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ABSTRACT: A theory-based approach for research on information displays in computer-supported decision making is proposed. Information display characteristics can influence the decision maker's selection of a cognitive strategy. Since the effectiveness of decision making depends, in part, on the strategy selected, knowledge about the display-strategy relationship can ultimately improve the quality of decision support by identifying displays that encourage the selection of effective strategies. Support for this approach is provided by a discussion of research on strategy selection, focusing on the cognitive effort and accuracy of decision strategies as components of a cognitive incentive system for decision makers. Relevant empirical research on information displays is reviewed and related to the cognitive cost-benefit approach. Methodological issues and proposed directions for information display research are discussed.

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1 Introduction

What is the best way to display information to decision makers? This issue is increasingly important because of the computer's ability to rapidly store, manipulate, and display information. As computers become common tools in a widening variety of decisions, it has become clear that characteristics of the computer system *itself* can influence the process of decision making. Researchers have proposed that the information display is an essential characteristic of all computer-based decision support systems and may be an important determinant of the effectiveness of those systems (DeSanctis, 1984; Ives, 1982; Zachary, 1986).

Previous research on information displays has largely been experimental in nature. Typically, subjects perform a decision making task using displays that differ on one or more factors related to: (1) the form of individual data items in the display, (2) the organization of display items in relationship to each other, or (3) the way in which information is arranged across multiple displays. Table 1 lists examples of display design issues that have been considered, along with representative citations. Dependent variables usually include some measure of performance quality or accuracy, as well as related measures like decision confidence or satisfaction.

While this has been an important and active area of research, clear conclusions about the impact of information displays on decision processes or the advisability of different display options have been slow to emerge (Jarvenpaa & Dickson, 1988; Jarvenpaa, Dickson, & DeSanctis, 1985). These authors cite several potential causes for these difficulties, including lack of underlying theory, problems with measurement reliability and validity, inappropriate research designs, and the use of diverse and incomparable experimental tasks (Jarvenpaa et al., 1985, pp. 142–145). In this paper, we focus on the first of these causes by proposing a cognitive mechanism that accounts for the impact of information displays on the decision maker's selection of a strategy for accomplishing the task.

The remainder of this paper is organized as follows: Section 2 describes how the concept of strategy selection can be used to explain the influence of information displays on decision processes. Section 3 reviews empirical evidence on the connection between information displays and strategy selection. Finally, Section 4 discusses some implications for research design and measurement and suggests directions for future research on information displays.

2 Theoretical Approach

In this paper, we will use the term "decision making" in the broadest possible sense: Decision making takes place in a number of different situations that we will refer to as *task environments*, namely environments linked with a goal (or task). This goal or task defines the nature of the problem confronting the individual (see Newell & Simon, 1972, ch. 3). We view decision making as encompassing a large number of possible tasks, including (1) choice under conditions of either certainty or uncertainty, (2) evaluative judgment, (3) predictive judgment. and (4) inferential judgment (see Einhorn & Hogarth, 1981, for a discussion of the relationship between judgment and choice). This perspective emphasizes the importance of the structure of the task environment and its influence on the information processing strategies that individuals use to accomplish the task. A *strategy* is a sequence of information processes that is intended to achieve the goal. In general, there are many possible strategies for performing any given task. Further, the set of strategies available for one task is generally different than that for another task. For example, strategies used for evaluative judgment have been found to differ substantially from those used for choice (Schkade & Johnson, in press; Tversky, Slovic, & Kahneman, in press).

Research on decision making has emphasized the adaptive interaction of the decision maker with the task environment: Decision makers use many different information processing strategies (e.g., Svenson, 1979) and adapt to changes in the task environment by switching strategies (Payne, 1982). One explanation for this behavior is that decision makers engage in a form of cognitive cost-benefit analysis: Strategy selection is the product of a trade-off between various positive and negative dimensions of alternative strategies for a task. Different strategies are selected in response to changing task characteristics if the values of these strategy dimensions change. A generalization of this cost-benefit view is to formulate the strategy selection process as a *metadecision* problem, in which one "decides how to choose" (Einhorn & Hogarth, 1981, p. 69). Thus, each decision strategy can be viewed as a multidimensional object, with the dimensions corresponding to the associated costs and benefits.

Our approach focuses on two particular dimensions of strategies: (1) the cognitive effort required to use a strategy, and (2) the ability of a strategy to produce an accurate ("correct") response. Strategy selection can be analyzed as

Table 1: Some Display Design Issues

- **Should information be presented as numbers or words?** Bell, 1984; Huber, 1980; Stone & Schkade, 1989; Wallsten et al., 1986

- **Should information be presented in tables or graphs?** Benbasat & Dexter, 1985, 1986; Benbasat, Dexter, & Todd, 1986a, 1986b; Benbasat & Schroeder, 1977; Carter, 1947; DeSanctis & Jarvenpaa, 1987; Dickson, DeSanctis, & McBride, 1986; Feliciano, Powers, & Bryant, 1963; Ghani & Lusk, 1982; Grace, 1966; Lucas, 1981; Lucas & Nielsen, 1980; Lusk & Kersnick, 1979; Painton & Gentry, 1985; Phelps & Shanteau, 1978; Powers et al., 1984; Remus, 1984, 1987; Tullis, 1981; Umanath & Scamell, 1988; Vernon, 1946; Washburne, 1927; Watson & Driver, 1983; Zmud, 1978; Zmud, Blocher, & Moffie, 1983

- **If graphical representations are chosen, what type should they be and what embellishments should be incorporated?** Cleveland & McGill, 1984; Croxton & Stein, 1932; Croxton & Stryker, 1927; Keller, 1985; MacGregor & Slovic, 1986; Simkin & Hastie, 1987; Schutz, 1961a, 1961b; Tversky & Gati, 1982; Washburne, 1927

- **How should color, highlighting, underlining, or other display features be used?** Benbasat & Dexter, 1985, 1986; Benbasat, Dexter, & Todd, 1986a, 1986b; Tullis, 1981

- **Is the order of presentation important?** Einhorn & Hogarth, 1985; Russo & Rosen, 1975

- **What information should be presented so that it will be read first?** Plott & Levine, 1978; Tversky & Sattath, 1979

- **Should information be presented simultaneously or in sequence?** Bettman & Kakkar, 1977; Bettman & Zins, 1979; Biehal & Chakravarti, 1982; Russo, 1977; Russo, Krieser, & Miyashita, 1975; Russo et al., 1986

- **Should information on different displays be presented in standardized or unstandardized formats?** Bettman, Payne, & Staelin, 1986 the product of a trade-off between the desire to maximize the likelihood of producing a correct decision and the desire to minimize the expenditure of cognitive resources. In this section, we first discuss the roles of effort and accuracy in strategy selection, and then propose that these concepts can be used to analyze the impact of information display options on strategy selection.

2.1 Effort and Accuracy in Strategy Selection

Accuracy has typically been defined relative to a criterion such as a normatively appropriate (optimal) response or some other relevant benchmark (Einhorn & Hogarth, 1981, pp. 55–61; Hogarth, 1981; March, 1978; Simon, 1978). Effort has typically been defined as the total expenditure of cognitive resources required to complete the task, as reflected by measures like total decision time or total number of cognitive operations (Johnson, 1979; Kahneman, 1973; Russo & Dosher, 1983). Since both the accuracy and effort associated with a strategy may vary with changes in task characteristics, different strategies will provide the best trade-off in different situations (Beach & Mitchell, 1978; Bettman, Johnson, & Payne, in press; Christensen-Szalanski, 1978, 1980; Johnson, 1979; Johnson & Payne, 1985; Klayman, 1983; Payne, 1976; Payne, Bettman, & Johnson, 1988; Russo & Dosher, 1983; Shugan, 1980; Thorngate, 1980; Wright, 1975). Factors other than accuracy and effort may also influence strategy selection (e.g., justifiability, awareness of conflict; see Beach & Mitchell, 1978).

Accuracy and related concepts, such as decision quality, have a well established place in the study of decision making. In contrast, while cognitive effort has played an important role in other areas of cognitive psychology, it has only recently been introduced to decision making research. Concepts like reduction of cognitive strain and conservation of cognitive resources have been used to account for performance in simple cognitive tasks like concept formation (Bruner, Goodnow, & Austin, 1956), mental arithmetic (Dansereau, 1969), and selective attention (Kahneman, 1973). These concepts have been extended to more complex tasks like problem solving (Newell & Simon, 1972; Simon & Hayes, 1976) and, recently, decision making (Payne, 1982). Seemingly minor variations in characteristics of task environments can lead to dramatic variations in the time required to use a particular strategy. For instance, Dansereau (1969) found that completion times in a simple mental arithmetic task can vary by a factor of as much as 100 across apparently similar problems. In a more complex problem solving task, Kotovsky, Hayes, and Simon (1985) found that completion times for isomorphic versions of the same problem can vary by a factor of as much as 16.

Although this is a relatively new area for decision making research, the existing empirical evidence on strategy selection can be summarized by several working assumptions about the roles of effort and accuracy. Five assumptions will be discussed in turn:

Working Assumption 1: The effort and accuracy associated with various strategies are uncertain quantities and must be estimated by decision makers. Strategy selection is a subjective process, based upon a decision maker's perceptions of effort and accuracy (Beach and Mitchell, 1978). One source of uncertainty may be unpredictability or ambiguity in the task environment. Limitations in the decision maker's knowledge or experience may also contribute. This problem is likely to be most pronounced when the task is unfamiliar or after unexpected changes in the task environment have occurred. Thus, strategy selection depends upon *anticipated* effort and accuracy.

Working Assumption 2: Decision makers are generally better at estimating effort than accuracy. It is not surprising that decision makers often have difficulty learning about accuracy, since many environments provide outcome feedback that is incomplete, ambiguous, and subject to long delays (Einhorn, 1980; Einhorn & Hogarth, 1978). Learning about accuracy can even be difficult in the presence of complete and accurate outcome feedback (Brehmer, 1980). Johnson and Payne (1985) suggest that decision makers' self-knowledge concerning cognitive processes is likely to be much more complete with respect to effort than accuracy, since feedback about the ease with which the decision process was implemented is usually more immediate and readily interpretable than outcome feedback. Furthermore, since the criteria for accuracy can vary widely across different decisions, it may be difficult to accumulate comparable experiences about the accuracy of a given strategy. On the other hand, cognitive effort is probably easier to compare across decisions, because the subjective experience of expending cognitive resources (e.g., as reflected in the time required to make a decision) is similar from one task environment to the next.

Working Assumption 3: The nature of the trade-off between accuracy and effort is sensitive to the values of the decision maker and characteristics of the task environment. Evidence clearly indicates that strategy selection is sensitive to considerations of both accuracy and effort (Payne et al., 1988). However, there is also evidence to suggest that decision makers place relatively greater emphasis on minimizing effort than on maximizing accuracy (e.g., Russo & Dosher, 1983). This emphasis could be due in part to the greater availability of knowledge about effort, mentioned above (i.e., decision makers pay more attention to effort because they know more about it). The trade-off between effort and accuracy may simply reflect the payoff structure in the environment: In some situations, errors are perceived to be very costly (e.g., medical diagnosis), while in others, they are not (e.g., purchasing coffee). Thus, a decision maker's willingness to expend additional cognitive effort will depend on the size of the perceived benefit to be derived from fewer errors.

Differences in the relative emphasis placed on effort and accuracy may also reflect the fact that in many tasks, either accuracy or effort is relatively insensitive to the choice of strategy. For instance, in very complex dynamic decision making tasks, simple strategies often provide good approximations to the accuracy of optimal strategies while conserving effort (Hogarth, 1981; Kleinmuntz, 1985). In situations where strategies have uniformly high accuracy, effort considerations are likely to have greater impact on strategy selection. The opposite effect might be expected in very simple tasks, where additional effort required to implement very accurate strategies may be a minor consideration (Payne, 1976). When effort is uniformly low, accuracy considerations should loom larger. Thus, effort or accuracy will influence strategy selection only to the extent that one or the other differs across strategies.

Working Assumption 4: In some circumstances, human information processing limitations can make some strategies infeasible. Processing limitations are caused by the small capacity of short-term memory and the serial nature of information processing operations (Simon, 1981, ch. 2). Tasks of sufficient complexity may overwhelm these limited capabilities. For example, if a choice problem involves a large number of alternatives and attributes, relatively simple strategies may be adopted not out of choice, but out of necessity (Payne, 1976). Similarly, if the decision must be made under time pressure, some strategies may not be able to reach a decision within the allotted time (Payne et al., 1988; Wright, 1974). In circumstances such as these, the upper bound on effort constitutes a constraint that must be satisfied irrespective of other dimensions of a decision strategy.

Working Assumption 5: The decision maker's knowledge and expertise influences strategy selection. One could assume that decision makers have a broad repertoire of standard decision strategies, and that strategy selection is merely a matter of determining which strategy happens to provide the best trade-off of anticipated effort and accuracy. Evidence on problem solving supports the notion that expert decision makers adaptively select strategies in this fashion (Larkin, McDermott, Simon, & Simon, 1980). However, in unfamiliar tasks, a decision maker's knowledge about strategies may be limited and only a subset of the available strategies considered (e.g., Kleinmuntz & Thomas, 1987). Another possibility is that the decision maker constructs new strategies as they are needed (J. Anderson, 1985, pp. 225–228; Luchins, 1942). Whether the end result of this process of constructing and testing strategies is consistent with the notion of trading off effort and accuracy is still very much an open question (for some interesting speculations, see Payne et al., 1988).

Our theoretical understanding of strategy selection is still being developed and modified. Some empirical findings on task effects have not yet been accounted for by this approach. For instance, Payne (1982) describes several experiments in which decision makers' responses to variations in problem presentation seem to be governed by basic principles of human perception rather than cost-benefit considerations. The best known phenomena of this type involve the shifts in preferences that are observed when the same problem is *framed* in different ways (Tversky & Kahneman, 1981; also see Kahneman & Tversky, 1979; Thaler, 1980, 1985). However, a cost-benefit approach appears capable of analysis and prediction of strategy selection across a variety of decision making situations. In particular, effort and accuracy have emerged as keys to understanding the relationship between task characteristics and the selection of decision strategies. Although a number of other factors can and do influence strategy selection, the way in which effort and accuracy change in response to variations in the task environment is crucial.

2.2 Information Displays and Strategy Selection

While many different characteristics of task environments can influence strategy selection, the information display deserves particular attention. The designer may have little or no control over other task characteristics, but the display options can be directly controlled. In contrast, the decision maker directly controls only the selection of strategy, while the display options, task characteristics, and even the decision maker's own knowledge are predetermined. Thus, the system designer can exert *indirect* control over strategy selection through *direct* control of display options.

A simple yet compelling demonstration of this indirect control was provided by Russo (1977), who was able to induce changes in purchase patterns in a supermarket through a simple reorganization of the display of product information. Specifically, he gathered unit price information on a single list that permitted shoppers to make less effortful comparisons than were possible while walking down the supermarket aisle. The observed result was a significant shift in purchases to products with lower unit prices. Although Russo's experiment did not use computer-based information displays, one can easily imagine a similar situation in which consumers could obtain product information entirely from a computer. In fact, product information may soon be routinely obtained from distributed databases and actual purchase decisions based in whole or in part on information derived from computer displays (e.g., via networks such as *Compuserve*).

A number of other studies, reviewed in the next section, also suggest that differences in the information display influence strategy selection because of changes in either the effort or the accuracy with which various information processing activities can be accomplished. Together with task characteristics and decision maker knowledge, the information display implicitly defines a *cognitive incentive system* for decision makers, comprising the cost-benefit dimensions discussed above. Specifically, differences in displays, task characteristics, and decision maker knowledge change the anticipated effort and accuracy of each available strategy and, therefore, provide an incentive for decision makers to use different strategies (see Figure 1). Presumably, a major source of decision maker knowledge is learning from previous experience, so that the experienced effort and accuracy of past decisions will influence subsequent anticipations.

How do differences in displays influence strategy selection? One way to think about this is to decompose strategies into sequences of simpler substrategies and then analyze the effects of displays on these components. For example, substrategies can be associated with distinct stages of the decision making process (e.g., information acquisition or evaluation; Simon, 1977), or more elementary cognitive operations (e.g., multiplication, comparison, retrieval from memory; Chase, 1978). We propose that the influence of display options on a strategy's effort and accuracy is the aggregate of the influences on each component substrategies' effort and accuracy.

To illustrate how differences in displays can influence a single substrategy or operation, imagine a decision maker who must choose a new computer system from a set of available alternatives. Each system is characterized by a set of features (e.g., price, ease of use, expandability, and speed). First, suppose that the information can be presented either one system at a time (i.e., the values of all features for a single system on the same screen) or one feature at a time (i.e., each screen contains the values of one feature for all systems). Consider a common substrategy like comparing the values of two systems on the same feature. The first type of display, organized around systems, does not present the two values simultaneously. This means that a comparison of this type will be more effortful than a comparison made with the second type of display, organized around features, in which the two values are displayed simultaneously (e.g., Bettman & Kakkar, 1977).

Now suppose that the system features can be presented either in a tabular display of numbers or in a set of graphical displays, like bar charts. Another common operation, reading the value of a particular feature for a particular system, can be accomplished with a relatively small chance of error when the information is presented in a table of numbers. In contrast, extracting a specific value from a bar chart is a more error-prone procedure because the decision maker must visually project the height of the appropriate bar onto the chart's scale (Simkin & Hastie, 1987). Thus, the accuracy of this substrategy will probably be lower for this type of graphical display.

The influence of display differences on the effort and accuracy of *substrategies* is important because strategies make use of particular substrategies to differing degrees. For instance, some strategies for choice require many comparisons across systems (e.g., majority of confirming dimensions or additive difference strategies) while there are other strategies that do few if any comparisons of this type (e.g., conjunctive or weighted additive strategies; see Svenson, 1979). Thus, changing displays in a way that makes this type of comparison easier would decrease the effort required for the former strategies more than for the latter. Similarly, choice strategies that use numerical calculations require many value extractions (e.g., weighted additive strategy), while many other strategies do not (e.g., the majority of confirming dimensions strategy requires no value extractions, while the elimination-by-aspects strategy requires a relatively small number of extractions). Thus, changing to a display that makes value extractions less accurate would affect the accuracy of the weighted additive strategy more than the others.

It is important to note that these effects will not exist in isolation. For instance, a single dis-

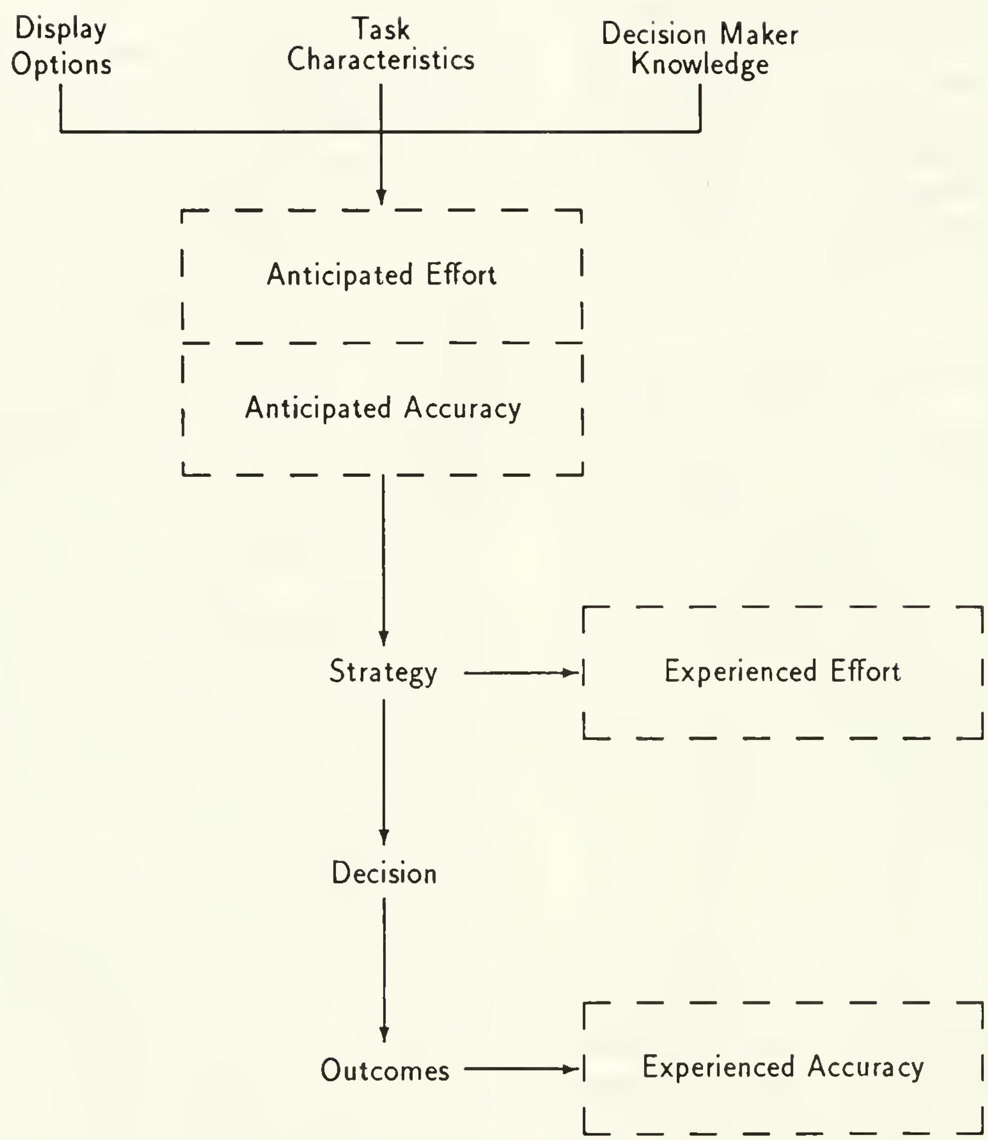

Figure 1: Overview of the Strategy Section Process

play change may influence *both* the accuracy and effort associated with a substrategy—value extraction from bar charts may be both less accurate and more effortful than from tabular displays (e.g., Carter, 1947). Furthermore, the support a given display provides to one substrategy or operation may be offset by the impact on another substrategy or operation: Switching from a table to a bar chart may make value extractions more difficult and less accurate, but on the other hand, recognizing trends or doing comparisons may become easier and more accurate (e.g., Vessey & Galletta, 1988). Thus, the impact of a particular display on a particular strategy is the product of the aggregate influence on all the component substrategies.

The effort-accuracy approach assumes that decision makers have learned over time about the aggregate effects of varying task characteristics on effort and accuracy. As display options are varied, the hypothesis is that the decision maker will adaptively choose strategies that are relatively efficient in terms of anticipated effort and accuracy (Payne et al., 1988, p. 550). To illustrate, consider the anticipated accuracy and effort of four hypothetical strategies with two different displays, shown in Figure 2. For instance, the points A and A' mark the accuracy and effort of the same strategy for the two different displays. Here, anticipated accuracy is scaled relative to the accuracy levels of optimal and random baseline strategies (e.g., utility maximization and random choice; adapted from Johnson & Payne, 1985). Similarly, anticipated effort is scaled relative to the effort levels required to implement the two benchmarks, with values plotted from most to least effortful.

Note that for display 1, strategy A *dominates* strategy B, achieving a higher degree of accuracy while requiring less effort. However, for display 2, A no longer dominates B—although B is still less accurate than A, it is now less effortful as well. More generally, for a particular display, strategies can be classified into two groups, dominated and nondominated. The nondominated strategies define a set of *efficient* alternatives—within this efficient set, increased accuracy can only be achieved by selecting a more effortful strategy, while reduced effort can only be achieved by selecting a less accurate strategy. Thus, under display 1, a decision maker who believes minimizing effort is more important than maximizing accuracy might prefer strategy C, while a decision maker who places more emphasis on accuracy might select strategy A. The composition of this efficient set will not necessarily be the same for different displays (e.g., the efficient set $\{A, C\}$ for display 1 versus $\{A', B'\}$ for display 2). Thus, the relative attractiveness of various decision strategies depends on the display, and decision makers should adapt to changes in displays by selecting different strategies.

Some authors have suggested that an appropriate display is one that "fits" the task (Benbasat, Dexter, & Todd, 1986b; DeSanctis, 1984; Jarvenpaa & Dickson, 1988; Jarvenpaa et al., 1985; Vessey, 1988). For instance, a graphical display might be appropriate for a pattern recognition task (e.g., detecting a trend), but inappropriate for a point-reading task (e.g, retrieving a specific value). These authors treat both task and display as independent variables and discuss the effect of matches or mismatches between them. Our analysis differs in an important respect: We assume that the task is held constant while treating the display and other task characteristics as independent variables. However, these two approaches are not necessarily incompatible: A display will "fit" a task to the extent that the efficient strategies for the task use substrategies that are supported by the display.

3 Empirical Evidence

What is the empirical evidence on the role of effort and accuracy in determining the connection between display options and strategy selection?

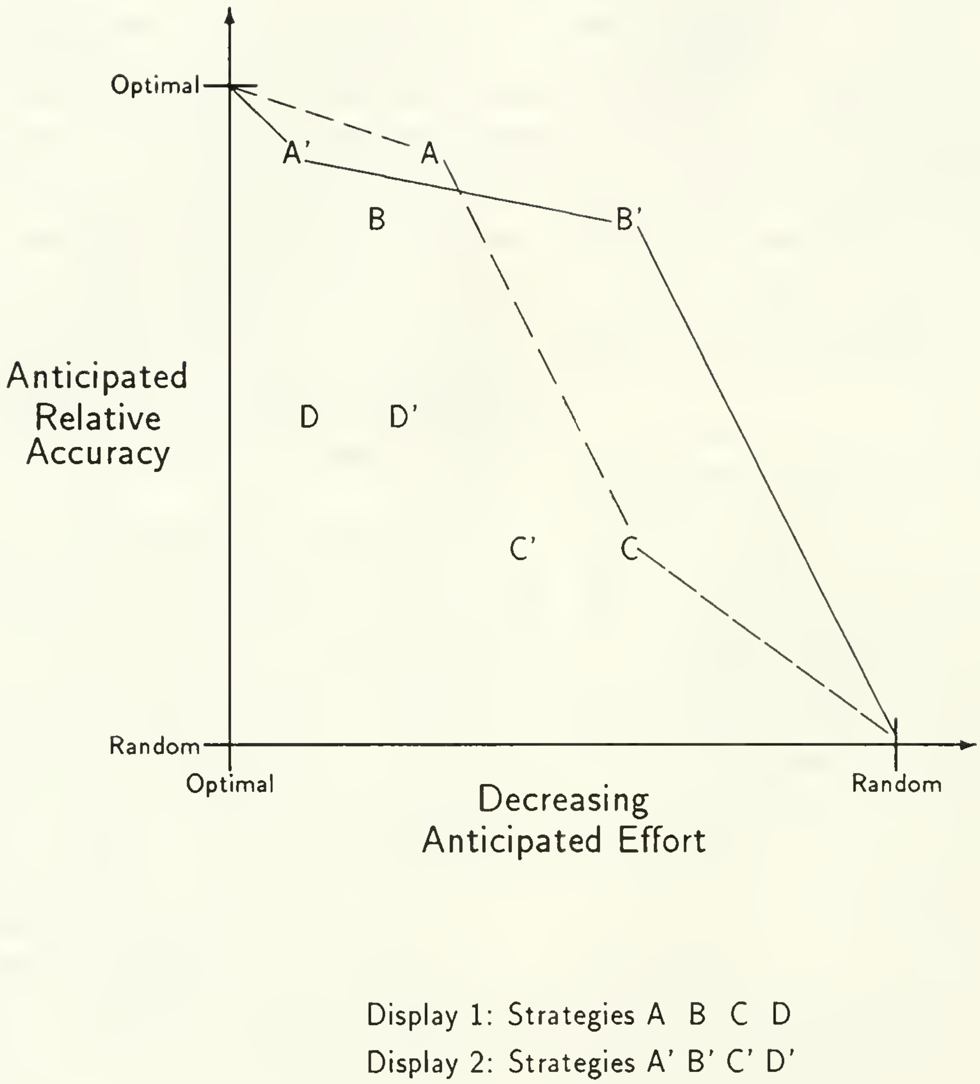

Figure 2: Effects of Display on Effort-Accuracy Trade-offs

The existing literature on information displays is large and varied. Of necessity, we focus our review on those studies that are directly relevant to our arguments. More comprehensive reviews can be found elsewhere (e.g., Bettman, Payne, & Staelin, 1986; DeSanctis, 1984; Jarvenpaa & Dickson, 1988).

Our discussion in the previous section suggests that there ought to be a relationship between display options and the variables shown in Figure 1, and that this relationship ought to be consistent with the cognitive incentives argument proposed above. Our discussion of the literature is organized around three categories of evidence: The influence of display options on (1) measures of *anticipated* effort and accuracy, (2) measures of *experienced* effort and accuracy, and (3) observations of actual strategy selection. We will discuss each of these in turn.

3.1 Anticipated Effort and Accuracy

Ideally, to study the effects of display options on anticipated cognitive incentives we would like to have measures of a decision maker's *a priori* estimates of the effort and accuracy associated with various strategies. Unfortunately, we have not been able to find any experiments in which displays were varied and decision makers were asked to assess effort or accuracy prior to engaging in decision making. However, the influence of display on perceptions of effort and accuracy may be reflected indirectly in other measures. Two such measures are: (1) stated preferences for one display over another, and (2) estimates of perceived effort or perceived accuracy obtained after a task has been completed.

Vessey and Galletta (1988) asked decision makers to express preferences for displays before attempting a task. They told subjects that they would have to perform one of two tasks, either retrieval of a specified item or comparison of items to be obtained from a display. Subjects were then asked whether they preferred to use a table of numbers or a graph for their assigned task. Subjects given the fact retrieval task preferred a table, while those given the comparison task preferred a graph. Further, the subjects were told in the initial instructions that although accuracy was relevant, speed was the primary goal. If the subjects responded to these instructions, then the difference in display preferences for the two tasks reflect the subjects' expectation that ease of processing for each task would be influenced by the nature of the display. Note that while the actual tasks, reading an item or comparing items, were quite simple, they are also important component operations of strategies in more complicated tasks.

Display preferences assessed *after* task completion may also reflect anticipated cognitive incentives, since perceptions of effort and accuracy from previous experiences with displays and tasks should form the basis for subsequent anticipations. In two studies that compared different types of graphs, Schutz (1961a, 1961b) used a task that required subjects to identify trends and patterns in time-series data. Preferences for displays were highly correlated with processing speed: Subjects preferred those displays in which judgments had been arrived at more quickly. In the first study actual task completion time and accuracy were also highly correlated, so this preference could be interpreted in terms of perceptions of effort, accuracy, or a combination of both. However, in the second study, the task was relatively easy and performance was uniformly good across displays (a ceiling effect). Thus, this preference appears to reflect perceived effort more than perceived accuracy.

Many studies of information displays have collected data on decision makers' level of confidence following a decision because confidence is thought to be closely related to perceptions of accuracy. There is some evidence that decision confidence varies with display. Using a forecasting task, DeSanctis and Jarvenpaa (1987) found that subjects were most confident with a combined graphical-tabular display, less confident with a table alone, and least confident with a graph alone. However, several other studies have found no effect of display on decision confidence (Chervany & Dickson, 1974; DeSanctis & Jarvenpaa, 1985; Schroeder & Benbasat, 1975; Zmud, Blocher, & Moffie, 1983). Although there are many possible explanations for these mixed results, they do illustrate an important point: Several of these studies did find that actual level of performance (accuracy) differed across displays, even though confidence levels did not. Note that: (1) confidence levels may, at best, be only weakly related to actual accuracy, and (2) inappropriately high levels of confidence have been observed across a variety of settings (e.g., Chapman & Chapman, 1969; Einhorn & Hogarth, 1978; Lichtenstein, Fischhoff, & Phillips, 1982). However, since we hypothesize that strategy selection is based on perceived rather than actual accuracy, evidence on decision confidence provides important information not available from accuracy data alone. Thus, a weak relationship between display variations and decision confidence suggests that perceived accuracy may not vary much across displays and may therefore be less important than perceived effort in strategy selection.

However, decision makers are not oblivious to changes in accuracy. Interesting indirect evidence is provided by two experiments that investigated display formats for nutritional information in supermarkets (Russo, Staelin, Nolan, Russell, & Metcalf, 1986). One experiment varied the format and organization of information on the levels of positive nutrients (e.g., vitamins and minerals) contained in various food products. In particular, several displays were specifically intended to reduce the effort required to search for and process this information. The researchers hypothesized that these displays would lead to greater use of nutritional information and a shift in purchase behavior toward more nutritious products. While consumers did appear to read and process these displays, there were no changes in purchase behavior. The second experiment attempted a similar display manipulation with a negative nutrient, the amount of sugar contained in the product. In this case, there was a significant shift toward purchase of foods with lower sugar content. The authors argue that the difference between the two studies was that the perceived benefit of increasing levels of positive nutrients was less than the perceived benefits of reducing negative nutrients. Display manipulations intended to reduce effort may only be effective if the perceived benefits of using the information are significant.

To summarize, research on display preferences and decision confidence suggest that display options can affect perceived effort and perceived accuracy. Further research that directly measures anticipated effort and accuracy is needed to delineate the relationship between display options and anticipated cognitive incentives.

3.2 Experienced Effort and Accuracy

If decision makers are considering anticipated effort and accuracy, and display options do shift these cognitive incentives, then one might also expect corresponding effects on experienced effort and accuracy. This would show up in the form of a speed-accuracy relationship: For example, when a display is changed, a decrease in the time taken to complete a task might indicate either a shift to a less effortful strategy or a speed-up of the same strategy. Similarly, an increase in performance when the display is changed may reflect either shifts to more accurate strategies or fewer errors in the execution of the same strategy. In this section we discuss studies that address the effects of display options on both decision time and on performance. Most of these studies required subjects to perform relatively simple tasks (e.g., point reading, comparison, proportion judgments, pattern recognition, interpolation) that are used as substrategies in more complex tasks. As discussed in section 2.2, it is the aggregate effect of display options on these simple tasks that will influence strategy selection in more complex tasks.

Studies of the effects of display on speed and performance have produced two main patterns of results. The first pattern is that display significantly affects speed but has relatively little effect on performance. Schutz (1961b) studied the effects of presenting multiple time series on separate or on superimposed graphs. When asked to compare trends, subjects showed little variation in accuracy but took less time when given the superimposed graphs. In an interpolation task, Carter (1947) found no accuracy differences for tables versus graphs, but found that interpolations were significantly faster with graphs. Vessey and Galletta (1988) found that graphs took substantially less time than tables in a comparison task, but were also slightly less accurate. Finally, in a more complex task, diagnosing trouble on phone lines, Tullis (1981) found that a narrative text format took longer than tables, which in turn took longer that either monochrome or color graphics (although tables were as fast as graphs with practice), but again found no performance differences among formats. It should be noted that absolute performance levels were high in all of these studies. This supports the notion that in relatively easy tasks, decision makers will shift to easier but still accurate strategies.

The second pattern of results shows one display to be better on both speed and accuracy. Two studies found that tables were better than graphs on both speed and performance for point reading tasks (Carter, 1947; Vessey & Galletta, 1988). Schutz (1961a) found that in a pattern recognition task, line graphs were best on both speed and performance, while vertical bar graphs were second on both criteria, and horizontal bar graphs were worst on both. Simkin and Hastie (1987) also found that for each of two simple tasks, proportion judgments and comparisons, the type of graphical display that produced the best performance was also the fastest. Thus, for many simple operations there appear to be certain display types that dominate others on both effort and accuracy, an idea that has been suggested elsewhere (e.g., Benbasat et al., 1986b; DeSanctis, 1984; Jarvenpaa & Dickson, 1988; Vessey, 1988).

One series of studies, using a more complex task, have obtained both result patterns. Benbasat and colleagues used a budget allocation task to investigate the effects of graphical and color-enhanced information presentation formats on decision time and performance (Benbasat & Dexter, 1985, 1986; Benbasat, Dexter, & Todd, 1986a, 1986b). The authors suggest that this task can be decomposed into discrete phases and that effective strategies for each phase are best supported by different display types. Specifically, they argue that the early stages require qualitative judgments of relative trends and slopes and that graphs are more appropriate than tables. However, later in the task, when precise quantitative responses are required, they argue tables are more appropriate than graphs, since exact numerical values can be obtained both easily and accurately. This reasoning implies that a combined tabular-graphical display might be better than either alone, since the decision maker could use the appropriate format for a given stage of the problem. One study did find a combined format to be both the fastest and the most accurate (Benbasat et al., 1986a).

To summarize, results on speed and accuracy show a clear influence from display variations. Although these results are consistent with our cognitive incentives argument, time and performance measures alone cannot distinguish between effects due to strategy shifts versus changes in the speed or effectiveness of the same strategy. Furthermore, since most of these studies used very simple tasks, it remains to be seen whether similar speed-accuracy results hold in more complex tasks. In the next section, we examine studies that use more complex tasks and collect direct measures of decision strategies.

3.3 Strategy Selection

The studies reviewed in this section use process tracing methods (protocol analysis and information search patterns) to infer which strategies are being used (Payne, Braunstein, & Carroll, 1978; Todd & Benbasat, 1987). This research has observed strategy selection across three categories of display manipulations: (1) simultaneous versus sequential displays of information, (2) variations in the relative proximity of information on a single display, and (3) the use of quantitative versus qualitative representations of information. Most of these studies use a multiattribute choice task, in which decision makers select the best of several alternatives, each of which is characterized on multiple attributes.

One set of studies observed choice behavior in tasks where information, displayed in booklets or on loose sheets of paper, was presented sequentially by attribute, sequentially by alternative, or simultaneously (Bettman & Kakkar, 1977; Bettman & Zins, 1979; Jarvenpaa, 1989). Each page presented the values of all attributes for one alternative, the values of all alternatives for one attribute, or a grouped presentation containing all the alternatives and their attribute values. Bettman and colleagues used tabular displays of numeric data, while Jarvenpaa used bar graphs. When sequential displays were organized by alternative (making operations across alternatives inconvenient), subjects tended to use alternative-oriented strategies such as the weighted additive and conjunctive rules. In contrast, when sequential displays were organized by attribute (making operations within an alternative inconvenient), subjects tended to use attribute-oriented strategies such as the elimination-by-aspects and additive difference rules. In the grouped data presentations, both types of strategies were used, but with differing conclusions in the three studies about which type of strategy predominates.

An appealing interpretation of the results of these three studies is based on cognitive incentives: Attribute-based presentations encourage attribute-based operations, since obtaining and working with information presented on the same page is easier than when it is on different pages (particularly when pages are arranged in booklets that prevent holding two pages side-by-side). Similarly, alternative-based presentations encourage alternative-based operations, while grouped presentations seem to be relatively neutral, so that direction of processing is left to the preferences and predilections of the decision maker. Significantly, field studies have observed display-induced changes in consumer choices that are consistent with strategy shifts of this type (Russo, 1977; Russo, Krieser, & Miyashita, 1975; Russo et al., 1986).

Other studies have examined variations in the organization of a single display, especially the physical proximity of items of information on the display. Russo and Rosen (1975) observed strong proximity effects in an analysis of eye movements in a choice task. Although only 47% of possible pairs of alternatives were spatially adjacent, 63% of all paired comparisons between alternatives and 73% of all sequential search operations were between adjacent alternatives, results that the authors attributed to ease of processing considerations. Engineering psychologists have also emphasized the importance of spatial proximity of information in the design of instrument displays (e.g., Wickens, 1987). Spatial proximity induces the use of simple strategies for scanning information displays: For instance, lists tend to be scanned from start to finish, while matrix displays tend to be scanned starting in the upper left-hand corner and proceeding along rows or columns (Bettman & Kakkar, 1977; Russo & Rosen, 1975). This tendency to scan in the order in which the information is presented is important since decision makers have been shown to assign greater weight to information that is presented either at the beginning or the end of a sequence (i.e., primacy and recency, see N. Anderson, 1981; Einhorn & Hogarth, 1985).

A final set of studies have dealt with the use of quantitative versus qualitative representations of information. Qualitative information forms (e.g., words or pictures) can increase the effort required to use strategies that require numeric calculations. Since these representations do not present explicit numeric values, these values must be obtained through an effortful process of translation or estimation prior to computation (Larkin & Simon, 1987). For example, consider how one might compute the difference between attribute values represented as "fair" and "excellent". In two experiments using choice tasks in which information was presented using either numbers or words, decision makers were observed to shift their decision strategies to avoid expenditures of effort: Huber (1980) found that operations within an attribute (such as finding the alternative with the maximum value on a specific attribute) were more frequent when attribute values were represented by words. Stone and Schkade (1989) found that when values were represented by words, decision makers used significantly fewer search and combination operations within attributes than they did when presented with numeric values. In two judgment tasks, assigning ratings and setting selling prices for gambles, Johnson, Payne, and Bettman (1988) found that decision makers were less likely to select strategies that used numeric computations when probabilities were presented as complicated fractions rather than as simple decimals. They explained this strategy shift in terms of the relative ease of computations with simple decimals. Surprisingly, although many studies have used a mix of quantitative and qualitative information in the same task (e.g., Bettman & Kakkar, 1977; Payne, 1976), there have been no systematic studies of the effects of mixing these forms (but see Tversky, 1969, for a discussion of this issue).

Another interpretation of the studies comparing quantitative and qualitative representations is that some operations are prohibitively difficult to execute when information is presented in certain forms. As noted in the discussion of Working Assumption 4, some displays preclude the use of strategies that employ these operations. For example, Simkin and Hastie (1987) argue when information is presented in graphs, decision makers may select strategies that employ operations that are not well-defined for words or numbers (e.g., a "projection" operation that mentally extends a line segment). Similarly, it may actually be impossible to "multiply" two words. If there are important differences in the sets of basic operations that are meaningful for various display types, then the set of available strategies will also change. If a desired strategy is not available, a decision maker's only recourse would be to either perform an effortful translation of the information into a compatible form or to select a different strategy. This may provide an alternative explanation for results of the words versus numbers studies cited above, and is an issue that deserves attention in future research (e.g., in studies of tables versus graphs).

All of the studies cited in this subsection used process-tracing methods. Process tracing data is particularly useful because it provides a more direct measure of information processing strategies than is possible when only measuring decision time or decision quality. As was the case with the other sets of studies, the evidence from these process tracing studies is consistent with the notion that decision makers respond adaptively, selecting strategies in response to the cognitive incentives induced by the display. Taken as a whole, we believe that the evidence discussed above is strong enough to warrant pursuing the effort-accuracy approach further. On the other hand, we do not wish to overstate the strength of this evidence, since these studies are relatively few in number and consider only a limited set of display options. The next section outlines what needs to be done to build from this starting point.

4 Implications

Our discussion raises a number of issues for researchers concerned with information displays in decision support. We first address methodological issues related to (1) dependent variables in information display experiments, (2) the use of simulation methods, and (3) outlines of possible experimental designs. Finally, we discuss possible extensions of the cost-benefit approach to other aspects of decision support systems.

4.1 Methodological Issues

Experiments concerned with computer-based decision support need to move beyond simply measuring whether or not a decision aid influences decision outcomes and toward designs that allow researchers to ask questions about *how* and *why* decision aids influence outcomes (Todd & Benbasat, 1987). This implies that researchers should design experiments that include dependent variables intended to measure strategy selection and effort in addition to the standard measures of decision quality or accuracy. These measures can be obtained using process-tracing methods like verbal protocols, information search records, and decision time (Johnson, Payne, Schkade, & Bettman, 1988; Payne et al., 1978; Russo, 1978). Protocols and search records can be coded and analyzed in order to make inferences about the strategies used by decision makers. Total decision time provides one overall measure of experienced effort, and more detailed timing data can be used to analyze the effort associated with basic cognitive operations or substrategies (Chase, 1978; Posner & McLeod, 1982). To illustrate, Payne and colleagues (1988) used the following dependent variables to make inferences about strategies in a risky choice task: amount of information acquired, average time spent per acquisition, proportion of acquisition time devoted to the most important attribute, proportion of time spent on probability rather than payoff information, variances of several of the previously mentioned measures, and various codings of the sequential pattern of information search. A more detailed discussion of coding and analyzing process tracing data can be found elsewhere (Carroll & Johnson, 1989; Ericsson & Simon, 1984).

Our discussion has emphasized that there are some important variables that mediate the relationship between display options and decision outcomes—decision makers anticipate the effort and accuracy of different strategies and adaptively select an efficient strategy for the task and display at hand. To test this relationship, display experiments should ideally measure all of the following dependent variables: (1) Anticipated effort and accuracy, either elicited directly from decision makers or indirectly from measures like display preferences or decision confidence; (2) strategy, obtained from process-tracing data; (3) effort-related measures like decision time; and (4) decision quality or accuracy.

Recent developments in use of computer simulation techniques may prove to be helpful in developing and operationalizing the cost-benefit approach to strategy selection. Johnson and Payne (1985) proposed a method for measuring the effort associated with decision strategies by decomposing strategies into a sequence of component processes, called *elementary information processes* (EIPs). These components, which are similar to the simple substrategies discussed earlier, are basic cognitive operations thought to be common to a wide variety of tasks (Chase, 1978; Newell & Simon, 1972). Examples include reading an item of information into short-term memory, adding two numeric items together, or comparing two items. Once a set of decision strategies is decomposed into a common set of EIPs, Monte-Carlo simulation techniques can be used to observe the choice made by each strategy over a large number of decisions while also counting the number of times each component operation is executed. A general measure of effort can be calculated from the total number of component operations required to execute a particular strategy in a particular task. Total decision time can also be predicted either with this measure or with a slightly refined measure, multiplying the number of times each EIP is used by an estimate of the time required to execute that EIP. This approach has been used to predict total decision time of subjects in a choice task (Bettman et al., in press) and task completion times in experiments involving other cognitive tasks (Card, Moran, & Newell, 1983; Carpenter & Just, 1975).

This simulation approach is valuable for several reasons: (1) Simulations incorporating componential analyses of this type permit a variety of decision strategies to be investigated over many variations in task characteristics. Simulation experiments that systematically vary display options, task characteristics, and strategies are capable of exploring the complex interactions among these factors. (2) Developing the simulations requires the researcher to specify the task environment and the decision strategies in great detail. This can help to uncover hidden assumptions and gaps in knowledge that might otherwise go unnoticed. (3) Results from simulations can be used to predict the efficient set of strategies for a particular display in a particular task and to provide quantitative predictions of both effort and accuracy (e.g., Kleinmuntz & Schkade, 1989). These predictions can be directly compared to the results of experiments: Do decision makers actually select strategies that the simulation identifies as efficient? Do measures of decision time and decision quality agree with the simulation's estimates of effort and accuracy? Thus, the simulations provide predictions that place the theory at risk of *disconfirmation*, an important component of cumulative theory development (Meehl, 1978).

Using the simulation approach generally requires the following four steps: (1) formally describe the task environment (e.g., specification of goals, constraints, problem structure, requirements for a solution, and so on); (2) characterize the set of available strategies (e.g., identify critical stages or subtasks and describe potential solutions for each); (3) describe each strategy as an organized sequence of elementary operations (e.g., a production system; Newell & Simon, 1972); and (4) analyze the impact of displays on elementary operations and use the strategy descriptions to determine the aggregate impact on each strategy (e.g., operationalize the strategies as computer programs and use Monte Carlo techniques). Note that these steps can be accomplished without formal simulation methods: In our examples in section 2.2, as in most previous cognitive cost-benefit studies, we derived *qualitative* predictions about the direction of display effects through an informal mental simulation. While the mental simulation approach has the practical advantage of being easy to implement, it lacks the quantitative precision of formal simulation methods and may fail to detect important interactions between display and task characteristics (see Payne et al., 1988, for an illustration of the advantages of the formal approach).

Ideally, research on displays in decision support should lead to generalizations about the influence of display options on strategy selection across a variety of tasks. Even at this preliminary stage, the discussion above suggests some examples of research propositions that warrant further investigation (listed in Table 2). Experiments designed to test propositions of this type would be considerably strengthened if (1) the independent variables include task characteristics other than the information display, and (2) information display options are manipulated as *within-subject* variables. Varying additional task characteristics (e.g., problem size, response mode, similarity of alternatives, presence of dominated alternatives) can help to account for seemingly conflicting results in previ-

Table 2: Examples of Research Propositions

- Proposition 1: Verbal and pictorial display forms discourage the use of strategies that require numerical calculations.
- Proposition 2: Decision makers tend to avoid strategies that require combining items of information with different forms.
- Proposition 3: Decision makers tend to choose strategies that use items of information that are in close physical proximity on the display.
- Proposition 4: Decision makers tend to choose strategies that use items of information that have similar display features.
- Proposition 5: Expert decision makers are more knowledgeable about available strategies and will exhibit greater adaptability to variations in display design.

ous studies. For instance, suppose a particular display manipulation has a large impact on decision strategies only when the problem is large. The only way to verify this is to manipulate both problem size and display in the same experiment. This type of comparison is enhanced by the use of within-subject designs in which a decision maker is presented with different displays of the same problems (e.g., Stone & Schkade, 1989). One advantage of this type of design is statistical power, which can help to compensate for the fact that the effort required for data coding can limit the number of subjects used in process-tracing studies.

4.2 Extensions to Other System Features

Our discussion has been based on a simplifying assumption that warrants further discussion: Specifically, we have assumed that display options do not affect other characteristics of the task. However, decision support systems are capable of modifying not only the display of a problem, but the underlying structure as well. These modifications could include adding variables (e.g., new information retrieved from a database or summary measures computed from other variables), removing variables (e.g., screening out redundant or irrelevant information), adding decision alternatives (e.g., searching remote databases to find new options), and removing alternatives (e.g., screening out options that are clearly inferior). In more complex tasks, a wide variety of model-based or knowledge-based inferences, predictions, and evaluations are possible (for an overview, see Zachary, 1986).

The effort-accuracy approach can be readily extended to these system features. For instance, if the computer performs operations that might otherwise be left to the decision maker, computationally intensive strategies become cognitively less costly, and the decision maker has less incentive to avoid them. Similarly, transferring computational operations to the system may reduce the number of errors, since the computer performs with greater consistency (Bowman, 1963; Dawes, 1979). However, it seems likely that factors other than effort and accuracy will need to be included in these cost-benefit trade-offs. For example, although providing summary measures might potentially increase accuracy and decrease effort, decision makers may reject them if they lack credibility and acceptance (Russo et al., 1986). Credibility issues may be even more pronounced when more sophisticated system capabilities are considered (e.g., model- or knowledge-based inferences; also see Fischhoff, 1980; Kleinmuntz, in press). While effort and accuracy are important determinants of decision behavior, they are not the only important factors.

On the other hand, treating the decision maker's cognitive strategy as a variable that mediates the relationship between system features and system effectiveness is a general approach that may prove to be useful. For instance, in a recent study, Todd and Benbasat (1989) use the cost-benefit approach to successfully predict the impact of decision aids on decision strategies. Of particular interest was an experiment in which they influenced strategy selection by selectively adding certain capabilities to a decision support tool: When provided with tools that explicitly reduced the effort required to use a particular substrategy, decision makers were observed to shift toward use of strategies that relied upon that substrategy. These results support the cost-benefit approach in general as well as the specific focus on cognitive effort in strategy selection.

An interesting issue in designing decision support systems is whether the decision maker should be given control over the choice of display or other system features (Sprague & Carlson, 1982, chapter 5; also see Silver, 1988a, 1988b). A system can provide varying degrees of flexibility to the decision maker: The designer could completely predetermine the set of display options or could design the system to provide either a small or large set of alternative display options, thereby permitting the decision maker to select among those options each time the system is used. Flexibility provides the decision maker with the opportunity to actively influence the cognitive incentives created by the task and the display. For example, if a decision maker wishes to use a particular strategy, then a display that facilitates that strategy can be selected. While allowing decision makers to alter the display to suit their own preferences seems appealing, there is the danger that the decision maker will only reinforce bad habits, particularly when decision makers suffer from misperceptions about the effort and accuracy associated with different strategies.

At present, empirical evidence relating to the impact of flexibility on decision processes is extremely limited. Dos Santos and Bariff (1988) found better performance when a system provided guidance in use of models, but did not collect any process data. There has been some research on a particular aspect of flexibility, the use of *agendas* in decision making. Results suggest that considering decision-relevant information in a constrained order can strongly influence the decision process (Hauser, 1986; Hulland, 1988; Plott & Levine, 1978; Tversky & Sattath, 1979). Thus, restricting the sequence in which information is presented on displays can have an impact on strategy selection. Further research on strategy selection in a variety of complex tasks will lead to a better understanding of the implications of allocating flexibility to the decision maker.

4.3 Conclusion

System designers need guidelines to inform them about how decision makers use (or choose not to use) various features of a system. Of course, it would be inappropriate to conclude that current display designs are completely insensitive to user needs and preferences. An interesting possibility is that future research will reveal that elements of current designs are in fact quite appropriate and useful. For instance, matrix-based information displays are widely used, most notably in spreadsheet software. Proposition 3 in Table 2 suggests that matrix displays containing large amounts of information may be preferable to a sequence of lists that each present limited amounts of information. This is because the availability of large amounts of information in close physical proximity makes a number of strategies relatively easy to execute, increasing decision makers' ability to adapt. Admittedly, very little of the empirical work supporting this argument has looked specifically at computer-based displays. However, if matrix-based displays prove to be equally effective when implemented on computers (a likely outcome), then this leads to a recommendation about display design that is not too surprising.

On the other hand, given the confusing and inconsistent state of knowledge about a number of other display options, it seems likely that a careful program of research will uncover recommendations that are both surprising and useful. System designers routinely make implicit trade-offs about the user's cognitive costs and benefits. Making those trade-offs explicit has the potential to improve the usefulness of computer-based decision aids and, ultimately, lead to more effective decision making.

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