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# Cognitive Processes and Information Displays in Computer-Supported Decision Making: Implications for Research

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*Both authors contributed equally to all phases of this research and their names are listed in alphabetical order. This work was supported in part by a grant from the Decision, Risk, and Management Sciences Program of the National Science Foundation. Helpful comments from Scott Hawkins, Sirkka Jarvenpaa, Don Jones, Eleanor Jordan, Benjamin Kleinmuntz, Dan Stone, three anonymous referees, and the associate editor are gratefully acknowledged. The second author is currently on leave at the Graduate School of Business, University of Chicago.

## ABSTRACT

A theory-based approach for research on information displays in computer-supported decision making is proposed. Display characteristics such as the form, organization, and sequence of information can influence a decision maker's selection of a decision strategy. Strategy selection can be analyzed in terms of a trade off between the desire to maximize the accuracy of a decision and the desire to minimize the effort required to reach that decision. Differences in displays influence the anticipated effort and accuracy of each available strategy and, therefore, provide an incentive for decision makers to use different strategies. Empirical research on the effects of information displays on strategy selection is reviewed and the connection between other display research and the strategy selection approach is discussed. Recommendations for the design and implementation of information display research are presented.

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## Introduction

What is the best way to display information to decision makers? The answer to this question 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 decision process. Both researchers and practitioners have proposed that the information display is an essential characteristic of all computer-based decision support systems that can be an important determinant of the effectiveness of those systems (DeSanctis, 1984; Ives, 1982; Rubinstein & Hersh, 1984; Zachary, 1986).

Research-based recommendations about the impact of information displays on decision processes or the advisability of different display options are slowly emerging (Jarvenpaa & Dickson, 1988). However, progress has been limited by a lack of underlying theory addressing the impact of displays (Jarvenpaa, Dickson, & DeSanctis, 1985). Further, while many studies have measured the impact of displays on decision outcomes, few studies have specifically examined how displays influence the decision processes that produce these outcomes (Todd &

Benbasat, 1987). The purpose of this paper is to address both of these points by proposing a cognitive mechanism that accounts for the impact of certain information display variables on the decision maker's selection of a strategy for accomplishing complex decision making tasks. Based on this approach, we make several recommendations for the design and implementation of display research.

The paper is organized as follows: Section 1 describes the specific characteristics of information displays that we address in this paper. Section 2 outlines the cognitive mechanism for strategy selection in complex decision tasks. This is used in Section 3 to account for the influence of information displays on strategy selection. Section 4 contains our recommendations for the design and implementation of display research.

# 1 Information Display

The number of potential visual representations of decision problems is virtually infinite. In thinking about how specific information displays influence decision making, it would obviously be useful to have a comprehensive taxonomy of visual representations. However, only initial efforts addressing specific parts of such a taxonomy have been proposed (e.g., Tan & Benbasat, 1989, describe a taxonomy of graphical representations of time-series data). In the absence of a comprehensive taxonomy, we will focus on three fundamental characteristics that apply to a broad range of displays: (1) the *form* of individual information items in the display, (2) the *organization* of display items into meaningful groups or structures, and (3) the *sequence* of individual items or groups of items. Later in the paper, we will argue that these characteristics are likely to influence decision behavior in predictable ways.

In order to define these display characteristics, we need to consider the nature of the information to be presented. Most decision problems have a common underlying structure: The information can be represented as a set of locations in multidimensional space, with each location described by a vector whose elements are locations on the individual dimensions. The interpretation of a vector and its elements is determined by the nature of the decision to be made. For instance, in choice problems, each vector is a decision alternative and the vector elements are attribute values that describe that alternative (e.g., choosing among cars described by price, comfort, performance, and other attributes). Another example is forecasting from multivariate time-series data, where each vector is a point in time and the vector elements are observations of various predictor variables at that point (e.g., predicting a company's future profits using revenues, operating expenses, and other financial information from previous time periods). The function of a display is to provide the decision maker with a visual representation of this information.

*Form:* Individual items of information (i.e., the vector elements) can be presented in at least three distinct forms: numerical, verbal, or pictorial. For example, the amount of memory in a personal computer could be represented as "640K", "maximum available", or as an image of a champion weightlifter (as opposed to a 98 pound weakling). There are also numerous variations possible for a given form. For instance, numerical representations can include fractions, decimals, or scientific notation. Verbal information can be presented using single words or short phrases, using specialized terminology or everyday vocabulary, and in various languages. Pictorial forms include common components of charts (bars, lines, wedges), faces, and numerous other visual symbols. Variations in all three forms can be achieved through changes in units of measurement or scaling.

*Organization:* Another characteristic of displays is the way in which items on the display are organized into meaningful structures such as groups, hierarchies, or patterns. For instance, information can be grouped in a table (e.g., a matrix with each row corresponding to a vector, each column to a dimension), or as a series of lists (e.g., paragraphs of text, with each paragraph describing a vector, as in the case of a travel guide listing hotels and resorts), or in hierarchical clusters having more complicated structures (e.g., labels on consumer products, which can include both lists and tables). In many displays, some information is represented by the relative position of items (e.g., in a line graph, the vertical positions of the lines reflect the values of vector elements). Note that some organizations explicitly depict the relations between items of information, while others do not. For instance, the patterns revealed in a line graph depend on the values of the particular items, while the general appearance of a table does not.

*Sequence:* A given organization does not completely specify the order in which individual items or groups of items must appear. For instance, a display may be organized as a series of lists, but the lists can appear in many different sequences, with the elements of each list also appearing in many different sequences. Similarly, the sequence of rows or columns in a table can vary. Sequence may be arbitrary, or it may be based on values of certain elements. For instance, a bar graph that represents a vector of values might be arranged so that they appear in decreasing order.

Form, organization, and sequence can, in principle, be varied independently. For instance, in a study of the impact of display organization on choice strategies, Jarvenpaa (1989) used bar graphs to replicate earlier studies by Bettman and colleagues that used tables of numbers (Bettman & Kakkar, 1977; Bettman & Zins, 1979). Furthermore, clever and judicious display design may permit novel combinations of form, organization, and sequence. For instance, Chambers, Cleveland, Kleiner, and Tukey (1983) proposed techniques for representing multivariate data with a tabular arrangement of univariate or bivariate graphical display elements. Graphical displays can also be composed in whole or in part from numerical or verbal elements (e.g., stem-and-leaf plots; also see Tufte, 1983, chapter 7).

Both in practice and in previous research on information displays, certain combinations of form, organization, and sequence have been used more often than others (Jarvenpaa & Dickson, 1988). For instance, numerical data are commonly organized into tabular arrangements, while there are a variety of standard graphical arrangements of pictorial elements (e.g., bar charts, scatter plots, and so on). Verbal information is most often arranged in sentences and paragraphs of text, though tabular arrangements are not uncommon. However, displays are often composed of a mixture of forms (e.g., tables or running text containing both words and numbers, graphics using words and numbers to label and scale the data elements). The influence of displays on decision processes may be easier to understand by aggregating the individual influences of these component characteristics.

## 2 Effort and Accuracy in Strategy Selection

Information display characteristics are just one type of task feature that can influence decision processes. This section outlines a general approach for understanding how decision makers adapt to decision tasks. Decision tasks are defined by a goal to be accomplished and the environment in which it is accomplished (see Newell & Simon, 1972, ch. 3). Decision making encompasses 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 connection between judgment and choice). In all of these tasks, there are generally many strategies for accomplishing the goal. We assume that decision makers engage in an initial planning stage, in which they select a strategy to implement. In what follows, we develop a theoretical account of this planning process, which is then used to account for the influence of information display characteristics on decision processes.

We define a *strategy* for a task as a sequence of information processes that is intended to achieve the goal. Not only are there many strategies for a given task but the set of strategies available for one task is generally different from that for another task (Newell & Simon, 1972, ch. 14). For example, strategies used for evaluative judgment have been found to differ substantially from those used for choice (Billings & Scherer, 1988; Schkade & Johnson, 1989; Tversky, Slovic, & Kahneman, in press). However, while the set of strategies available varies across tasks, the planning process is essentially the same.

The most important similarity is that decision makers adapt to variations in features of a given task by selecting different strategies. Decision makers have been observed to switch strategies in response to variations in problem complexity, response mode, similarity of alternatives, and characteristics of the information display, among other features (Payne, 1982). For instance, decision makers respond to an increase in the number of alternatives in a choice task by switching to simpler, less accurate strategies (Payne, 1976). One explanation for this strategy switching is that decision makers engage in a form of cognitive cost-benefit analysis, trading off various positive and negative dimensions of alternative strategies for a task. If the features of a given task change, then the costs and benefits associated with each strategy may also change. If this change is large enough to alter the balance of costs and benefits, then a different strategy would be selected.[1]

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 the product of a trade-off between the desire to maximize the probability of producing a correct decision and the desire to minimize the expenditure of cognitive resources (Johnson & Payne, 1985). 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 features, 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, 1974, 1975). It has also been suggested that factors other than accuracy and effort may influence strategy selection (e.g., justifiability; 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 re-

[1] We wish to clearly distinguish between variations in tasks (e.g., judgment versus choice) and variations in features of a given task (e.g., different levels of problem complexity). In this paper, we are primarily concerned with the influence of variations in features of a given task, particularly features of the display. To avoid confusion, we will refer to features of the task related to the display as *display characteristics* and all other features as *task features*.

sources 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 task features 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 varied 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 varied by a factor of as much as 16.

When selecting a strategy, 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 & Mitchell, 1978). One source of uncertainty may be unpredictability or ambiguity in the task. Another source may be limitations in the decision maker's knowledge about the task. 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 a decision maker's *anticipations* of effort and accuracy.

Decision makers may be better at estimating effort than accuracy. For example, 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, because feedback about the ease with which decision processes are implemented is usually more immediate and readily interpretable than outcome feedback. On the other hand, decision makers often have difficulty learning about accuracy because many environments provide outcome feedback that is incomplete, ambiguous, and subject to long delays (Einhorn, 1980; Einhorn & Hogarth, 1978). Learning about accuracy can be difficult even in the presence of complete and accurate outcome feedback (Brehmer, 1980). 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. In contrast, 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 situation to the next.

A theoretical understanding of strategy selection is still evolving and some empirical findings have not yet been accounted for by this approach. For instance, Payne (1982) reviewed 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). One reason why cost-benefit explanations have not yet accounted for framing effects may be that the problems studied were so simple that planning could not play a meaningful role. However, a cost-benefit approach focusing on effort and accuracy does appears capable of analysis and prediction of strategy selection across a variety of complex decision making situations.

# 3 Information Displays and Strategy Selection

While many different task features can influence strategy selection, information displays deserve particular attention in the context of computer-based decision support systems. A system designer may have limited control over other task features, but display characteristics can be directly controlled. Moreover, because every system must have an information display, these design decisions can not be avoided. Display design is important because the system designer can exert *indirect* control over strategy selection through *direct* control of display characteristics.

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 result was a significant shift in actual purchase decisions to products with lower unit prices. Although Russo's experiment did not use computer-based information displays, one can easily imagine a similar situation where consumers 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*).

### 3.1 Displays as Cognitive Incentives

A number of other studies, reviewed below, also suggest that differences in information displays influence strategy selection through changes in either the effort or the accuracy with which various information processing activities can be accomplished. Together with task features and decision maker knowledge, information displays implicitly define a *cognitive incentive system* for decision makers. Specifically, differences in displays, task features, 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.[2]

We propose that the effects of displays on strategies should be analyzed in terms of the effects of displays on components of those strategies. Because decision making tasks are often complex and human information processing capabilities are limited, decision strategies generally achieve their goal by breaking the task into a sequence of simpler *subtasks*. Thus, strategies can be described as a sequence of simpler *substrategies* that are intended to achieve each of these subtasks (Newell & Simon, 1972, ch. 14). For example, substrategies can be associated with distinct stages of decision making (e.g., information acquisition, evaluation), simple subtasks (e.g., pattern recognition, summarizing information), or with more elementary cognitive operations (e.g., multiplication, comparison, retrieval from memory). The influence of display characteristics on a strategy's effort and accuracy thus becomes the aggregate of the influences on the effort and accuracy of each component substrategy.

To illustrate how differences in displays can influence a single substrategy, imagine a decision maker who must choose a new computer system from a set of available alternatives. Each system is described by a set of attributes (e.g., price, ease of use, expandability, and speed). Consider a manipulation of display organization in which the information can be presented either one system at a time (i.e., the values of all attributes for a single system on the same screen) or one attribute at a time (i.e., each screen contains the values of one attribute for all systems). A common substrategy in many choice strategies

[2] For completeness, we could have included a number of feedback loops in Figure 1 (e.g., from experienced effort to decision maker knowledge). These have been omitted for clarity.

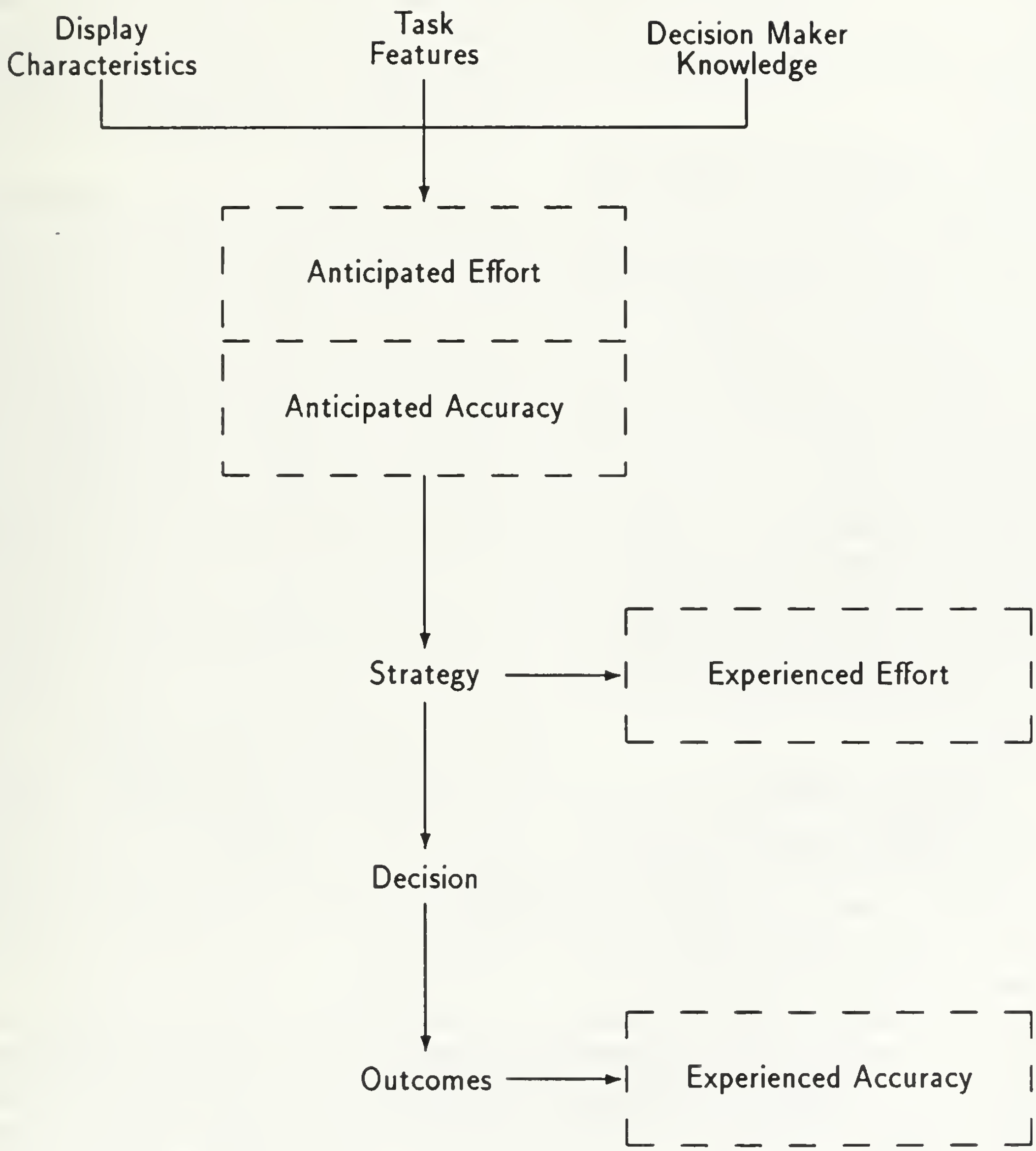



Figure 1: Overview of the Strategy Selection Process

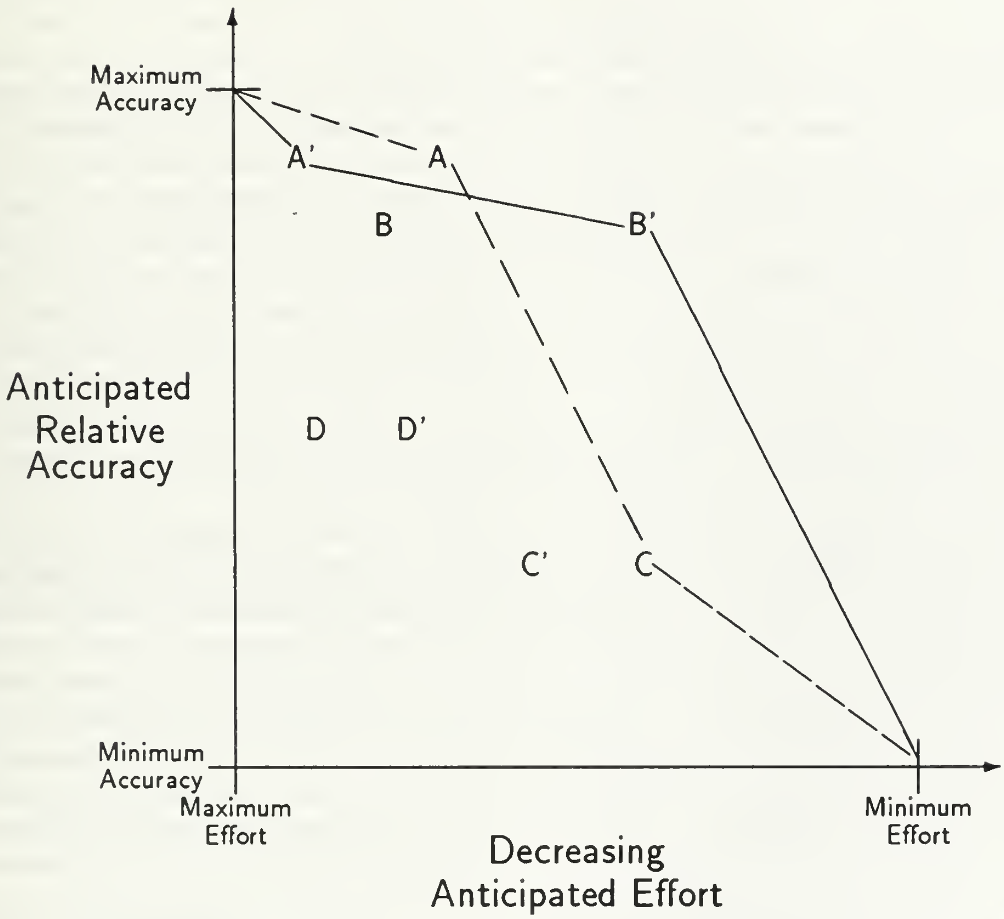
is comparing the values of two systems on the same attribute. The first type of display, organized around systems, does not present the two values simultaneously, while the second type of display, organized around attributes, does. This means that a comparison of this type will be more effortful with the first than with the second type of display.

Now consider a manipulation of display form, where the system attributes can be presented either as a set of lists of numbers or as a set of bar charts, where each list or bar chart presents the attribute values for a single alternative. Another common operation, extracting the numerical value of a particular attribute for a particular system, can be accomplished with a relatively small chance of error when the information is presented as numbers. In contrast, extracting a numerical 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 with 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 a display in a way that makes this type of comparison easier (e.g., switching from sequential to simultaneous display organization) would decrease the effort required for the former strategies more than for the latter. Similarly, choice strategies that use numerical calculations require many extractions of numerical values (e.g., weighted additive strategy), while many other strategies do not (e.g., the majority of confirming dimensions strategy requires no numerical value extractions, while the elimination-by-aspects strategy requires only a relatively small number). Thus, changing to a display that makes numerical value extractions less accurate (e.g., changing form from numbers to bars) would affect the accuracy of the weighted additive strategy more than the others.

It is important to note that these effects do not exist in isolation. For instance, a single display change may influence *both* the accuracy and effort associated with a substrategy—numerical value extraction from line graphs or bar charts may be both less accurate and more effortful than from numerical displays (Jarvenpaa & Dickson, 1988). However, the support a given display provides to one substrategy may be offset by the impact on other substrategies used by the same strategy. For instance, switching from a table to a bar chart may make numerical 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). Since strategies make use of numerical value extractions, trend recognition, and comparisons to varying degrees, the impact of a particular display on a particular strategy will be the product of the aggregate influence on all these component substrategies.

It is this aggregate influence of displays on the effort and accuracy of strategies that forms the basis for the strategy selection process. 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 anticipated accuracy and effort of the same strategy for the two different displays. Here, anticipated accuracy is scaled relative to the accuracy levels of the most and least accurate strategies (e.g., utility maximization and random choice; adapted from Johnson & Payne, 1985). Similarly, anticipated effort is




Display 1: Strategies A, B, C, D

Display 2: Strategies A', B', C', D'

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

scaled relative to the effort levels required to implement the most and least effortful strategies. Because expending less effort is more desirable, the horizontal axis represents decreasing effort levels.

Note that for Display 1, strategy $A$ *dominates* strategies $B$ and $D$, 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. On the other hand, strategy $B'$ now dominates both $C'$ and $D'$. 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.

## 3.2 Empirical Research on Displays and Strategy Selection

This subsection reviews those studies that are directly relevant to our arguments—studies specifically examining the connection between information display and strategy selection. Our review examines, in turn, the influence of form, organization, and sequence and concludes with a critical evaluation of the existing evidence. The following subsection (3.3) examines the relation between other information display research and the strategy selection approach. More comprehensive reviews can be found elsewhere (e.g., Bettman, Payne, & Staelin, 1986; DeSanctis, 1984; Jarvenpaa & Dickson, 1988).

### 3.2.1 Form

Several studies have compared quantitative versus qualitative forms of information. Information in qualitative forms (e.g., words or pictures) can increase the effort required to use strategies that use numerical calculations. Since these representations do not present explicit numerical values, these values must be obtained through an effortful process of translation or estimation prior to computation (Larkin & Simon, 1987). For example, it is difficult to 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 less frequent when attribute values were represented by words. Similarly, Stone and Schkade (in press) found that decision makers used significantly fewer search and combination operations within attributes when values were represented by words than they did when presented with equivalent numerical values. 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).

In two judgment tasks, assigning ratings or selling prices for lotteries, Johnson, Payne, and Bettman (1988) found that decision makers were less likely to select strategies that used numerical 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.

Another interpretation of these studies is possible. Some operations are prohibitively difficult to execute when information is presented in certain forms, thus precluding 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 is impossible to directly "multiply" two words. If there are important differences in the sets of basic operations that are meaningful for various display forms, then the set of available strategies will also change. If a familiar 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).

### 3.2.2 Organization

Studies of organization have focused on simultaneous versus sequential presentation of information. One set of studies observed choice behavior in tasks where information displayed in booklets or on loose sheets of paper was presented sequentially by alternative, sequentially by attribute, or simultaneously (Bettman & Kakkar, 1977; Bettman & Zins, 1979; Jarvenpaa, 1989). Each page presented the values of all alternatives for one attribute, the values of all attributes for one alternative, or a grouped presentation containing all the alternatives and their attribute values. Bettman and colleagues used tabular displays of numerical 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 (simultaneous) data presentations, both types of strategies were used, but with differing conclusions in the three studies about which type of strategy predominates.

The results of these three studies can be interpreted in terms of 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 these three laboratory studies. Russo's (1977) study of how display organization influenced the use of unit price information was discussed earlier. Two other experiments investigated the influence of display organization on the use of nutritional information in supermarkets (both experiments are reported by Russo, Staelin, Nolan, Russell, & Metcalf, 1986). One experiment varied the organization of displays presenting 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 were observed to read and attend to 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 various products. In this case, there was a significant shift toward purchase of foods with lower sugar content. Although there were many differences between the two studies, the authors argue that the principal difference 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.

### 3.2.3 Sequence

The sequence in which information is presented may influence decision processes because it affects the physical proximity of items of information on the display. For instance, the first and second item on a list will be closer together than the first and last. 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 Anderson, 1981; Einhorn & Hogarth, 1989).

### 3.2.4 Critical Evaluation

These studies of the influence of form, organization, and sequence are consistent with the idea that decision makers respond adaptively, selecting strategies in response to the cognitive incentives induced by the display. Taken as a whole, this evidence is strong enough to warrant pursuing the effort-accuracy approach to display research 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 may be criticized in several other respects.

First, most of these studies use multiattribute choice tasks. Clearly, research in this area needs to be extended to judgment tasks of various types. Studying the influence of display characteristics on strategy selection in an evaluative judgment task or a prediction task would help to test the limits of the approach.

Second, only a restricted range of display characteristics have been studied. For instance, while the evidence on information sequence discussed above is suggestive, these studies did not explicitly manipulate sequence, nor have any studies examined the influence of combinations of form, organization, and sequence. Furthermore, most of these studies use tabular displays of information. A significant exception is the study by Jarvenpaa (1989), which successfully extended previous research on strategy selection into the realm of graphic displays with results that were essentially consistent with previous studies of tabular displays. This study demonstrates the feasibility of applying the cost-benefit approach to graphical displays. Also, Simkin and Hastie (1987) have provided some useful conceptual and methodological developments for comparing different graphical displays, particularly the identification of additional elementary operations or substrategies. These developments will facilitate the application of the strategy selection approach to a broader range of displays.

Finally, none of the studies to date have focused explicitly on the distinction between anticipated and experienced effort and accuracy. It is possible that decision makers' anticipations will differ systematically from the actual levels of effort and accuracy they will experience. However, no study to date has even attempted to measure anticipations. We will discuss this issue further in section 4.

To summarize, these studies are consistent with our theoretical interpretation of the influence of displays on strategy selection. However, they suffer from limited generalizability with respect to both task and display. There are a number of studies in the literature that examine other displays and other tasks, though they do not deal directly with strategy selection. Next, we will discuss the relevance of this research for understanding the relation between displays and strategy selection.

### 3.3 Other Display Research

As noted earlier, most of the research on displays has been concerned with decision outcomes rather than decision processes and, therefore, did not collect evidence relevant to strategy selection. Some researchers have argued that this literature can be interpreted in terms of how appropriate a display is for the task being performed (Benbasat, Dexter, & Todd, 1986b; DeSanctis, 1984; Jarvenpaa & Dickson, 1988; Jarvenpaa et al., 1985; Vessey, 1988). The idea is that both effort and errors can be minimized by selecting the right display for the task (i.e., the display that *matches* the task). Because a given display may match one task but not another, the appropriateness of the display depends on the task. For instance, a major theme of these studies has been to compare the influences of tables and graphs. In their comprehensive review, Jarvenpaa and Dickson (1988) conclude that graphs are superior for summarizing data, recognizing trends, and comparing points and patterns, while tables are superior for value extraction.

What is the connection between the matching approach and the strategy selection mechanism discussed in this paper? One important difference is that studies investigating the match between displays and tasks treat task as an independent variable. In contrast, our analysis assumes that the task is held constant while treating the display and task features as independent variables. Another important difference is that matching has been most successful in explaining display effects in relatively simple tasks (e.g., trend recognition, comparisons, value extraction), while strategy selection research has been largely concerned with more complex tasks (e.g., multiattribute choice). To illustrate, Jarvenpaa and Dickson (1988) found that the matching concept worked well for elementary tasks, but for studies of higher-level decision tasks, the results were inconclusive. In contrast, the strategy selection approach has accounted for display effects in complex choice problems (reviewed above), but has been less successful for simple perceptual judgments (e.g., framing effects; see Payne, 1982).

One possibility is that matching and strategy selection are distinct concepts that can not be applied to the same tasks. In introducing the cost-benefit approach, we emphasized that it applied to complex tasks in which the notion of planning (i.e., selecting a strategy) was meaningful. For elementary tasks, like point-reading or pattern recognition, strategy selection may be less useful than the matching approach for understanding the influence of displays. Because there are generally many equivalent means to achieve the goal in these simple tasks, strategies will differ little with respect to effort and accuracy (Brunswik, 1952). Thus, strategy selection may have little significance, because the effort required to choose among the equivalent strategies will exceed any benefit to be derived.

The results of one series of studies illustrate the possibility of matching displays to complex tasks. 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 suggested that this task can be decomposed into discrete phases (i.e., subtasks) and that effective performance for each phase is best supported by different display types. Specifically, they argued 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 argued 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 each stage of the problem. In the only study that investigated a combined format, they found it to be both the fastest and the most accurate (Benbasat et al., 1986b).

For complex (i.e., higher-level) tasks, the matching and strategy selection approaches may be compatible. Our account of strategy selection provides a mechanism that can explicitly map out how display characteristics can influence effort and accuracy in a particular task. Recall that strategies for complex tasks achieve their goal by defining a series of subtasks. A display will match a complex task to the extent that the efficient strategies for the given task require subtasks (and therefore, substrategies) that match the display. In another task, that same display might not match as well because the efficient strategies for that task may rely on subtasks that do not match the display. Because these subtasks include the elementary tasks often studied in the matching literature, the results of matching studies can be used as building blocks for studies of strategy selection in complex tasks.

## 4 Issues for Research

We have proposed that information displays influence decision making through the process of strategy selection. Specifically, differences in displays change the anticipated effort and accuracy of each available strategy and, therefore, provide an incentive for decision makers to use different strategies. Furthermore, the aggregate effects of displays on strategies should be analyzed in terms of the effects of displays on component substrategies. Researchers concerned with computer-based decision support need to move beyond simply measuring whether a display influences decision outcomes and should focus on how and why display characteristics influence the decision processes that produce these outcomes. Pursuing a strategy selection approach raises a number of issues in the design and implementation of display research. We address, in turn, issues related to measurement of dependent variables, research design issues, issues related to the distinction between anticipated and experienced effort and accuracy, and finally, possible extensions of the cost-benefit approach to other aspects of decision support systems.

### 4.1 Dependent Variables

Our emphasis on cognitive processes 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, Braunstein, & Carroll, 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 detailed discussion of coding and analyzing process tracing data can be found elsewhere (Carroll & Johnson, 1989; Ericsson & Simon, 1984).

Using verbal protocols to study displays with graphical elements may be more challenging because decision makers can have difficulty articulating valid verbal statements about visual encodings (Ericsson & Simon, 1984). However, at least one study has successfully used verbal protocols with displays of this type (e.g., Jarvenpaa, 1989). In addition, other process-tracing methods, particularly eye-movement data, may prove effective (Russo, 1978).

Our discussion has emphasized that there are some important variables that mediate the relation between display characteristics 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 connection, display experiments should ideally measure all of the following dependent variables: (1) Anticipated effort and accuracy, (2) strategy, (3) effort-related measures like decision time, and (4) decision quality or accuracy. Of these four categories, only the first has not been examined in previous research. Anticipations must, by definition, be measured prior to performing the task. This can be accomplished by asking for direct estimates of the effort and accuracy that the decision maker expects to achieve. One way to do this would be to present the decision maker with a list of possible strategies, and request predictions of effort and accuracy for each strategy. Another way would be to use indirect measures, such as presenting examples of displays and strategies and asking the decision maker to express preferences among them.

Recent developments in the 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 numerical items together, and 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 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 features. Simulation experiments that systematically vary display characteristics, task features, and strategies are capable of exploring the complex interactions among these factors. (2) Developing the simulations requires the researcher to specify the task features 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. These predictions place the theory at risk of *disconfirmation*, an important component of cumulative theory development (Meehl, 1978; Popper, 1959). This predictive test can be accomplished by directly comparing simulation results 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? Deviations from predicted behavior could also provide insight into the connection between anticipated and experienced effort and accuracy. For instance, suppose that a decision maker uses a strategy that the simulation identifies as inefficient. This might occur if the strategy appears to be efficient on the basis of the decision maker's biased anticipations. Thus, when simulations and actual behaviors fail to agree, biased anticipations provide one possible explanation for the disagreement.

Using the simulation approach generally requires the following four steps: (1) formally describe the 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 substrategies (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 3.1, 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 characteristics and task features (see Payne et al., 1988, for an illustration of the advantages of the formal approach).

## 4.2 Designs

Our approach also suggests some issues for the choice of independent variables and research designs. Figure 1 identifies three categories of independent variables that could be included in experiments: display characteristics, task features, and decision maker knowledge. We will discuss each of these in turn.

What display characteristics should be studied? The approach advocated here is to analyze displays in terms of form, organization, and sequence. The strategy selection research discussed above has typically manipulated these factors one at a time. The obvious alternative would be to examine them in combination. As an example, consider the studies of display organization discussed above (section 3.2.2). Jarvenpaa's (1989) study was noteworthy because it used a different information form yet produced results similar to previous studies. However, an even more compelling design would have been to examine form and organization in the same experiment—comparing simultaneous and sequential organizations using both numerical and pictorial information forms. Manipulating both independent variables in a single experiment permits the individual and joint influence of these display characteristics to be directly measured, enhancing the generalizability of the results. A particularly powerful way to design such studies is through the use of within-subject designs in which a decision maker is presented with different displays of the same problem (e.g., Stone & Schkade, in press). 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.

In studying display issues that have been raised in practice, analyzing displays in terms of form, organization, and sequence may be helpful. For example, the research comparing tables versus graphs has typically confounded form and organization. Consider a study that presents a set of observations of some variable either as a table of numbers or as frequencies on a bar chart. These two displays use different forms (numbers versus bars) but also use different organizations (a rectangular array versus a profile of the density of observations). In this study, there is no way to determine whether any effects on decision making are due to differences between the displays in form or in organization. A design that disentangles these two factors would need to include a display that combines bars with a rectangular array (e.g., a table composed of bars whose heights represent individual data values) and another that combines numbers with a density profile (e.g., stem-and-leaf diagrams; Tukey, 1977, ch. 1). Examining all four combinations permits us to determine whether differences result from the unique combinations of display characteristics rather than the individual influences of form and organization.

In a similar vein, there are task features that are known to influence strategy selection (e.g., problem size, response mode, similarity of alternatives, presence of dominated alternatives; Payne, 1982). These features should be included as independent variables to help evaluate the generalizability of display effects. For instance, suppose a particular display characteristic has an 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. One reason why different studies of the same display characteristic in the same task might produce seemingly conflicting results is that these other task features are not comparable across those studies.

Differences in decision maker knowledge may moderate the effects of displays on strategy selection. For example, in new or unfamiliar tasks a decision maker will have limited knowledge about strategies and will consider only a subset of the available strategies (e.g., Kleinmuntz & Thomas, 1987). In contrast, in familiar tasks the decision maker may have a large repertoire of standard decision strategies. Predictions of the influence of a display on strategy selection would have to account for differences in the set of strategies considered. Similarly, if a decision maker is unfamiliar with a particular type of display, certain operations may be quite difficult. Over time, the decision maker may learn how use the display more effectively, making those operations less effortful. This shift in cognitive incentives could lead to differences in strategy selection with the same display.

### 4.3 Anticipations and Experiences

Previous cost-benefit research has typically assumed that decision makers learn over time about the effects of varying task features on effort and accuracy. Consequently, strategy selection has only been analyzed in terms of experienced effort and accuracy. To the extent that anticipations differ from experiences, it is important for display research to maintain the distinction between the two. Research on the relation between display characteristics and anticipations promises to produce useful results.

To illustrate, the three display characteristics identified earlier (form, organization, and sequence) may have qualitatively different influences on a decision maker's anticipations. In particular, the influence of some display manipulations will be easier to detect and anticipate than others. Consider presenting all the information simultaneously on a single screen versus presenting information divided across a sequence of screens. It is easy for the decision maker to observe the difference between these two display organizations and anticipate that the ease of locating a particular item of information will differ between them. Finding an item of information that might be on one of a number of screens will obviously involve the extra effort of switching from screen to screen until the information has been located. On the other hand, from the decision maker's perspective, once the item is located, this organization manipulation will appear to have little effect on the ease of encoding the item or combining it with other information already in memory.

In contrast, information form will appear to have just the opposite effect—little if any influence on search and acquisition, but a large influence on encoding and combination operations. Consider presenting information either using numbers or equivalent verbal categories. If one holds organization constant (e.g., use a tabular display and replace the numbers with words), then from the decision maker's perspective, the anticipated effort required to locate any particular item of information is unaffected by the form manipulation. On the other hand, the information combination phase of decision making may require computing sums or differences, which will appear to be much harder with words.

In these two examples, we hypothesize that display organization primarily influences anticipations about information search and acquisition, while display form primarily influences anticipations about information combination and evaluation. This difference could be critical in determining the relation between anticipations and experiences because display changes that influence early stages of the decision process (i.e., information search and acquisition) may have a greater effect on anticipations than display changes that influence later stages (i.e., combination and evaluation of information). A decision maker may not be able to foresee all the steps necessary to complete a complex task. Consequently, those task features that are anticipated to have a large influence on early stages of the decision process may then have an inordinate influence on anticipations about the overall task. If decision makers base their anticipations for the whole task primarily on the parts they can see at the outset, then anticipations of overall effort and accuracy may be biased.

In contrast to form and organization, variation in information sequence may not be apparent to the decision maker at the outset of the task, and the decision maker may not be able to anticipate sequence effects at all. For instance, in a choice task, one could arrange to present either the choice alternatives or the attributes in different orders. Research on *agendas* in decision making suggest that presenting decision-relevant information in a constrained order can influence the probability of a particular alternative being chosen (Hauser, 1986; Hulland, 1988; Plott & Levine, 1978; Tversky & Sattath, 1979). For instance, suppose we know a decision maker intends to use a satisficing strategy (i.e., a conjunctive strategy) and we wish to increase the chance that one alternative is chosen over some others. The display could be arranged so that the favored alternatives are presented first (e.g., arranging the sequence of flights listed on an airline reservation system so one company's flights are listed ahead of the competition). If the decision maker evaluates alternatives in the order presented on the display, then the first acceptable alternative is likely to be the favored one.

An important aspect of this example is that the favored alternative is more likely to be selected only if the decision maker is unaware of the sequence manipulation. Decision makers who know about the manipulation may be able to anticipate the effect it will have on choice outcomes and possibly switch to a strategy that is not subject to the manipulation (e.g., a strategy that does not choose an alternative until all other alternatives have been examined). However, changes in information sequence can be quite subtle, so decision makers may not be able to detect them on their own. This highlights the fact that understanding the relation between displays and strategy selection will require an analysis of both anticipations and experiences.

## 4.4 Extensions to Other System Features

Our discussion has been based on a simplifying assumption that warrants further discussion: Specifically, we have assumed that display characteristics do not affect other features 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), and removing alternatives (e.g., screening out inferior alternatives). 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, 1990). 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 relation 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) used 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 or not 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 characteristics or could design the system to provide either a small or large set of alternative display characteristics, thereby permitting the decision maker to select among those characteristics 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. 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.

### 4.5 Conclusion

We have proposed that a theoretical understanding of cognitive processes in decision making can be useful for predicting and explaining the influence of information displays. This perspective is needed because previous display research has focused almost exclusively on the relation between the display and decision outcomes, with relatively little attention to the intervening relation between displays and decision processes. Given the confusing and inconsistent state of knowledge about display characteristics, a careful program of research based on cognitive approach has the potential to produce a new understanding of display effects that should ultimately lead to practical design guidelines. A cost-benefit approach seems particularly appropriate since system designers routinely make implicit trade-offs about users' 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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