Human-Centered Information Visualization

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Abstract: Information visualization should be human-centered because by definition it is the process of designing information to match the processing characteristics of human visual system. This is largely true for many special purpose visualization products regardless of whether the human-centered approach is taken deliberately in the design process. However, this type of human-centered visualization is typically only at the level of representations, which are relatively independent of tasks, users, and functions. In this paper we argue that human-centered visualization should be considered not just at the level of representations but also at the levels of functions, users, and tasks. This multiple level approach is important for the design of complex information systems that support multiple types of users performing varieties of tasks in different contexts to achieve different goals. We will first describe a framework of multilevel human-centered visualization. Then we will use one simple example to demonstrate the concept of this multilevel human-centered approach, focusing on the relations between tasks and representations.

1. Introduction

Information visualization is the static or dynamic presentation of information in an external representation such that the information can be processed by efficient human visual mechanisms. Significant advances have been made in the theoretical frameworks, empirical studies, methodologies, tools, and products of information visualization (Card, Mackinlay, & Shneiderman, 1999). The key idea of information visualization is to make use of people's powerful visual system to efficiently process information that otherwise requires more cognitive effort. Human visual system is powerful because it can process information in parallel, automatically, and unconsciously, and it can bypass the bottleneck of human working memory that is limited in capacity. The information in a visualization resides in external representations (Zhang, 1997b, 2000; Zhang & Norman, 1994), which are the knowledge and structures in the environment, as physical symbols, objects, or dimensions (e.g., written symbols, beads of abacuses, dimensions of a graph, etc.), and as external rules, constraints, or relations embedded in physical configurations (e.g., spatial relations of written digits, visual and spatial layouts of diagrams, physical constraints in abacuses, etc.). External representations have the following nice features that make visualization attractive:

- Provide short-term or long-term memory aids so that memory load can be reduced.
- Provide information that can be directly perceived and used such that little effortful processing is needed to interpret and formulate the information explicitly (Gibson, 1979; Zhang & Norman, 1994).
- Provide knowledge and skills that are unavailable from internal representations (Chambers & Reisberg, 1985; Reisberg, 1987).
- Support perceptual operators that can recognize features easily and make inferences directly (Larkin & Simon, 1987).
- Anchor and structure cognitive behavior without conscious awareness (Norman, 1988; Zhang & Norman, 1994).
- Change the nature of a task by generating more efficient action sequences (Norman, 1991, 1993).
- Stop time and support perceptual rehearsal to make invisible and transient information visible and sustainable (Tweney, 1991, 1992).
- Aid processibility by limiting abstraction (Stenning & Oberlander, 1995).
- Determine decision making strategies through accuracy maximization and effort minimization (Kleinmuntz & Schkade, 1993).

Information visualization, by its very nature, should be human-centered, because by definition it is the process of designing information to match the processing characteristics of human visual system. This is largely true for many special purpose visualization products (e.g., TreeMaps, Hyperbolic View, Cone Trees, etc.), regardless of whether the human-centered approach is taken deliberately in the design process. This type of human-centered visualization is typically only at the level of representations, which are relatively independent of tasks, users, and functions. In this paper we will argue that human-centered visualization should be considered not just at the level of representations but also at the levels of functions, users, and tasks. This multiple level approach is important for the design of complex information systems that support multiple types of users performing varieties of tasks in different contexts to achieve different goals. We will first describe a framework of multilevel human-centered visualization. Then we will use one simple example to demonstrate the concept of this multilevel human-centered approach.

2. The Framework of Multilevel Human-Centered Visualization

In the design of human-centered computing systems we need to consider not just the surface level user interfaces but also deeper structures of tasks, users, and functions. This approach, central to the general field of human-computer interaction and user interface design, is applicable to visualization as well because visualization is the design of an information system (simple or complex, static or dynamic). Figure 1 shows the framework of multilevel human-centered visualization. Most information visualization systems are primarily at the level of representational analysis. We first discuss the component levels of this framework. Then we will use one simple example to demonstrate its principles.

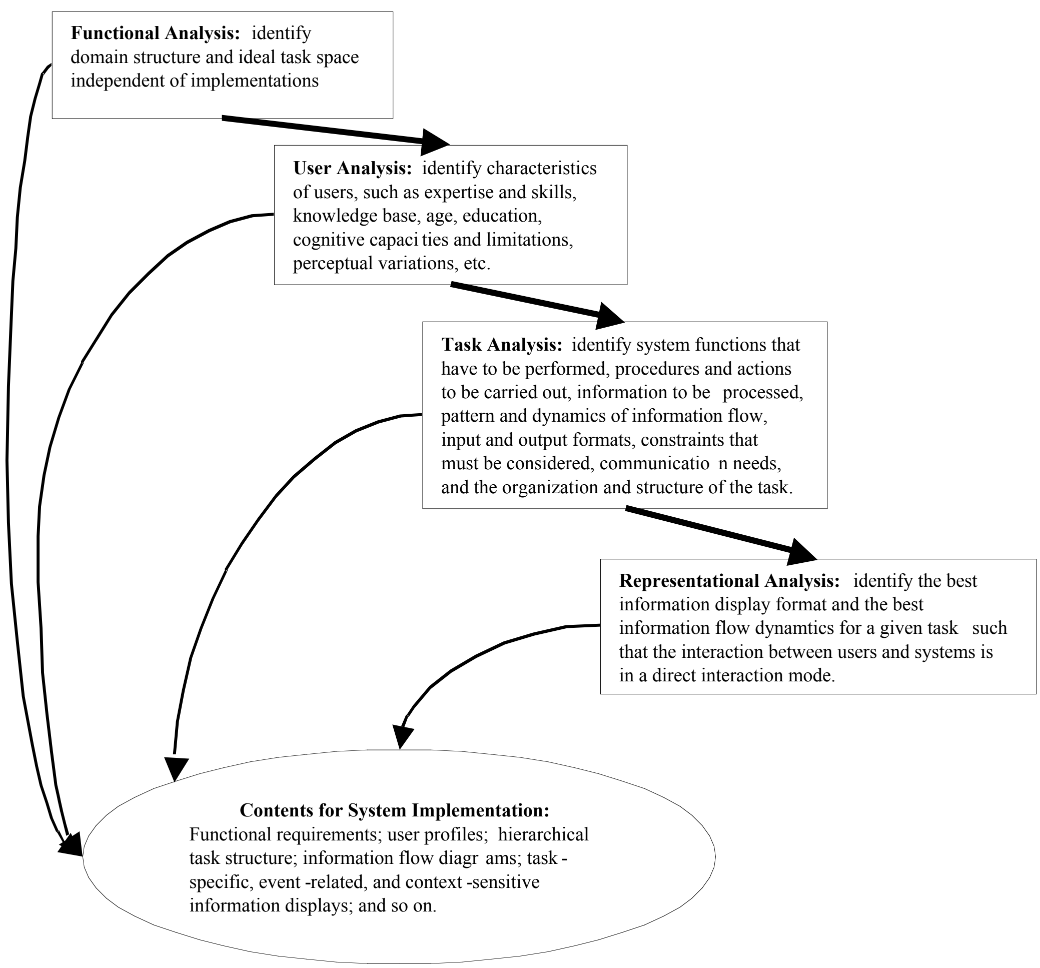


Figure 1. The Framework of Multilevel Human-Centered Visualization.

2.1. Functional Analysis

Functional analysis is the process of identifying critical domain relationships, goals and means to achieve the goals, ideal task structure and information flow, and the structures of problem space. Work domain analysis and cognitive work analysis are two examples of functional analysis (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). Functional analysis is performed based on extensive interactions with expert practitioners in the domain.

2.2. User Analysis

User analysis is the process of identifying the characteristics of existing and potential users, such as expertise and skills, knowledge base, education background, cognitive capacities and limitations, perceptual variations, age related skills, cultural background, personality, time available for learning and training, frequency of system use, etc. User analysis will help us design visualization systems that have the right knowledge and information structure that match that of the users. User analysis can be performed along two dimensions. Horizontal user analysis focuses on different users who use different parts of the system, such as installers, maintainer, system administrators, users who prepare input for the system and users who use the end product or output of the system. Vertical user analysis focuses on different users who have different levels of understanding of the same component of the system, such as beginners, novices, intermediate users, and experts.

2.3. Task Analysis

Task analysis is the process of identifying system functions that have to be performed, procedures and actions to be carried out to achieve task goals, information to be processed, input and output formats that are required, constraints that must be considered, communication needs that have to be satisfied, and the organization and structure as well as the information categories and information flow of the task (e.g., Hackos & Redish, 1998; Kirwan & Ainsworth, 1992). The general purpose of task analysis is to ensure that only the necessary and sufficient task features that match users' capacities and are required by the task will be included in system implementations. Extra fancy features and features that do not match users' capacities or not required by the task will only generate extra processing demands for the user and thus make the system harder to use. The goal-device-task language is typically used to describe task analysis. Goal is a state of a system to be achieved; device is an instrument, method, agent, tool, technique, or skill that is used to achieved a goal; and task is the sequence of activities required to achieve a goal using a particular device.

Hierarchical task analysis is the basic analysis for any task. It is to describe a task in terms of a hierarchy of operations and plans by using a graphical representation of a decomposition of a high level task into its constituent subtasks and operations. It typically shows the big picture of the components of the task and the relations among the components. Cognitive task analysis is a specialized technique that takes into account both physical and mental activities (Schraagen, Chipman, & Shalin, 2000). It is important for the design of any human-centered visualization system.

One important end product of task analysis for visualization is a taxonomy of tasks based on the types of information processing needs. For example, there are information tasks for retrieval, gathering, seeking, encoding, transformation, calculation, manipulation, comparison, organization, navigation, and so on. The identification of different information processing needs is essential for the creation of task specific, context-sensitive, and event-related information visualizations.

2.4. Representational Analysis

Representational analyses can be performed on system functions and features that are identified through the functional, user, and task analyses described above. Representational analysis is the process of identifying the best information display format and the best information flow structure for a given task performed by a specific type of users such that the interaction between users and systems is in a direct interaction mode (Zhang, 1996, 1997a; Zhang & Norman, 1994, 1995). With direct interaction interfaces, users can directly, completely, and efficiently engage in the primary tasks they intend to perform, not the housekeeping interface tasks that are barriers between users and systems (Hutchins, Hollan, & Norman, 1986; Shneiderman, 1983). Representational analysis is meanwhile a methodology that can systematically generate innovative visualizations of data and information. It has been applied to the analysis of the relative representational efficiencies and degrees of directness of several systems, including relational information displays (Zhang, 1996), numeration systems (Zhang & Norman, 1995), and cockpit instruments (Zhang, 1997a). Representational analysis is based on three representation principles: hierarchical, isomorphic, and distributed representations, which can be used to systematically generate an unlimited number of alternative visualizations for exploration, evaluation and selection. Distributed representation is the major principle for analyzing how information distribution patterns affect the performance level of a distributed cognitive system.

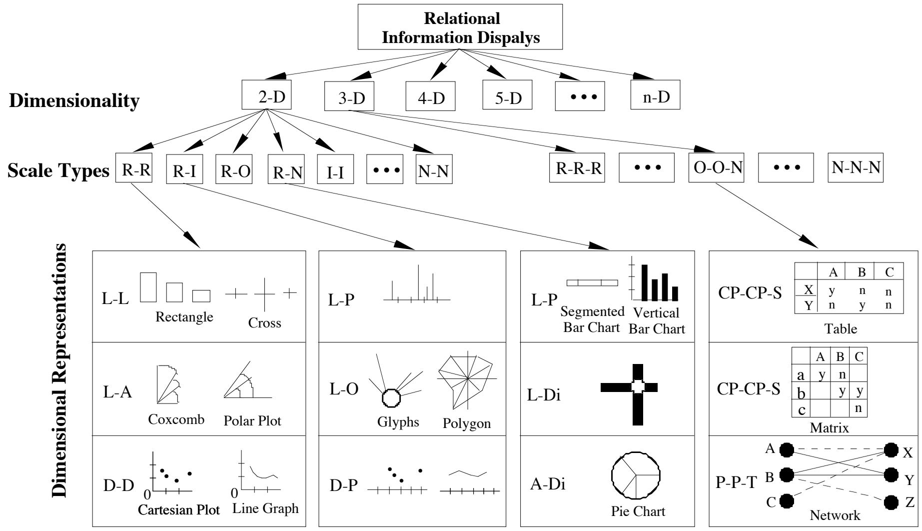


Figure 2. A representational taxonomy of relational information displays. A = Angle, CP = Cell Position, D = Distance, Di = Direction, L = Length, O = Orientation, P = Position, S = Shape, T = Texture. (Zhang, 1996).

One major topic in information visualization is the representation of relational information. (Zhang, 1996) developed a representational taxonomy that can categorize all types of relational information displays, as shown in Figure 2. At the level of dimensionality, different displays can have different numbers of dimensions. At the level of scale types, the dimensions of a display can have different scale types: ratio (R), interval (I), ordinal (O), and nominal (N) scales. At the level of dimensional representations, each scale type can be implemented by different physical dimensions. For example, a ratio scale can be represented by length, distance, and angle; interval scale by position and orientation; an ordinal scale by cell position; and a nominal scale by shape, direction, texture, and position. The representational taxonomy of relational information displays, when combined with a task taxonomy of display tasks, can systematically determine the best display format for a specific task. During the representational analysis of a visualization system, alternative displays for each task can be identified in the task taxonomy of different information processing needs and the best match between a display and a task for each unique event under each unique situation can be determined. This collection of task-specific, context-sensitive, and event-related displays is the basic elements for the implementation of visualization systems.

3. Information Displays for Altitude in Aviation

In this section, we use a simple example to demonstrate the principles of the framework of multilevel human-centered visualization. We use the framework to analyze a set of preexisting displays: altimeters in aviation. The altimeter in an airplane cockpit is an instrument display that indicates the altitude of the airplane. The three diagrams at the top of Table 1 show three typical altimeters used in many airplanes.

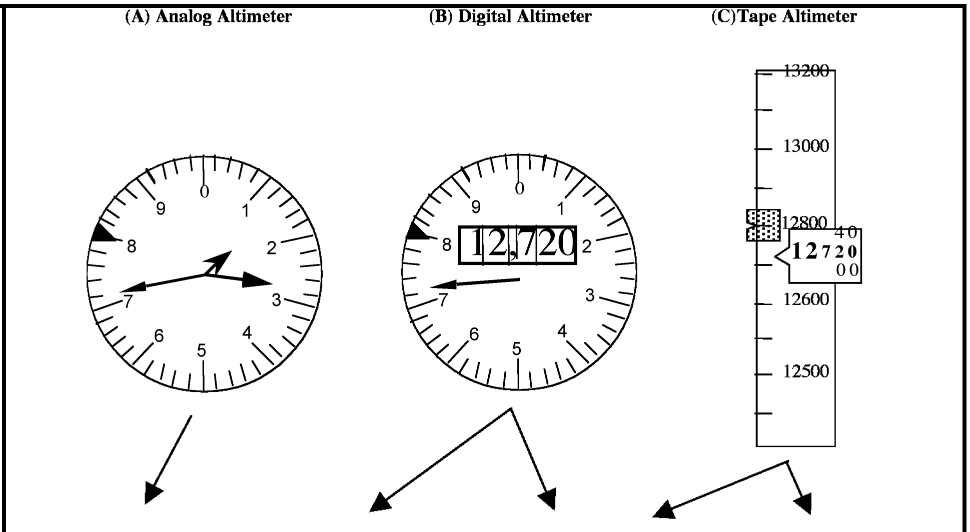
3.1. Functional Analysis

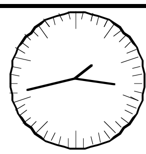
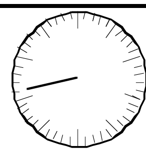
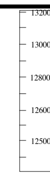
The primary function of an altimeter is to provide altitude information (static or dynamic) to the pilots for the taxing, taking off, cruising, and landing of an airplane. This function can be provided by many different implementations. The three altimeters in Table 1 are only a few of them.

3.2. User Analysis

Pilots are the only users of the altimeters in a cockpit. Pilots are highly trained domain experts who are trained on every cockpit instrument, including the altimeter. Altimeter is one of the many instruments a pilot uses, especially during taking off and landing. High workload and multitasking during taking off and landing can significantly affect the pilot's processing of altitude information. A good design of the visual information is essential for the safe operation of the aircraft.

Table 1. Altimeters: The Mapping between Tasks and Representations



Altimeter Tasks	(A) Analog Altimeter		(B) Digital Altimeter	(C) Tape Altimeter
			12,720	
Reading Number	Poor	Poor	Good	Moderate
Perceiving Motion	Moderate	Moderate	Poor	Good
Perceiving Position	Moderate	Poor	Poor	Moderate
Capturing Altitude	Moderate	Moderate	Poor	Good
Maintaining Altitude	Good	Good	Poor	Good

3.3. Task Analysis

Providing the value of an altitude is only one of the many functions that an altimeter is designed for. An altimeter in a cockpit is typically used to perform five different tasks:

- Reading the absolute numeric value of an altitude.
- Perceiving the direction of vertical motion.
- Perceiving the vertical position of the airplane.
- Capturing a specific altitude.
- Maintaining a specific altitude.

3.4. Representational Analysis

Three altimeters were selected for the representational analysis. In the analog altimeter, the numbers (altitudes) are represented by two dimensions (see Zhang & Norman, 1995, for detailed analysis of number representations). The base dimension is represented by orientations. The power dimension is represented by the three hands of different lengths: long hand = 10^2 feet, medium hand = 10^3 feet, short hand =10^4 feet. The little triangle inside the altimeter is the altitude bug used to remind a pilot of a specific altitude. The digital altimeter is composed of two parts: the digital part and the analog part. The digit part is represented by Arabic numerals, which have two dimensions: the base dimension represented by shapes and the power dimension represented by positions. The analog part has one dimension represented by orientations, which only represent altitudes on the order of 10^2 feet or less. The little triangle inside the altimeter is the altitude bug used to remind a pilot of a specified altitude. The tape altimeter is also composed of two parts. The digital part is the same as that in the digital altimeter. The tape part has one dimension represented by height. The darkened label pointing to 12800 feet is the altitude bug used to remind a pilot of a specific altitude.

3.5. The Relations Among Functions, Users, Tasks, and Representations

The altimeter is a simple display that is used by a very specialized user group for a well-defined function. The interesting and significant relations among functions, users, tasks, and representations are mainly between tasks and representations. For other complex information systems, however, all relations may be important. The following paragraphs mainly describe the relations between tasks and representations of altimeters.

Analog altimeter. The analog altimeter is poor for reading the numeric value of an altitude (Table 1). First of all, the reading requires shifting attention to three different places indicated by the three hands. Second, one must learn the relation between the lengths of the three hands and the powers they represent: the shorter the hand, the higher the power they represent. Third, the absolute value of an altitude has to be computed, because the readings of the three hands have to be multiplied by their powers (10^2, 10^3, 10^4) and then added. The perception of vertical motion is easy by noting the rotation of the hands. However, the relationship between the hands' rotation and the direction of an airplane's vertical motion is arbitrary (clockwise means ascending, counterclockwise means descending). This relation is culturally defined and has to be learned. The analog altimeter represents the vertical position of an airplane poorly. First, the vertical position is one-dimensional. But the analog altimeter has two dimensions. Second, orientations do not map vertical distances directly. The altitude bug is usually set to a specific altitude such as cruising altitude, decision height, or minimum descent altitude. The analog altimeter is relatively easy for the task of capturing a specific altitude by noting the agreement of the longest hand and the altitude bug. However, because the longest hand only has 100-foot intervals, the readings from the other two hands are also needed in order to capture a specific altitude. Maintaining an altitude is easy with the analog altimeter: simply keep the longest hand pointing to the altitude bug that is set to the specific altitude.

Digital altimeter. The digital altimeter has two parts. The digital part is good for reading the numeric value of an altitude. However, it is poor for motion perception for two reasons. First, the base dimension of Arabic numerals is represented by shapes. Second, the numerals change too rapidly to let the direction of change be seen clearly. The digital part is poor for position perception, because the Arabic numerals have two dimensions. It is also poor for capturing and maintaining a specific altitude, because it is hard to keep tracking the change of the numerals. The analog part is poor for number reading, because it does not specify the full range of altitude (it can only show the values on the power of 10^2). It is moderate for motion perception, poor for position perception, moderate for capturing specific altitudes, and good for maintaining specific altitudes, for similar reasons discussed for the analog altimeter.

Tape altimeter. The tape altimeter also has two parts. The digital part is the same as that of the typical digital altimeter. The tape part is moderate for number reading, because though it does not require shifting attention to different positions, it only shows the numeric values accurate to the order of 10^2. It is moderate for position perception. On the one hand, it is one-dimensional, which directly corresponds to the spatial property of altitudes. On the other hand, though the tape cannot display the full range of the height of an airplane, it can at least show the interval information of height, which is a ratio dimension. (The tape is on an interval scale because it only shows a portion of the full range of altitude, that is, it does not have an absolute zero). The tape part is good for motion, because the vertical motion of an airplane is reflected by the motion of the tape. Unlike the analog altimeter, which needs not only to align the longest hand with the altitude bug but also the readings from the other two hands, the tape part is good for capturing a specific altitude, because the altitude bug on the tape shows the specific altitude directly. The tape part is also good for maintaining a specific altitude, because the task is simply to keep the altitude bug in alignment with the central pointer.

From the above analyses of the three altimeters, we can see that different representational formats are good for different tasks. Sometimes different representations that are good for different tasks are combined such that the combined representation can be good for a larger set of tasks, as the digital and the tape altimeters show. If we consider the digital and the tape altimeters as combined units, then the tape altimeter is better than the digital altimeter, which in turn is better than the analog altimeter. The analyses of the representational properties of altimeters and the mappings between tasks and representations can be used to find out relative representational efficiencies of existing altimeters and to guide the design of new altimeters.

Conclusions

Information visualization should be human-centered not just at the level of representations, as it is typically the case in many visualization products, but also at the levels of functions, users, and tasks. Without the consideration of human-centered design at all of the four levels mentioned above, a visualization may only be a good representation of the surface features of a domain. An average visualization of a different task structure that has the same functions of the same domain might be much more efficient than an excellent visualization on a poor task structure of the same domain. Visualizations are also critically dependent upon the users of the visualizations. A good visualization for one user may not be a poor visualization for a different user because the variations of user characteristics. As a general principle in human-centered display design, there is no best display for every user performing every task in every context. The framework of multilevel human-centered visualization we developed here provides a systematical conceptual guideline for the design of human-centered information visualization systems.

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