The Limits of Multiple Resource Theory in Display Formatting: Effects of task integration

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Abstract

Multiple Resource Theory proposes that multi-variable displays will be better processed when information is presented in several different display formats (i.e., verbal, spatial, visual, auditory). We argue here that this superiority of separate formats does not hold if the displayed elements are correlated or must be integrated into a single mental model. We report two experiments that confirm this hypothesis: In experiment 1, subjects monitor two numerical displays. If the Task calls for separate independent decisions concerning the value of each display, performance is best when one is spatial (analog) and the other verbal. If the task calls for integration of both displays into a common decision rule, performance is best when homogeneous display formats are used. In experiment 2 subjects monitor the display of several dynamic elements that compose a dynamic system. Performance is found to be better if these correlated elements are integrated into a configural "object" display, than if they are displayed as separate bargraphs.

Introduction

The concept of multiple resource theory has been proposed as a guideline to formatting displays for complex multi-task systems (Wickens, Sandry & Vidulich, 1983; Wickens, 1984ab). According to this theory the human operator possesses separate processing resources or capacities related to auditory and visual input, and to the processing of spatial and verbal material. Hence the time-sharing efficiency of several tasks will be better if the information for the tasks is displayed using these different formats, than if all information is concentrated within one format. For example, efficiency will improve if the information for one task is displayed visually while that for the other is auditory. In a more general sense the guidelines of multiple resource theory predict that time-sharing efficiency will be greater the farther apart" the two tasks are displayed in some functional space defining human processing capacities.

While the multiple resource guidelines have been well confirmed for displaying information for two separate and independent tasks, the question addressed in the present paper is whether these guidelines also hold when information from two tasks must be integrated into a single "mental model." As an example of different sources of information that must be integrated consider the X, Y & Z positions of several aircraft in an Air Traffic Control display. It is imperative that the Air Traffic Controller maintain a single mental model of the relative position of all aircraft in the airspace in order to control effectively. In this case it is unlikely that best performance would be obtained when information is distributed across the multiple resource space. Instead, performance should be best when all information is presented via the visual-spatial format (Wickens & Boles, 1983). We report here two experiments that investigate this issue in greater detail.

Experiment 1: Integration of Numerical Information

Method. The purpose of experiment 1 was to determine if the requirement to integrate two numerical indicators, rather than to process them separately, increased the advantage of employing common display codes (i.e., both verbal or both spatial). Twenty-four subjects were presented a series of number pairs. The pair could be displayed in either of three formats shown across the top row of figure 1. In the Heterogeneous format, shown above the left column, one numerical value was indicated by the vertically printed digit name, and the other by a bar graph (either could range in value from 1 to 10). In the two homogeneous formats to the right, the numerical information was presented either as a pair of spatial bar graphs or a pair of verbal digits. Three groups of eight subjects were randomly assigned to one of three tasks to be performed on the digit pair. These tasks are listed down the left edge of figure 1. At the top, the BOTH task was essentially a dual task pair. Subjects had to judge if one number was greater than 5 and if the other was an odd number, and indicate the response to each task with a separate button press. The nature of the two responses are shown in the cells of figure 1.

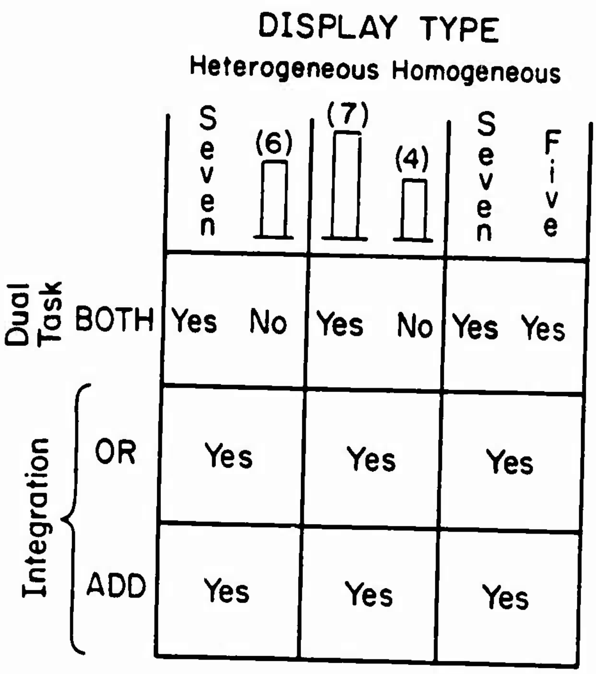

Figure 1: The 3 tasks and 3 display types used in Experiment 1. The nature of the response(s) is shown within the cells of the matrix. The digit over each bargraph representing its value was not present in the actual display

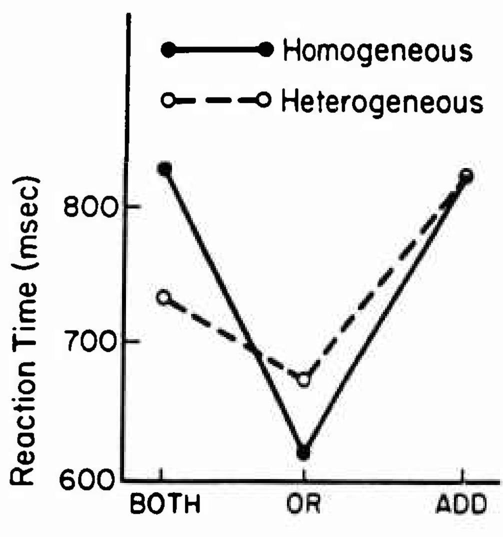

Figure 2: Results of Experiment 1 (averaged over the 2 homogeneous display types).

The bottom two tasks required integration. The OR task required the subject to judge if either digit was greater than 5. The ADD task required the subject to sum the two digits and indicate with a single response if the sum was greater than 10. According to the predictions of multiple resource theory, performance on all three task configurations should be best with the Heterogeneous display configuration, since this configuration distributes the load across verbal and spatial resources. On the other hand the modification of the theory proposed here predicts that this heterogeneous advantage should hold for the BOTH task, but not for the integration ADD and OR tasks.

Results and Discussion. The latency to respond to the stimuli as a joint function of display format and task are shown in figure 2. The data for the two homogeneous display combinations have been averaged, and for the BOTH task only the latency for the first of the two responses is indicated. Figure 2 indicates the predicted interaction of display homogeniety and task type ($F_{2,18} = 9.34$, $p = .002$). Decomposition revealed the "crossover" nature of this interaction. In the BOTH task the heterogeneous display generated faster performance as predicted by multiple resource theory ($p < .01$). In the ADD task this advantage evaporated, and in the OR task the homogeneous display combination produced reliably faster performance ($p < .01$). In summary the limitations of the multiple resource theory were confirmed in the predicted direction. The use of separate resources facilitated performance in a dual task situation, but had either no effect, or actually hindered performance when two information sources needed to be integrated or compared before a single response was made.

Experiment 2: Information Integration and the Object Display

Method. In experiment 1, "display proximity" was defined by use of the same display format for both information sources. Experiment 2 investigates the effect of proximity within a display format. All information is presented in analog visual format. However, we contrast a format in which information is displayed on a series of separate bar graphs (low proximity) with a format in which the display dimensions are integrated into a single polygon object, not unlike the iconic display used to present safety parameter information in nuclear power plants (Wood, Wise & Haines, 1981). The task confronted by the subject was to monitor two dynamic systems, each of which contained an output driven by two inputs. The systems were either additive ($O = aI_1 + bI_2$) or

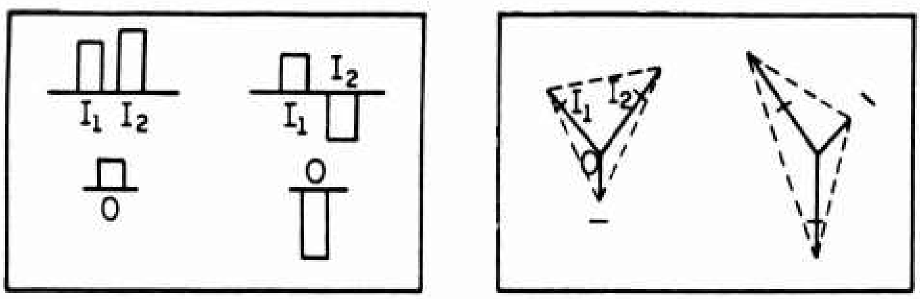

Figure 3: The two systems shown on the bargraph display (left) and on the polygon display (right). The short lines crossing each variable in the polygon display indicate the zero point.

multiplicative ($O = aI_1 \times I_2 + b$). Inputs were slow, semi-random functions uncorrelated with each other. The pair of systems presented on a given display were always both of the same type (multiplicative or additive), but each had different coefficients. Examples of the system pairs presented in each display format are shown in figure 3. At unpredictable intervals, one system or the other would fail. A failure occurred when one of the coefficients would gradually change its value, either increasing or decreasing to zero. The subject's task was to detect which system had failed.

For each system, the task therefore called upon the subject to integrate three sources of displayed information in order to compare these values against a single internal model of the dynamics of a correctly functioning system. As a consequence of this need for integration it was predicted that performance would be superior with the "closer" object display. Eight students at the University of Illinois received extensive briefing about the systems they were to monitor. They were shown the defining system equations, graphic representations of the relation between system variables, and examples of the systems in operation with the occurrence of failures indicated by supplementary visual signals. Following this training, a series of failure detection trials were performed across three sessions.

Results and Discussion. Because of the intrinsic nature of the ramp failures in which the dynamics change became progressively more salient as time went on, practically all failures were eventually detected. Hence the primary dependent variable of interest was latency. These latencies are shown in table 1. It is evident from these data that, as predicted, latency for this integrative type of task is reduced for the "holistic" polygon display relative to the separated bar graph display ($p < .05$). Latencies for the multiplicative systems were shorter than for the additive systems. The advantage of the object display was statistically the same for both system types.

	Additive	Multiplicative
Bargraph	5.1	4.4
Polygon	3.9	3.0

Table 1: Detection Latencies in Experiment 2 (seconds)

In interpreting these results, it is important to realize that the visual angle subtended by the two display formats shown in figure 3 was identical, as were the amplitude and velocity of the variable changes. Hence the advantage to the object display cannot be attributed to the fact that it required less visual scanning or gave rise to more salient display motion. Instead the advantage seems to reflect the greater configural characteristics that resulted when the variables were tied together by the object-defining contours. In terms of the general theory proposed at the outset, the fact that the external inputs were causally related by the system dynamics, and the fact that these variables needed to be integrated in a single mental model, to determine if the systems were functioning normally, produced superior performance when the elements were tied more closely together in visual space.

General Conclusions

Both experiments reported here obtained better performance in tasks requiring information integration when greater proximity between display elements was achieved. In experiment 1 proximity was directly defined in terms of shared processing codes of the multiple resource model. In experiment 2 it was defined in terms of the interconnectedness of display elements. These results in no way invalidate the multiple resource model, but only define limits to its applicability. For the dual task environment, as in the BOTH task of experiment 1, the model is still perfectly valid. Furthermore, the boundary conditions that define the limits can be specified a priori. Task integration defines formally a situation in which the optimal response to one stimulus or display variable cannot be specified without specifying the level of another variable. Models that prescribe optimal system design are rarely applicable under all circumstances. Once such models are developed it is necessary to specify their boundary conditions. The present research has attempted to perform this function.

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