Visual momentum: a concept to improve the cognitive coupling of person and computer

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(Received 29 March 1983, and in revised form 27 October 1983)

Computer display system users must integrate data across successive displays. This problem of across-display processing is analogous to the question of how the visual system combines data across successive glances (fixations). Research from cognitive psychology on the latter question is used in order to formulate guidelines for the display designer. The result is a new principle of person–computer interaction, visual momentum, which captures knowledge about the mechanisms that support the identification of "relevant" data in human perception so that display system design can support an effective distribution of user attention. The negative consequences of low visual momentum on user performance are described, and display design techniques are presented to improve user across-display information extraction.

Introduction

An area that has received little attention in the design of computer-based display systems is how the user integrates data across successive displays (cf. Badre, 1982). This issue is particularly important because the computer display user's task entails examining a succession of displays where the physical display surface available at any given time is very much smaller than the number of potential displays.† The problem of across-display processing is analogous, on a macroscopic level, to the question of how the visual system combines data from successive glances (fixations) into a stable percept of the world (Hochberg, 1978). In this article, research results from cognitive psychology on the latter question are used to formulate guidelines for the computer display designer on the former one.

"Getting lost" and "keyhole" phenomena in multiple display networks

Existing display construction guidelines tend to focus on the characteristics of individual displays. Failure to consider the requirements for effective across-display user information processing can produce devastating effects on user performance. One example is the "getting lost" phenomenon reported in large multiple display networks (Robertson, McCracken & Newell, 1981). Getting lost in a display network means that the user does not have a clear conception of relationships within the system.

† Display construction guidelines often attempt to avoid across-display issues by suggesting that each display frame should support a single task or sub-task. However, the user's sub-tasks must still be linked together to accomplish overall goals. Moreover, as Hollnagel & Woods (1983) and Badre (1982) point out, when displays support complex user tasks such as surveillance, fault detection and decision-making, user tasks are highly interrelated and spill over across display frames.
does not know his present location in the system relative to the display structure, and finds it difficult to decide where to look next within the system. The result is inefficient and incomplete utilization of display system data resources.†

A second example concerns the issue of serial versus parallel presentation of data. When the requirements of across-display information processing are ignored, computer-based display systems become a serial data presentation medium. The narrow “keyhole” the visual display unit (VDU) then provides can degrade user information extraction compared with so-called “parallel” presentation modes where all of the data is displayed simultaneously (Pope, 1978), for example, conventional hardwired control boards in process control applications.

The “getting lost” and “keyhole” phenomena are not inevitable consequences of using computer-based displays; neither do they represent human limitations (for example, short-term memory) that must be compensated for through memory aids or walls of VDUs. Across-display processing difficulties are the result of a failure to consider man and computer together as a cognitive system (Hollnagel & Woods, 1983), that is, a failure to match the system’s image of the user’s processing mechanisms to the actual characteristics of human cognitive function.

In contrast to the problems associated with serial data presentation, “parallel” (that is, simultaneous) presentation of data is claimed to be superior because, as Pope (1978, p. 4) states, “the human is used to having his total information system displayed and being able to sample and timeshare from his system by a movement of the eyes and his interpretive skills” (emphasis added). This suggests that the advantage attributed to parallel over serial data presentation is based on the characteristics of human perception and attention, rather than the mode of data presentation. Even when the entire data base is simultaneously available, the narrow field of view (2°) of the fovea (the high resolution portion of the retina) constrains the amount of data a viewer can acquire in any single glance. This is no limitation when viewing real-world scenes because there are psychological mechanisms which convert a “serial” input through a succession of eye fixations into what we commonly think of and experience as “parallel” data acquisition. User information extraction across displays can be improved if knowledge from cognitive psychology about the above perceptual and attentional mechanisms is applied to display system design.

Visual momentum

The effects of display system characteristics on across-display processing are best understood by examining the mechanisms the visual system uses to direct eye fixations and to integrate data across successive glances. Based on research into these questions (Bouma, 1978; Hochberg & Brooks, 1978a, b) one can define “visual momentum” as

† Across-display processing is not just display selection techniques: one thesis of this paper is that characteristics of the set of displays are also potent variables affecting user information extraction across displays. Cases such as Robertson et al. (1981) point out that across-display problems such as the getting lost phenomena occur even in systems which provide display selection mechanisms in accordance with accepted human factors guidelines.

Neither is the solution to across-display problems merely providing walls of VDUs. If the principle of visual momentum is not incorporated into the display structure, the visual guidance mechanisms will still be unable to fulfill their function.
a measure of the user's ability to extract and integrate information across displays, in other words, as a measure of the distribution of attention.†

When the viewer looks to a new display there is a mental reset time; that is, it takes time for the viewer to establish the context for the new scene. The amount of visual momentum supported by a display system is inversely proportional to the mental effort required to place a new display into the context of the total data base and the user's information needs. When visual momentum is high, there is an impetus or continuity across successive views which supports the rapid comprehension of data following the transition to a new display. It is analogous to a good cut from one scene or view to another in film editing. Low visual momentum is like a bad cut in film editing—one that confuses the viewer or delays comprehension. Each transition to a new display then becomes an act of total replacement (i.e. discontinuous); both display content and structure are independent of previous "glances" into the data base. The user's mental task when operating with discontinuous display transitions is much like assembling a puzzle when there is no picture of the final product as a reference and when there are no relationships between the data represented on each piece.

Low visual momentum is the equivalent of serial data presentation; the consequences are cognitive performance problems such as the getting lost and keyhole phenomena. On the other hand, high visual momentum represents what is meant by parallel data presentation, not simultaneous data presentation, but support for the user to sample data based on "a movement of the eyes and his interpretive skills". What are the psychological mechanisms that underlie these skills?

What guides our glances?

When observers scan a visual scene or display, they tend to look at "informative" areas.‡ There are two mechanisms which support this ability: an analysis of the global properties of the stimulus (Marr, 1976; Navon, 1977); and concept-driven or top-down analyses which start from information which the viewer already possesses (Biederman, 1972).

The global analysis process organizes the visual field into the psychological units (i.e. figures and ground) that attentional processes operate on (cf. Neisser, 1967; Kahneman & Henik, 1981). Global analysis is based on figural cues (such as shape, structure, and context). The global analysis process is driven by both bottom-up and top-down mechanisms. Bottom-up mechanisms are based on the properties of the stimulus, such as color, texture, and form. Top-down mechanisms are based on the viewer's knowledge and expectations about the stimulus. These mechanisms work together to help the viewer organize and interpret the visual scene.

†The concept of visual momentum as elaborated here is not the same as the concept of visual momentum as used by Hochberg & Brooks (1978a, b). At a general level, both concepts refer to the visual impetus or continuity across displays. At a more detailed level, Hochberg's visual momentum refers, in an esthetic sense, to visual interest; while visual momentum in a display system context refers to the user's ability to effectively extract information across displays.

‡Mackworth & Morandi (1967), Antes (1974) and Dobson (1980) have shown that areas judged as "highly informative" attract eye fixations. Yarbus (1967) has shown that eye movement patterns strongly depend on the viewer's task or specific information the viewer attempts to extract. Loftus (1976) and Loftus & Mackworth (1978) found that informativeness defined in a cognitive sense as redundancy or predictability affects fixation patterns. Based on these studies, informativeness, defined as some relation between the viewer and scene (for example, importance, expectation, predictability) rather than as only a property of the scene, is an important determinant of eye movement patterns. In other words, displays present data; data becomes information only when used to answer a question or to perform some task (S. L. Smith, 1963).
color, and location) that help define relationships across the stimulus field; in other words, which stimulus elements belong together and which belong apart (Kubovy & Pomerantz, 1981).

Finding and fixating "informative" areas is also based on concept-driven analyses which help to determine quickly the gist of a scene. This form of analysis is based on information or knowledge that the system already possesses in the form of schemata or internal models. Concept-driven analysis controls viewer data sampling behavior through cognitive and semantic factors; for example, an object incongruent with the active schema is informative (Loftus & Mackworth, 1978; Stark & Ellis, 1981).

Hochberg (1978) defines a schema as "the structure by which we encode (and can generate or reconstruct) more information than we can retain from individual items". In other words, a schema is an integrated representation of the relationships in a scene (Biederman, 1981). But schemata are not internal images; they also function as plans for obtaining more information about objects and events (Neisser, 1976). A pattern of eye fixations is like an exploration route of the visual scene. Like any explorer, the process will be much more organized and efficient if a map or representation of the area being explored is available for guidance. Concept-driven analysis utilizes a map or schema of the available and potentially available information in the stimulus world to guide and control data-gathering activities.

One corollary of concept-driven behavior is that the word observation is an empty term unless accompanied by a notation of what guides and/or activates the observation process. Observation looks for something, i.e. is guided by knowledge. Even browsing activities are guided; for example, I might go to the science fiction section of a library to look for a book I would enjoy. This example points out that the factors that guide the observation process can range from the very specific (I am looking for one book in particular) to the general (any science fiction book or even any "interesting" book). This is very often overlooked in interface design where the designer assumes, usually implicitly, that the user searches only for answers to specific, well formulated questions (cf. Goldstein & Bobrow, 1981).

The above conceptualization sees information processing as a perceptual cycle (Neisser, 1976; Fig. 1) where early, partial analyses of input focus subsequent data

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**Fig. 1.** The perceptual cycle [adapted from Neisser (1976)].
gathering (shifts in looking behavior or in attention) on regions that show signs of "interesting" activity. This view models cognitive processing, not as a fixed series of linear stages, but as a recursive set of operations including both data-driven and concept-driven activities (Palmer, 1975; Norman & Bobrow, 1976; Kubovy & Pomerantz, 1981) and emphasizes that perception is an active, inherently selective process of data gathering, that is, part of cognitive processing, rather than a process of passive reception and transmission prior to cognitive processing.†

The consequences of low visual momentum

The amount of visual momentum depends on the level of compatibility between the characteristics of the display system and the characteristics of perceptual processing and selective attention that direct our glances and help to integrate data across successive glances. When display system structure provides a visual frame of reference that describes the relationships among data points as well as the data points themselves, the viewer's attentional mechanisms can identify highly "informative" areas (high visual momentum). When no perceptual cues are available to support the global and concept-driven processing activities for guiding information acquisition, visual momentum is absent. Instead, the user must rely on other mental processes, of more limited capacity, to generate where to look and to know how the data acquired in one "glance" into the data base relates to data he has examined in the past and to data he might examine in the future.

When high capacity (i.e. automatic) perceptual mechanisms are bypassed due to interface characteristics, there is a mismatch between the system's image of the user's cognitive skills and his actual skills. Mismatches in the man-machine cognitive system increase the user's mental workload because demands are increased on limited capacity processing systems and because additional, irrelevant mental tasks are imposed on the user (Richards, Green, & Manton, 1979; Rasmussen, 1980).

Across-display performance problems are often observed as memory bottlenecks, and proposed solutions focus on aids to compensate for limited human short-term memory (cf. Robertson et al., 1981). However, memory problems are not the cause of performance difficulties like the "getting lost" phenomena; instead they are symptomatic of the mismatch in the man-machine cognitive system represented by low visual momentum.

The following passage, from a study of process control operator performance (Hollnagel, 1981), illustrates how the characteristics of a computer display system produced low visual momentum in the control performance of one operator.

The most interesting thing about the S's model of the system was the lack of correspondence between the Hot Well and the Feedwater Tank. As mentioned in the discussion of the S's performance, it was not until rather late that he realized, that the water which was pumped

† Is the principle of visual momentum intended to enhance how the user finds data or also how the user thinks about the data? In other words, is the principle visual or cognitive momentum? Based on the theoretical viewpoint that perception is part of human cognitive function, I have chosen to use the term visual momentum. The label "visual" emphasizes the role of high capacity perceptual processing within the domain of human cognition (cf. Chase & Simon, 1973). Whatever the label, the principle includes what are often called cognitive factors, for example, concept-driven behavior.
from the Hot Wells was ending up in the Feedwater Tank. He afterwards commented that he found the pictures of the Feedwater System quite difficult to use, among other things because the subsystems (Condensate and Feedwater) looked different from the Feedwater System (cf. the pictures). He complained that it was difficult for him to see on which side of the Feedwater Tank he was, when he only looked at a picture of a subsystem. Although this may be the case, it is nevertheless not sufficient to explain his curious forgetting of the Hot Well/Feedwater Tank relation since that should be evident from a purely functional analysis of the system. That means that he was heavily influenced by the way the system was represented in the pictures, and that this surface representation therefore limited the S's ability to reason about the deep structure (i.e. the functional structure) of the system. (Hollnagel, 1981, p. 133; emphasis added.)

This operator's performance shows how the perceptual characteristics of displays can affect human problem-solving behavior. Many studies in both applied and basic research contexts have shown that the form of problem representation can greatly influence problem-solving performance. Brooke & Duncan (1981) found, in studies of fault-finding performance, that display format affects "the ability of the diagnostician to perceive what is relevant and what is not" (Brooke & Duncan, 1981, p. 188; emphasis added). Problem-solving performance improves when representations have an integrated internal structure so that users can chunk data into higher order units (Mayer, 1976). Richards et al. (1979) studied how computer programmers processed different representations of conditional statements and found that good representations improve problem-solving because the user can solve the problem through a simpler mental process (cf. also, Pylshyn, 1979). "Making it easy to discover the facts can often be a matter of supplying perceptual cues, and so it turns out that tasks that at first sight seem deeply cognitive, such as comprehending a computer program, are susceptible to essentially perceptual factors" (Richards et al., 1979, p. 13; emphasis added).

The breakdown in the viewer's attentional processes represented by low visual momentum can also be seen in what has been described as "disintegration of the visual field" (Bartlett, 1943) or "cognitive tunnel vision" (Moray, 1981). Cognitive tunnel vision occurs when the user's attention is locked on a subset of variables to the exclusion of others. This decrease in the size of the field of attention (or deviation from optimum sampling patterns) can lead to monitoring failures, especially when the unexpected occurs or when correct state identification is a function of integrating data from several sources. In addition, tunnel vision effects can be exacerbated by high data density (Mackworth, 1976), by high arousal (Broadbent, 1978), and fatigue (Bartlett, 1943). Failures of selective attention such as the above can explain situations where a person has difficulties with a problem whose solution seems obvious with hindsight or to outside observers.

Consequences of low visual momentum can include: (a) cognitive tunnel vision, i.e. decreases in the size of the viewer's field of attention (Mackworth, 1976; Moray, 1981); (b) impaired ability to locate "important" data (Biederman, 1972; Loftus & Mackworth, 1978); (c) getting lost in display networks, i.e. the user finds it difficult to decide where to look next (Robertson et al., 1981); (d) memory bottlenecks due to increases in mental workload (Rasmussen, 1980; Rasmussen & Lind, 1981; Richards et al., 1979; Goldsmith & Schvaneveldt, 1982); and (e) decreases in problem-solving performance (Richards et al., 1979; Brooke & Duncan, 1981). In other words, low visual momentum degrades the user's ability to extract information from a display system.
Converting serial to parallel data presentation

When visual momentum is absent, the transition between displays is an act of total replacement of both data and format. The negative consequences for user information extraction have just been described. What techniques can be used to eliminate the problems associated with discontinuous display transitions?

The first technique display designers have applied to across-display processing problems is to provide a fixed format for each display frame. With this approach, classes of data are identified and assigned to specific screen locations so that the viewer can learn to link spatial location with data type; for example, message or menu areas. While the fixed format technique is useful, alone it is insufficient to prevent across-display processing problems (e.g. Robertson et al., 1981).

Based on studies of how people integrate data across successive views (e.g. Hochberg & Brooks, 1978a, b), there are a series of techniques available to increase the visual momentum a display system supports (Fig. 2). The key element in all of these concepts is to provide the viewer with data about the location of one view with respect to another or, more generally, with data about the relationships across display frames. The goal is to use the perceptual context to help the user construct and maintain a cognitive map or schema of the data structure. It is this internal model that results in the simultaneous representation of information.

It is important to note that across-display integration can refer to two types of display transitions: successive views across different units within the data base (different fields of view within a single representation) and successive shifts in the kind of view or representation of a single data unit (or, for that matter, shifts in representation across the entire data base). All of the techniques described here can be used in both types of situations. Furthermore, these techniques all work to aid across-display processing by building a spatial framework that reflects the semantic structure (meaning in relation to user function/tasks) of the data base.
LONG SHOT

A long shot or establishing view provides an overview of the display structure as well as summary status data. It is a map of the relationships among data that can be seen in more detailed displays and acts to funnel the viewer's attention to the "important" details. As a result, the viewer does not have to remember or construct a model of the data structure in his head. Bolt (1979), Herot (1980) and Engel, Andriessen & Schmitz (1983) contain examples of this technique.

For a summary display to provide an effective world view, the display system structure must explicitly incorporate a set of inter-display relationships that are important to the user's tasks to be portrayed in the long shot. Merely summarizing data is insufficient for effective across-display information extraction. For example, user performance suffered in the example from Hollnagel (1981) because the summary display did not portray the important functional relationships in the lower level displays.

PERCEPTUAL LANDMARKS

Another technique to join together successive views is to provide across-display landmarks (Hochberg & Gellman, 1977). Clear landmarks help the viewer to integrate successive displays by providing an easily discernable feature which anchors the transition, and which provides a relative frame of reference to establish relationships across displays. For example, Allen, Siegel & Rosinski (1978) found that across-display landmarks aided users in judgements that required integrating data across successive views. Landmarks are "features that are visible at a distance and that provide information about location and orientation" (Hochberg & Gellman, 1977, p. 23), that is, distinctive features which can be recognized through the global analysis mechanism. When some feature or object is immediately recognizable in a scene, schemas can be quickly activated to guide subsequent looking behavior. "Once an object is identified in a scene, we may quickly know the kind of company it keeps" (Biederman, 1981, p. 239).

DISPLAY OVERLAP

Another type of "glue" to enhance comprehension across display transitions is the use of display overlap. In one sense, a display system is one large display of the entire data base that the user examines in discrete chunks, or frames. From this point of view, the design of individual displays is the process of cutting the large data representation into pieces that will fit on the available display surface. To help the viewer integrate the individual pieces back into the complete representation, a simple technique is to overlap the pieces. Physically overlapping displays is a standard cartographic technique to increase viewer comprehension. Just as in maps, the overlap sections should not be presented at the same level of detail as the main portion of the display frame. Only those features needed to establish across-display relationships and to call the viewer's attention to other data and display frames should be incorporated as display overlap. In other words, display overlap can be used to support the global analysis mechanism in human perceptual function, although analysis of the viewer's decisions and tasks is required in order to choose the size and content of the overlap area effectively.

Overlap between successive views can also be established through the use of overlays. Overlays are a standard cartographic technique where several layers of data are presented on top of a common geographical framework. This technique could be used
in display design when a set of user tasks have some common ground. For example, in process control, different operations that are accomplished through manipulation of a common set of equipment could be represented by a configuration map with multiple overlays of task specific data (for example, execution rules) for the particular maneuvers performed on this topology.

The technique of physical display overlap can be limited because the amount of practical overlap is restricted by the available display surface. Furthermore, representing only the geographical relationships among data does not adequately support all of the user's mental tasks (cf. Rasmussen & Lind, 1981). A powerful alternative user aid is functional display overlap.

Functional overlap is a technique to present pictorially the functional relationships that cut across display frame boundaries. A display frame presents data with respect to a single topic; functional overlap occurs when each frame also contains data or pointers to data on semantically related topics such as goals or functional siblings (i.e. alternative means to achieve a goal). Displays of functional, rather than physical, form have long been used to portray electronic circuits (Bainbridge-Bell, 1953). In process control applications, if a system is designed to transport material to maintain inventory in some reservoir, the display should show data about system operation (for example, is there flow?) and data about goal achievement (for example, is inventory at target levels?).

Rasmussen & Lind (1981) have pointed out that systems can be described at different levels of representation that vary in abstraction (such as the physical components of the system, physical geography, functional structure, purpose) and field of attention (field of attention changes in size inversely with level of abstraction). Functional overlap also applies to integrating successive shifts in level of representation by serving as a pointer to outline relationships across representations. For example, a single physical component may support multiple goals and a given goal may have alternative physical implementations. In this case, functional overlap across levels of representation could take the form of annotating goal-related data with data on the types of activities which can achieve the goal and annotating each activity with data on the goals it can achieve. Using overlap in this fashion supports user cognitive tasks of goal-oriented assessment and goal-directed search (cf. Woods & Hollnagel, in preparation).

A related mechanism which can support continuity across representation shifts is to organize display windows in terms of levels of representation (Goodstein, 1982), for example, display windows to describe the status of any process, the status of the goals served by that process, and status of conditions required for that process. This technique of recursively defined functional display windows is particularly powerful for complex systems such as process control applications where there is a network or hierarchy of person-machine system goals (Rasmussen & Lind, 1981).

It is important to note that functional overlap can be implemented only if the functional relationships among data points are specified (i.e. how the data relate to the user's task?). By identifying relationships between data and user tasks and by paralleling those relationships in the structure of the display system, the user can more easily locate "important" and "informative" data.

**SPATIAL REPRESENTATION**

The long shot, landmark and overlap techniques all increase visual momentum by providing data about the location of one view with respect to another (for example,
what are the physical or functional relationships between successive views?). These techniques help to establish a spatial representation or frame of reference that describes the relationship between displays or between levels of representation.†

Spatial organization of data (spatial coding) is a potent aid to human cognitive processing (Miller, 1968; Bennett, 1971). The priority of space as an organizing principle is so compelling that non-spatial data is often given a spatial representation to improve user comprehension, for example, taxonomic trees in biology or computer program flow-charts. Spatial organization translates the normative user internal model into a perceptual map. The user sees, rather than remembers, the organization of data in the system and can move within the system just as he moves in an actual spatial layout. For example, there are office information systems organized around the spatial characteristics of the physical office, where virtual equivalents of physical objects are manipulated in a conceptual space or "desktop" (cf. for example, Zloof, 1977; D. Smith et al., 1982). Other examples of information systems that use spatial representation concepts include Bolt (1979), Nierergelt & Weydert (1980), Herot (1980) and Engel et al. (1983).

The display access mechanisms provided in a display system can help reinforce spatial representations of data. Display access methods and display system structure cannot be considered separately; they jointly determine the user's ability to process data across frames. For example, spatial access mechanisms will help to make the user's display selection task the equivalent of visual scanning in natural environments. One spatial access technique is to organize the data base as a topology and then provide the viewer with a mechanism to move through the space (cf., for example, Bolt, 1979). This can be accomplished by discrete moves (up/down, left/right, into/out of) through a network of fixed frames or by analog mechanisms (either scrolling or windowing) that allow the viewer to scan a large display plane through the VDU aperture. However, for the analog selection mechanisms to be effective, the user must be able to anticipate subsequent views; one method is to use a high resolution viewing area surrounded by a lower resolution, wide field-of-view area analogous to the fovea/periphery structure of the visual system (for example, Bolt, 1979). Bolt (1979) reports improved data access when the function of travelling over the data landscape is kept distinct from the function of examining a neighborhood in more detail.

Other spatial access techniques focus on route knowledge. Given a spatial representation, inter-display movements can be conceptualized as itineraries or paths through the space. Nievergelt & Weydert (1980) have used the concept of a trail as an object that can manipulated in person-computer dialogue. For example, in most display systems the user's path through the display structure is not remembered. When the user "turns around" to see where he has been, his path has disappeared. A back-up view allows the user to see and to retrace his steps without imposing a memory load.

A third example of spatial access is the use of display structure maps instead of or as a supplement to menus. The map function allows the user to see the set of display options while reinforcing his perception of the relationships across display frames.

† The concept of visual momentum is not simply a call for mimics as computer displays. Mimics, that is, displays of the physical geography of a system, can show low visual momentum as in the example from Hollnagel (1981) because (a) the pieces of the physical description are not integrated, (b) because the particular physical description does not portray the significant task related data, i.e. information, or (c) because a description in terms of physical geography is inappropriate to the user's tasks that the display set should support.
For example, Billingsley (1982) found that users can locate data targets within a display system faster and with fewer data requests using map- rather than menu-based data selection. After practice with both retrieval schemes, users were required to work in less-familiar parts of the display system. The shift from familiar to unfamiliar sections of the system did not affect map-based data selection performance; however, menu-based performance regressed to novice levels.

Spatial representations and spatial access provide structural information that reflects meaningful relationships in the data base. This makes the display system more transparent; that is, the process of finding data becomes a more automatic perceptual function rather than a limited capacity thinking function.

**SPATIAL COGNITION**

One goal of establishing visual momentum in a display system is to build an analogical representation or map of the underlying system or process to support human spatial reasoning skills (Oatley, 1977). In analogical representations, "the structure of the representation [i.e. the display system] gives information about the structure of what is represented" (Sloman, 1971, p. 216). For example, distance within a spatial representation can be used to indicate semantic relationships (cf. Nierergelt & Weydert, 1980). This characteristic produces significant economies of processing:

Using a map we can “get at” all the relationships involving a certain place through a single access point, . . . By contrast, each part of the region would have to be referred to many times, in a large number of statements, if the same variety of information were expressed in linguistic descriptions [or more generally, in propositional representations—the structure of the representation is independent of the structure of what is represented]. Moreover, a change in the configuration represented, may, in an analogical representation, be indicated simply by moving a dot or other symbol to a new position, whereas very many changes in linguistic descriptions of relationships would be required. (Sloman, 1971, p. 221.)

The economies of analogical representation reduce mental workload (for example, the memory and referencing demands of propositional representations) and increase the transparency of interface systems (i.e. reduce the attention demanded by the interface since relationships in the interface reflect relationships in the underlying system or process).

Spatial knowledge can occur in the form of routes, that is, itineraries such as particular data sampling patterns or task sequences, or in the form of general maps, that is, a specification of the domain or world that routes occur within (Toulmin, 1960). One property of maps (i.e. analogical representations) is that all points are simultaneously available (“parallel” data acquisition). This equiavailability principle (Levine, Jankovic & Palij, 1982) is shown by (a) the ability to generate specific routes as task demands require (that is, to derive new and unforseen information, particularly in the form of new relationships among data), (b) the ability to traverse or generate new routes as skillfully as familiar ones [note Billingsley's (1982) results with map-based versus menu-based data selection], (c) orientation abilities, that is, the development of a concept of “here” in relation to other places. The result is an advantage of analogical representations that is equivalent to

the marvel of cartography: the fact that, from a limited number of highly precise and well-chosen measurements and observations, one can produce a map from which can be read off an unlimited number of geographical facts of almost as great a precision. (Toulmin, 1960, p. 111.)
Route knowledge becomes available in parallel, not because it is simultaneously available in the user's short-term memory (a catalog of itineraries), but because analogical representation supports a route generation process (in the sense of a mental skill). Memory bottlenecks occur when there are problems in the route generation mechanism; for example, because the user has no perceptual or internal map.

The above set of techniques for increasing the visual momentum within a display system provides designers with data on how to improve across-display continuity. These techniques lead to the advantages associated with parallel data presentation through support for the user's perceptual and attentional skills at locating "informative" data. These skills can be supported through the construction of a spatial framework that reflects meaningful relationships among data elements, that is, by constructing a conceptual or virtual space to represent data, particularly data that is not directly or necessarily spatial in character.

Discussion

MENTAL WORKLOAD

At several points, I have suggested an inverse relationship between visual momentum and user mental workload. Given that a person has limited mental resources and that mental operations vary, from automatic to effortful, in the amount of these resources they require (Kahneman, 1973), visual momentum can affect mental workload in several ways: (a) by making information location and integration a more perceptual process; (b) through changes in the organization of mental processes (simpler, more compatible); for example, the economies of analogical representations; and (c) by providing spatial/perceptual cues which are automatically encoded with and serve as retrieval cues for content-related information on system state (Hasher & Zacks, 1979); for example, we often use memories for the location or appearance of the source of some piece of information as cues in order to search for or to recall that information.

DATA SAMPLING BEHAVIOR

Across-display information extraction is closely related to questions of user data sampling behavior. Based on the Sampling Theorem of Shannon, an optimum frequency of data sampling can be determined in a single control task (Senders, Elkind, Grignetti & Smallwood, 1966). This type of sampling model has been expanded to include other factors; for example, the effects of payoff structure (Sheridan, 1970).

Additional factors become important in sampling behavior when one considers the characteristics of dynamic decision environments (Moray, 1981). Moray (1981, p. 187) notes that in complex person–machine systems such as process control: (a) there are multiple dynamic data sources; (b) there is a hierarchy of performance goals; (c) the data elements are richly interconnected (therefore, they vary in degree of correlation); and (d) the data elements are diagnostically ambiguous (the state of one variable is generally insufficient to characterize the status of the process). As a result of this analysis, Moray points out that information on the physical or functional structure of the process should be used in the generation of search tactics.

To extend Moray's analysis, data elements are often indirect measures of the quantities of interest, and the relevant interconnections between data points vary with
process state and user task. In other words, the operator must synthesize the information required to perform his tasks by integrating and interpreting data elements. Given the above characteristics of dynamic decision environments, successful data sampling is a function of the user's ability to group "relevant" data elements together and to distinguish "relevant" from "irrelevant" data. As discussed earlier, what is relevant depends on the context, that is, the relationship between user expectations/tasks and data, i.e. the perceptual cycle. Visual momentum captures knowledge about the cognitive activities that support the identification of "relevant" data in human perception so that display system design can support an effective distribution of attention.

PRINCIPLES OF HUMAN-MACHINE COGNITIVE PERFORMANCE

Ergonomic guidelines on the design of computer displays generally attempt to ensure that human sensory limits are not strained. If the design process stops at this level, there is an implicit assumption that if the user can potentially see/read the data, then he will and should find, integrate, and interpret all of the "right" data at the "right" time. However, human performance problems in display systems such as the getting lost phenomena and cognitive tunnel vision demonstrate that the potential to see/read data does not guarantee successful user information extraction.

In addition to ergonomic guidelines, principles of human–machine interaction at the level of cognitive performance, such as visual momentum, are needed to improve the "cognitive coupling" (Fitter & Sime, 1980) between person and computer. These principles† are a mechanism to translate knowledge (data/models) from cognitive psychology into a form useful to designers (Fig. 3). They describe how characteristics of the interface affect or interact with the user's cognitive skills and can help the designer achieve a better match between the system's image of the user's cognitive skills and actual user characteristics (Hollnagel & Woods, 1983). For example, the principle of visual momentum relates several human performance problems with display

Fig. 3. Knowledge from cognitive psychology applied to interface system design.

† These concepts are called principles because they are not guidelines that can be rote or directly applied; rather, they are meta-guidelines which the designer can use to derive the specific guidelines to match the specific application.
systems to a single underlying mechanism and identifies techniques that can be used to help solve them. The result is that the process of developing improved forms of person–computer interaction becomes principle-driven rather than ad hoc or trial-and-error.

I thank Erik Hollnagel, Jens Rasmussen, Robert Tain and James Little for the many discussions of person–computer interaction that helped to develop these concepts and for many helpful comments on earlier versions of the manuscript. Requests for reprints should be sent to D. D. Woods, Westinghouse R & D Center, Pittsburgh, Pennsylvania 15235, U.S.A.

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