VISUALIZING OPERATORS’ COGNITIVE STRATEGIES IN MULTIVARIATE OPTIMIZATION

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The proposed “Tracking Resource Allocation Cognitive Strategies” tool (TRACS) allows for post-hoc visualization of the cognitive steps exhibited by a human operator while interacting with a multivariate resource allocation decision-support interface. This tool was applied to both mission planning for multi-criteria resource allocation for military strikes, and also multi-variable geospatial path planning problems for astronaut moon traversals. Both domains involve a human operator interacting with an automated decision-support system in order to find a solution to a complex planning problem involving multivariate and constrained optimization for a cost function. With the help of TRACS, clear patterns of behavior were identified that could be correlated to performance in both applications.

INTRODUCTION

Tracking cognitive strategies of an individual using a decision support system provides insight into a user’s interpretation, approach, and resultant actions in a task. The study of cognitive strategies also potentially provides important information on how training, procedures, or user interface design affects task performance. In order to track and assess these cognitive strategies, we propose a tool, TRACS (Tracking Resource Allocation Cognitive Strategies) that provides a visual representation of a user’s decision-making processes while interacting with a multivariate optimization-based decision-support system. TRACS depicts transitions in a user’s thought process and actions, or mode changes, allowing for identification and evaluation of where individuals spend cognitive resources. Because TRACS is a standardized representation of an individual’s cognitive strategy, it can be used to compare strategies between different users performing the same tasks, or to compare strategies across different interfaces.

In this paper, we describe TRACS development and its implementation for operators using automated decision support in multivariate resource allocation and geospatial path planning problems. Such optimization problems require that human operators integrate different sources and types of information at different levels of certainty in order to find solutions that satisfy not only constraints, but also overall mission objectives and goals.

INITIAL DESIGN

TRACS was designed to reflect both the cognitive steps and types of information operators typically use in computer aided problem-solving. These general steps and information types are assigned to two separate axes (Figure 1). The first axis, named “Mode” represents the cognitive steps or action types a user can perform to solve a particular problem. In the case of a multivariate resource allocation problem, these steps can include “browse”, “search”, “select”, “filter”, “evaluate”, “backtrack”, “automatch” or “update”, which all represent key actions in such a decision-making process as determined by the specific task. The second axis, named “Level of Information Detail” (LOID), represents the information types that could be accessed by an operator. The LOID axis is divided into two sub-axes: one for data and one for criteria (the rules used to solve the problems). Within each sub-axis, items are ordered to reflect the level of abstraction of the information. The criteria sub-axis features “individual criterion” and “group of criteria”. The data sub-axis features “data item”, “data cluster” (a collection of data items with one common characteristic), “individual match” (a pair of matching data items, according to the search criteria), and “group of matches” (a cluster of individual matches).

Figure 2 depicts an example cognitive strategy. The underlying assumption of this tool is that each of the user’s mouse clicks within the system is considered an action and corresponds to one specific cognitive step and information type. For each click on the interface, a circle is added to the representation in the cell corresponding to the cognitive step, i.e., Mode and LOID. If this cognitive step is a repeated action, the circle’s width is increased. Circles are connected by lines when two states are visited in sequence. Similarly, the thickness of the lines increases every time one connection is performed. Essentially, the thickness of the connecting lines and circles’ width directly map to the number of times an action was repeated.

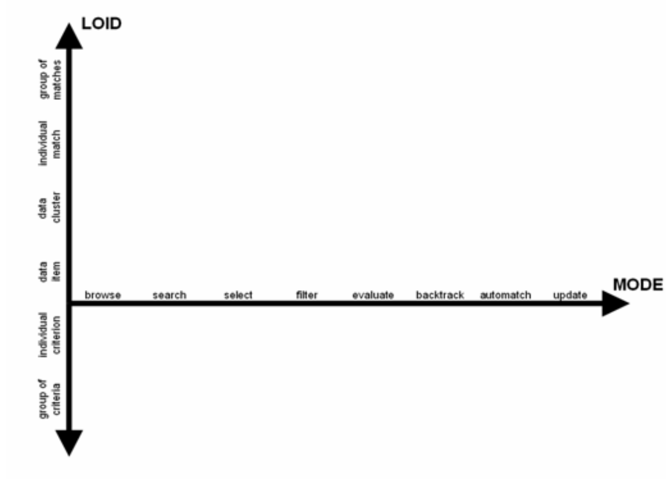

Figure 1: Initial TRACS framework axes

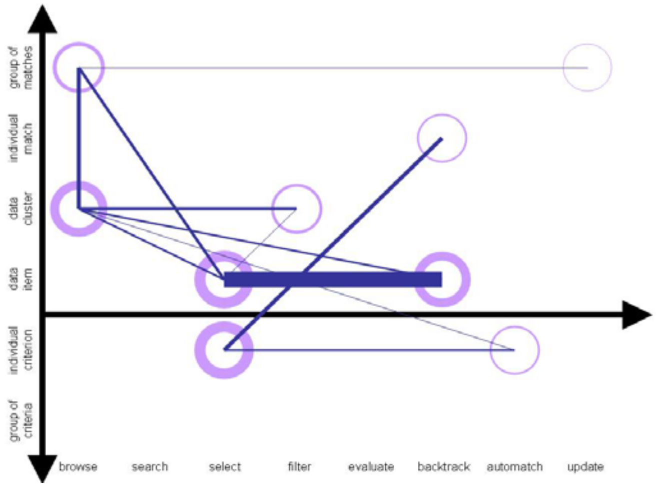

Figure 2: Example of cognitive strategy depicted using the initial TRACS framework

The TRACS visualization tool was initially developed to study collaborative human-computer decision-making in the complex, multivariate resource allocation problem of military missile strike planning. In this planning, the human operator was tasked to create a list of assignments of Tomahawk missiles to specific missions. The user had to match individual missiles with missions, taking into account numerous considerations such as optimizing cost functions, integrating probabilistic information, and satisfying various hard constraints (Bruni & Cummings, 2005; Bruni & Cummings, 2006).

An experiment was designed to test the relevance of different interfaces to perform the task (Bruni & Cummings, 2006). Several post-experiment visualizations were created; using video capture, users' interactions with the interfaces were tracked through the mouse clicks applied when solving the task. From these the cognitive steps were inferred, as represented by TRACS visualization. Clear differences across participants were observed. For example, Figure 3 and Figure 4 present the TRACS visualizations of two individuals who performed the same task with the same interface. One subject reached the best solution in less than 5 minutes (Figure 3), whereas the other subject, although coming within 5% of the best solution, took more than 20 minutes to complete the task (Figure 4). The difference in performance is illustrated in TRACS, as the subject who performed well shows a "clean" strategy based on four main cognitive steps: searching, selecting, and backtracking on data items, and selecting individual matches. The subject in Figure 4 who performed poorly (despite showing elements of that same strategy) presented an overall cognitive picture that is more nebulous. The secondary cognitive steps were more numerous: more browsing was performed (browsing of data items, data clusters and groups of matches) and more manual filtering happened (filtering data clusters). In addition, extra steps appeared for this subject: backtracking on group of matches (typically on a computed solution), and most importantly the use of automatch, computed solutions based on a heuristic search algorithm. It also appears that the sequence (the order in which cognitive steps follow each other) was not as rigorous for the latter subject. Contrary to the earlier representation where a clear set of steps was characterized (Figure 3), the TRACS visualization of Figure 4 illustrates a disorganized succession of steps.

During the post-experimental debriefing, the subject of Figure 4 explained that she had no idea how to solve the problem and tried several different strategies without any apparent goal. TRACS clearly shows the problem faced by the user: she continuously navigated between the two techniques of creating a solution manually (using the main steps identified in Figure 3) and of leveraging the automated tools (characterized by the filtering and automatch steps). Mixing those two strategies was not efficient in terms of performance.

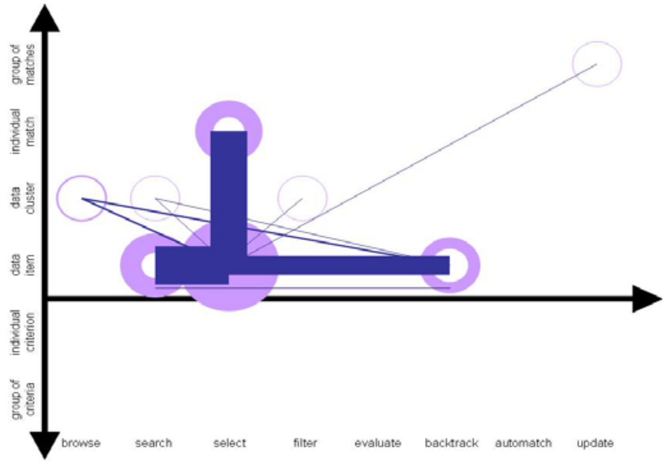

Figure 3: Example of strategies visualized using TRACS, which resulted in good performance

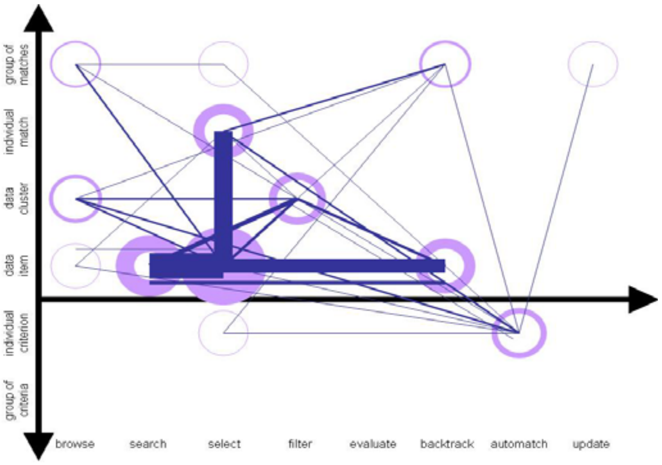

Figure 4: Example of strategies visualized using TRACS, which resulted in poorer performance

In addition to helping assess or understand performance, TRACS allows for the identification of the features used by the users, specifically the extent to which automation was used in their strategies to solve problems. Figure 5 shows the strategies of a subject who only used the manual features of the interface. The mapping of these cognitive steps is restricted to just the upper left corner of the TRACS visualization. In contrast, Figure 6 shows the visualization for a subject who used the automated features of the interface, which transfers into cognitive steps located in the lower right corner of the TRACS visualization. These examples show how the TRACS visualizations enable the easy recognition of the automation levels accessed by the operators.

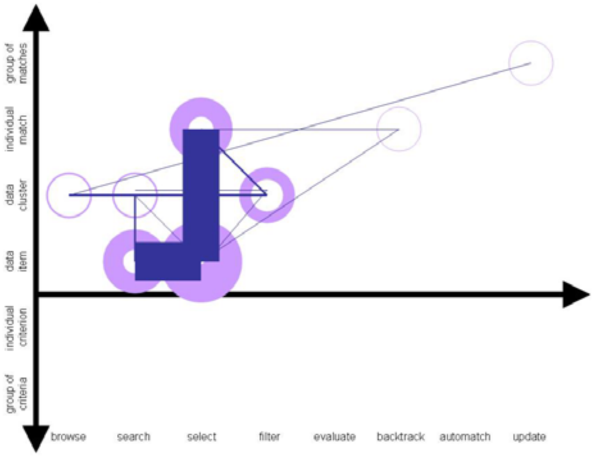

Figure 5: Example of strategies visualized using TRACS, at a low level of automation (manual)

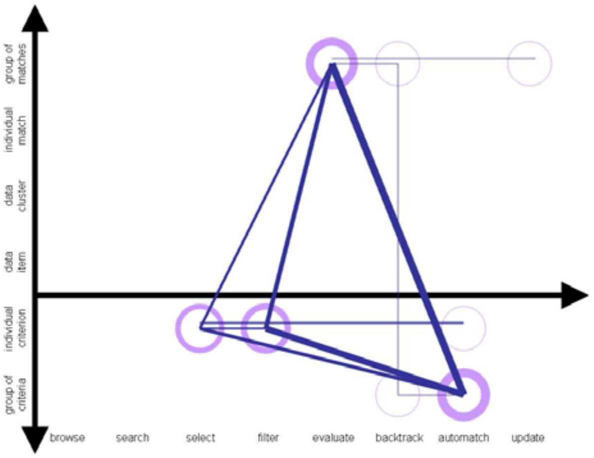

Figure 6: Example of strategies visualized using TRACS, at a high level of automation

TOWARDS A BROADER FRAMEWORK

After visualizing TRACS within the mission-missile resource allocation problem, the framework was improved upon in order to make the tool more applicable to various domains. The first step was to modify the axes representations to make them more generic. The LOID axis was changed to range from specific to aggregate information, thus representing less abstract information to more abstract information. Similarly, the Mode axis regroups the actions into two categories: 1) modes that describe obtaining solutions, and 2) modes that describe evaluating solutions. The intersection of the LOID and Mode axes was chosen as the end-point of all strategies, where the user makes the final decision. This broader TRACS framework is shown in Figure 7, where the upper half of the LOID scale (above the Mode axis) describes actions undertaken with more automation assistance, while on the bottom half, the actions are manual and involve less automation. Both halves order information from low level details to high level aggregation. This is consistent with the original TRACS layout, enabling rapid recognition of levels of automation.

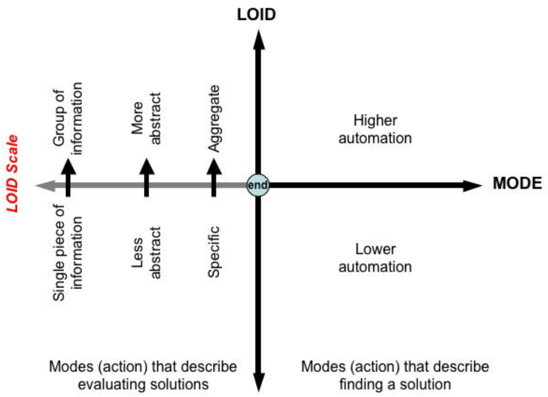

Figure 7: TRACS, Version II

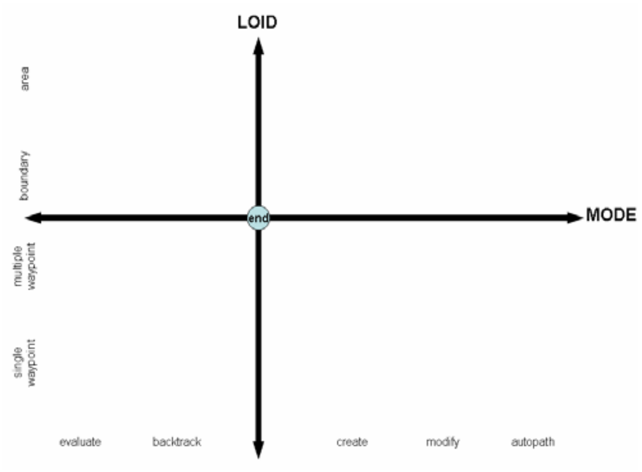

Figure 8: TRACS II, applied to geospatial problem solving

Once reformatted, TRACS was applied to assess cognitive strategies implemented during a geospatial problem solving task of path optimization for astronaut traversals during Moon or Mars exploration (Figure 8). A path planner interface was developed that inputs start and goal locations, a critical way-area, a terrain map with obstacles, and a cost or objective function to optimize. In an experiment, participants were asked to create least-costly paths that pass through the critical way-area. Costs were based on the objective function, such as distance or optimal lighting conditions. Participants planned paths either manually (entering waypoints), or leveraged an automated path planner, which automatically plotted portions of a least-costly path (Marquez, Cummings, Roy, Kunda, & Newman, 2005).

The first step in applying TRACS to this case was to adapt the axes to the specific path planner interface (Table 1 and Table 2). For both resource allocation and geospatial problems, evaluation modes were identified as “evaluate” and “backtrack”. For the geospatial problem of low-cost path planning, “browse” and “search” were not relevant as participants were asked to make paths. “Create” and “modify” modes were analogous to the resource allocation “select” and “filter” modes, and automatch was replaced with autopath. In keeping with the broader implications of the LOID scale, information types were identified for the geospatial problem, which included “area”, “boundary”, “multiple waypoints”, and “single waypoint”. The first two relate specifically to the higher automation actions and the critical way-area.

Generalized Mode Axis	**Geospatial Problem**
Evaluate	Evaluate
Backtrack	Backtrack
Browse	Not applicable
Search	Not applicable
Select	Create
Filter	Modify
Automatch	Autopath

Table 1: TRACS modes for geospatial path-planning problem

Generalized LOID Axis	**Geospatial Problem**
Data Item	Single Waypoint
Data Cluster	Multiple Waypoints
Individual Match	Not applicable
Group Match	Not applicable
Individual Criterion	Boundary
Group of Criteria	Area

Table 2: TRACS LOID for geospatial path-planning problem

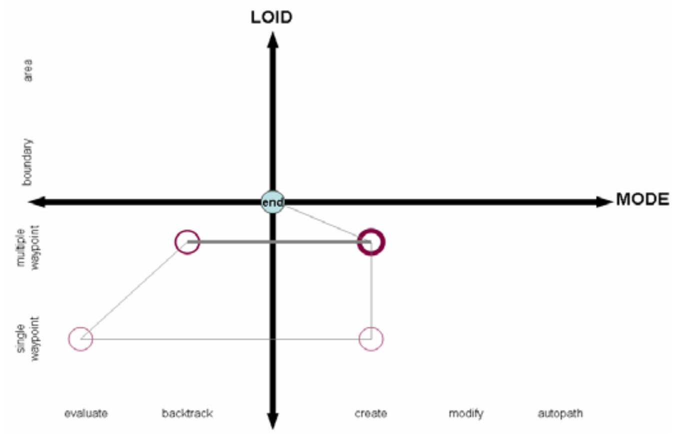

Figure 9: Example of TRACS visualizations for a geospatial problem with good performance.

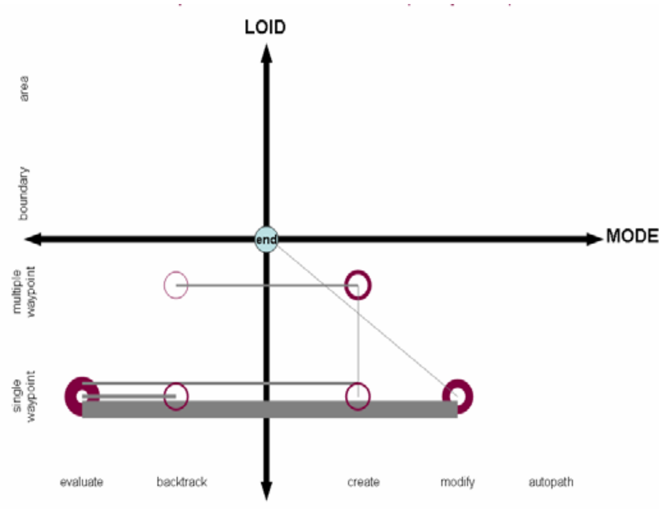

Figure 10: Example of TRACS visualizations for a geospatial problem with poor performance

The TRACS framework, though initially developed for resource allocation problems described previously, was successfully implemented for geospatial problem solving, resulting in similarly interpretable visualizations. Examples of TRACS visualizations for the geospatial path-planning problem can be seen in Figure 9 and Figure 10. Figure 9 shows a subject that performed well, with small path cost errors and relatively short task time completion (making a low-cost path). Figure 10 shows a subject who performed poorly, with large path cost errors and longer task completion time. Upon inspection of the TRACS visualizations, it is clear the subject who performed worse spent significant time attempting to optimize with small changes on a single waypoint. This strategy was repeated continually, graphically depicted with a thick connecting line between “evaluate” and “modify” within the single waypoint. While the better performing subject did use this strategy briefly, he spent more time making overall paths instead of minute changes, the ineffective strategy used by the poorer performing subject.

DISCUSSION

In both of the presented multivariate optimization problems, the TRACS visualization depicts that prompt, near-optimal performance is characterized by clear, well-defined strategies. For participants who performed well (Figure 3 and Figure 9), their strategies were straightforward and constrained, meaning they selected and repeatedly applied a small set of cognitive steps that minimized display overhead. In contrast, Figure 4 and Figure 10 depict the result when participants chose a poor strategy that did not include a correct stopping rule, resulting in poor performance. Moreover, participants who had ambiguous cognitive strategies (Figure 4), tended to be “all over the place” in their attempts at solving the problem, often employing multiple sub-optimal strategies in a disorganized manner. In general, TRACS visualizations helped identify cognitive strategies that lead to good and poor performance. Furthermore, these strategies are easily identifiable by shape (e.g., the inverted T in Figure 3, or the trapezoid in Figure 9). By searching for organization and shapes in a TRACS representation, we can see if participants were deliberate and methodical in their approach to a task, i.e., if they had a dominant cognitive strategy that guided them correctly through their task. Although this is not a definite indicator of good performance (in current TRACS versions), a clearly defined cognitive strategy shows user understanding of a task and an interface.

FUTURE DEVELOPMENTS

One of the limitations of TRACS is that the modes and actual levels of information detail are tied to particular aspects of the task and interface used for problem solving. This can be readily seen in the extension of TRACS for geospatial problems from the original design for resource allocation. For example, TRACS for geospatial problem solving does not include the mode of “browse”. This does not mean that participants did not “browse” their potential solutions, but rather that the interface was designed in a manner that did not allow the tracking of browsing through user mouse clicks. Thus the LOID and Mode axes capture the information types and actions undertaken with a particular decision support aid, and must be modified for every different interface and possibly task. Nevertheless, this is also a strength of the TRACS framework in that it is adaptable to different problems, regardless of interface. The TRACS framework, however, can only be applied to interactive interfaces with recordable human manipulation, and cannot be utilized with interfaces used solely in monitoring tasks.

While we have demonstrated TRACS implementation for two different optimization problems, resource allocation and geospatial problems, in the future, it will also be applied to scheduling problems. In particular, TRACS will be applied to the problem of scheduling multiple time-critical events in a high-pressure environment. This will entail adding a third independent axis in the TRACS framework for the time component, resulting in a 3D visualization. The incorporation of time is necessary when capturing cognitive behaviors in time-critical or time-sensitive tasks or environments, as human behaviors may change under time pressure. Additional future uses of TRACS include the application to other problems such as time-sensitive targeting, collaborative team planning, or command organizational structure.

TRACS could also be used to evaluate the effectiveness of interfaces. The framework has the potential of revealing flaws or strengths of an interface based upon the documented strategies a user implements in performing a task. By comparing the cognitive strategies across users, designers could potentially identify the pitfalls created by their interfaces which hinder operator task comprehension and performance.

Until now, all TRACS visualizations have been post-hoc, i.e., after the experiments. This was accomplished by reviewing screen captures of users with their corresponding decision support aid. Future development of TRACS will involve real-time incorporation of the visualization as the subject is using decision-support automated assistance. TRACS could be presented to the experimenter during the experiment session to notify them of the subject’s cognitive strategy, progress, and understanding of the task. Moreover, the tool could be used directly in training for the task or during experimental scenarios. Lastly, in the near future, TRACS will not only be a tool for behavior monitoring and understanding, but also a basis for the development of predictive models of human behavior.

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