similar to a parallel coordinates plot), each parameter is assigned a column. Parameters are ordered by the priority set for the high-level task (the most important is the leftmost; parameter priorities are represented by column widths). Each of the three plans (A, B, and C) is assigned a unique color and letter. The quality of each plan for specific parameters is mapped onto parameter columns. For example in Figure 5, Plan B is the best plan to use to maximize ETE and Plan C is the best plan to maximize dwell time. Parameter columns are normalized and the yellow and red dashed lines represent threshold levels. This approach depicting multiple plans is under evaluation, as well as other novel displays for transparency into autonomous systems and intuitive interaction methods to support bi-directional human-autonomy dialog.

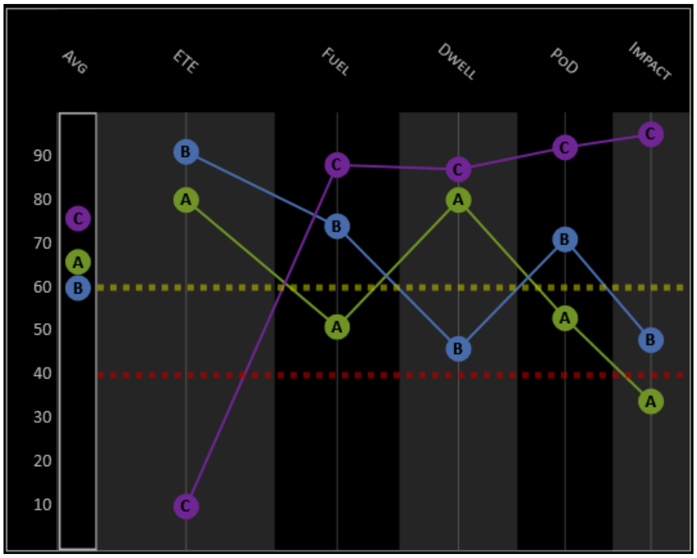

Figure 5. Illustration of Plan Comparison Chart prototype designed and under evaluation by the Air Force Research Laboratory to display the tradeoffs of multiple mission related parameters for multiple autonomy-generated vehicle plans.

Acknowledgements

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