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Information visualization and its application to medicine

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Abstract

This paper provides an introduction to the field of information visualization (IV) and a discussion of its application to medical systems. More specifically, it aims at: (i) defining what IV is and what are its goals (ii) highlighting the similarities and differences between IV and traditional medical imaging (iii) illustrating the potential of IV for medical applications by examining several examples of implemented systems and (iv) giving some general indications about the purposes and the effective exploitation of an IV component into a medical system. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The amount and the complexity of data available at clinicians' fingertips are constantly increasing as a result of technology advancements in computer performance and storage capacity. Unfortunately, due to well-known cognitive and perceptual limitations, the quantity of information a user can examine and handle at a given instant is very limited. Therefore, the various members of the clinical staff (physicians, technicians, nurses, students, managers) will not be able to take advantage of these increasingly large amounts of data and will also incur the risk of being overwhelmed by them, if computer applications do not take adequately into account effective presentation and interaction with data. Answers to these problems are a central theme of study and development in the rapidly growing area of information visualization (IV).

IV can thus play an important role in the development of most kinds of medical systems, and the purpose of this paper is both to provide an introduction to the field of IV and to

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highlight its importance in medical applications. First, we will define more precisely what IV is, what are its goals, and what are the kinds of data it operates on. Then, we will concentrate on IV for medical data, also illustrating significant case studies in different categories. The concluding section contains some remarks about the effective exploitation of IV in medical systems.

2. Information visualization: definition, goals and taxonomy

Visualization is generally defined as "the act or process of interpreting in visual terms or of putting into visible form" [11]. Information visualization can be defined as "the process of transforming data, information, and knowledge into visual form making use of humans' natural visual capabilities" [7] or, more concisely, as "the computer-assisted use of visual processing to gain understanding" [1].

IV aims at reducing the complexity of the examination and understanding of information for humans, by designing proper techniques for the visual display of data. These techniques are aimed at achieving a number of goals, such as: (i) allowing users to explore available data at various levels of abstraction (ii) giving users a greater sense of engagement with data (iii) giving users a deeper understanding of data (iv) encouraging the discovery of details and relations which would be difficult to notice otherwise and (v) supporting the recognition of relevant patterns by exploiting the visual recognition capabilities of users.

As highlighted by the last two goals, IV aims at making the user an active element in pattern recognition, allowing him/her to detect what would pass unnoticed through automatic recognition systems. From this point of view, IV components and data mining components can have complementary and synergic roles inside the same application.

Different research groups in IV have proposed diverse approaches to achieve one or more of the above mentioned goals. Some attempts at proposing taxonomies for the different kinds of IV have been made in the literature. The most cited and influential proposal appears in [23], where Shneiderman classifies IV approaches along two dimensions: data type and task. The task dimension of the classification identifies seven high-level tasks [23]: overview (gain an overview of the entire set of data), zoom (zoom in on a subset of items of interest), filter (filter out uninteresting items), details-on-demand (select one or more items and get details), relate (view relationships among items), history (keep a history of actions to support undo, replay, and progressive refinement), extract (allow extractions of subsets of items).

Seven data types for the items to be displayed are identified [23]: 1D (linear data organized in a sequential manner, such as alphabetical list of names, program source code, or textual documents), 2D (planar or map data covering some part of an area, such as maps, newspaper layouts, or photographs), 3D (data with volume and potentially complex relations with each other, such as molecules, the human body, or buildings), temporal (data with a start time, finish time, and possible overlaps on a timescale, such as that found in medical records, project management, or video editing), multi-dimensional (data with n attributes which becomes points in a n-dimensional space, such as records in relational and statistical databases), tree (collections of items linked hierarchically by a tree structure, such as computer directories, business organizations, genealogy trees), network (collections of items linked by a graph structure, such as telecommunication networks, World Wide Web or hypermedia structures).

The data items in each above mentioned category can have multiple attributes (e.g. a 3D object could have additional attributes such as color, level of transparency, and brightness; a node item in a tree could have additional attributes such as a name, a creation date, a modification date; and so on). Therefore, the separation among the different categories is not always strict, e.g. temporal data can be also seen as an instance of multi-dimensional data. However, this separation is useful for orienting the choice of IV techniques, e.g. when the temporal aspect is dominant in the considered data, display techniques that give a central role to time (such as timelines to visualize personal histories [16], temporal animations to show the evolution of physical phenomena using a familiar VCR metaphor, and so on) can give better results than more general techniques which do not assume specific relations among the multiple attributes. Similar considerations hold between pairs of other data types where one data type can be seen as a specialization of the other (e.g. tree and network, 3D and multi-dimensional).

In general, many display design options exist for mapping each of the above described categories into a visual representation. For example, a first possibility to display a large tree structure can be to map it into the traditional 2D geometric representation we are accustomed to. However, more innovative mappings have been proposed in IV. For example, a second possibility can be the Camtree [19,20], which exploits a 3D geometry to display hierarchical structures in a more compact way than 2D: the sons of every node are placed on a 3D cone that connects them to the father, so that the growth of the tree is less than the corresponding 2D geometry; when a node is chosen, the different cones rotate in order to take the node and its parents into closer view; the projection of 3D shadows highlights the presence of possibly hidden parts. As a third possibility, we can apply a graphic distortion technique to a standard 2D representation of the large structure to achieve contextual focalization (i.e. allowing the user to concentrate on the part of current interest without losing the general context). For example, one well-known technique of this kind is the fish-eye view [21], that magnifies the objects visualized in the point of greater focal attention for the user, and progressively decreases the size of more distant objects. In general, various IV techniques can be combined together in order to provide the user with an environment that can be flexibly used to examine his/her data (e.g. Card et al. [3] propose such a workspace for interacting with the World Wide Web).

As one can begin to notice from the previous examples, interactivity is a typical feature of IV systems: an high level of interactivity is indeed important to increase the engagement of the user in the observed data and enhance his/her exploration abilities. More elaborate examples will be described in Section 3, which focuses on IV in the medical context. For a broad survey of generic IV techniques, we refer the reader to [2].

3. Information visualization for medical systems

3.1. Visualizing medical data

Interest in visualization for medical applications has a long tradition in the field of medical imaging. However, it must be pointed out that the scope of this interest has been narrower than the broad definition and illustration of IV given in the previous section. Medical imaging is more concentrated on problems such as image acquisition (e.g. by means of tomography scans) and the processing needed to visualize the acquired images (i.e. a large number of different techniques ranging from anti-aliasing to volume rendering).

In general, IV can be a strategic component to achieve several goals in the development of a medical system. We can organize those goals in three groups:

- Visually present medical data in more intuitive, easy to understand, easy to learn, easy to recognize, easy to navigate, easy to manage formats.
- Visually magnify subtle aspects of the diagnostic, therapeutic, patient management, and healing process, which otherwise could be difficult to notice.
- Prevent information overload and allow members of the clinical staff to master larger quantities of information.

We can thus think of IV in medicine as an evolution or an extension of medical imaging. With its broader scope, it can both (i) augment traditional medical imaging applications with new capabilities (e.g. more interactivity and ease of use) and (ii) tackle applications that deal with data (e.g. patient records) which are outside the scope of medical imaging. In the following, we illustrate both perspectives by examining several significant examples.

3.2. A gallery of IV applications in medicine

An example of interactive visualization for browsing a large dataset of medical images is given by the Visible Human Explorer interface [14,15] developed for the Visible Human digital library of anatomical images. The interface displays a miniature version of the human body in a 2D front-view longitudinal cut, and separately shows a 2D cross-section perpendicular to the longitudinal one. The user can move both the longitudinal and the orthogonal planes through the body using two sliders. An horizontal indicator in the longitudinal cut indicates the position on the body of the separately shown cross-section, while an indicator in the cross-section highlights the position of the longitudinal cut. The two displayed images are coordinated and change dynamically as the sliders are moved. This allows the user to easily explore the contents of the entire dataset, and to download high-resolution images only for the sections of interest.

An IV workspace for neuroimaging is proposed in [13]: the environment does not only allow to render 3D neuroimages, but helps the user in their interpretation by linking them with contextual information such as entries from the BrainMap database (a large collection of neuroscience information which relates brain locations to human behavioral functions and data sources) and slices from the Talaraich atlas of the human brain.

Some techniques for the visualization of multi-dimensional data concerning clinical examinations are illustrated in [6]. For example, the Cube technique is based on the notion of multiple parallel diagrams and allows the clinician to visually examine and manipulate data concerning multiple cases of different patients with the purpose of recognizing interesting patterns. The clinician can choose a number of patient's attributes (e.g. diagnosis, smoking habits, drugs, allergies). The system displays a 3D cube containing a number of parallel planes: each plane is devoted to one of the chosen attributes, and points on that plane display the individual values of the attribute for specific patients, e.g. one of the two coordinates on the plane can be chosen as a function of the attribute value and the other as a function of the patient's name (obtaining an alphabetical order) or other parameter (e.g. time of examination). For example, if the value of the smoking habits attribute is ''smoker'' for half of the patients and ''non-smoker'' for the other half, then the corresponding points on the plane will look as two separated sets of points, each one aligned on the same value of a coordinate. Graphical connections between points in adjacent planes are then drawn in such a way that each patient's case is visually represented by a line connecting the individual points referring to it in the different planes. This allows one to visually recognize interesting patterns (e.g. a group of patients with similar profile will result in parallel lines).

Another approach to the visualization of multi-dimensional data in clinical databases is presented in [25], and is based on interactive tables which are capable of displaying the different records and their attributes in highly compressed format such that they can fit onto the screen. The user can directly manipulate the table (e.g. performing zoom and filter operations) which reacts by dynamically rearranging itself. For example, each column of the table can correspond to a patient, and each of the rows can correspond to an attribute such as age, sex, diagnosis, and the result of a clinical test. When many records are displayed in extremely compressed form, it obviously becomes impossible to show the values of attributes in detail. Therefore, to display lines in a meaningful format, the system relies on visualization criteria such as (i) neighboring cells with identical values are combined into a larger cell (e.g. if the table is sorted by the attribute sex, the corresponding line will be divided into two regions whose size gives an indication of the relative proportion of male and female patients in the database) and (ii) if there is no space to display a numeric value in its line, it is substituted by a small horizontal line indicating its relative height (e.g. showing that the result of a clinical test falls in a given range for most patients, and highlighting the exceptions).

The temporal data type has a particular relevance in medical IV. One of the first systems proposed for this kind of data was the Time Line Browser [5] which visualized instant events (such as the measurement of a clinical parameter with its value) and intervals with duration (such as the status of the patient) on a timeline. A more elaborate visualization is proposed in Lifelines [17], a system that faces the problem of visualizing patient's histories. Lifelines provides a compact overview of the relevant events and intervals, organized into different screen areas, each one devoted to a different aspect of the medical record (such as consultations, conditions, hospitalizations, medications): the user can select items of interest and get details on demand (e.g. a laboratory report) or perform a temporal zoom-in/zoom-out of the examined range of time, causing a dynamic rearrangement of the events and intervals displayed. KNAVE [22] is a system that focuses on the visualization and interactive exploration of temporal abstractions (e.g. ''bone marrow toxicity of a given grade'') of medical raw data (e.g. a series of measurements of platelet counts and granulocyte counts). Users can dynamically examine temporal information at multiple levels of abstraction (e.g. granulocyte counts is more detailed than granulocyte state, which is in turn more detailed than bone marrow toxicity) and change the level of granularity (e.g. years, days, hours). The AsbruView [9] system enriches the timeline graphical representation by adopting a 3D visualization (especially tailored for representing medical therapy plans): besides the two usual dimensions on which the different (possibly overlapping) parts of plans are temporally laid out, a third dimension is used to add graphical elements which convey further information (e.g. when a plan is completed, or might be suspended, or aborted). The graphical elements are chosen in such a way that the resulting visualization resembles a running track, which the physician has to run along as the treatment of the patient evolves. Finally, another interesting problem with medical temporal data is to augment existing standard representations used by clinicians with the visualization of additional information. For example, Lowe et al. [10] consider the display methods typical of anesthesia monitors and propose some extensions which convey additional information concerning certainty and vagueness of the displayed data, e.g. color coding is used to give an indication of different levels of certainty by means of various shades of the same color.

A special class of 3D visualizations is given by virtual reality (VR) approaches. User immersion and realism are crucial goals for these approaches: the interactivity of the displayed 3D models can be led to the point of high-fidelity simulation of physical processes (e.g. bleeding as an organ reaction to the operation of a virtual surgical instrument) and often special hardware is used (such as 3D displays, multi-channel audio, and force feedback devices) to enhance realism and immersion in the representation as much as possible. A detailed discussion of the different applications of VR in medicine is provided in [12]. While the availability of VR representations of patient's anatomical parts is appealing to physicians for several purposes from education and training to actual preoperative planning and procedure simulation, VR systems can be used also by patients for specific kinds of medical therapy, such as the treatment of phobias or rehabilitation.

As an example of VR systems aimed at clinicians, Sørensen et al. [24] developed an interactive, VR visualization of cardiac magnetic resonance data that allows the surgeon and the cardiologist to examine the heart as if it were in their hands (by using special hardware such as the Holobench, shutter glasses, and tracking devices). The system is meant to give the clinicians a better understanding of the patient's cardiac morphology, thus helping in the planning of cardiac operations. VR is being experimented also for other kinds of preoperative planning, e.g. tumor neurosurgery [4].

As an example of VR systems to be used by patients, Hodges et al. [8] created VR representations of real-world experiences (such as going to the top of a building using an external elevator) for exposure therapy of acrophobia (i.e. the abnormal fear of heights). The same approach is being experimented for other phobias such as fear of flying.

4. Final remarks

In spite of the growing number of IV techniques in use in medical applications, a word of caution is needed for the developer who wants to add an IV component to his/her system: since only a few tested guidelines exist [18], and no disciplined design methodologies and engineering principles have been yet identified, special care is needed in order to obtain an effective design.

For example, in contrast to most medical imaging data, IV focuses also on abstract information which cannot be automatically mapped to the physical world because it has no natural and obvious physical representation. Discovering new visual metaphors for representing information and understanding what task they support is thus, a (key) research problem for IV [7].

Card and Mackinlay [1] point out how a mapping between data and its visual presentation can be classified. One has to precisely identify (i) the marks (e.g. point, line, area) to which data is mapped (ii) how their graphical properties (e.g. color, size, texture, position) are determined and (iii) the transformations (e.g. distortion techniques) that have been possibly applied. They stress that the key issue for the effectiveness of a visualization lies in the ability of the user to invert the mapping, thus perceiving the data in the visualization.

At a very high level, the two general design principles to follow are [18]: (i) a mapping between elements/relations in the chosen domain and visualized elements/relations has to be found in such a way that conceptually important aspects are made perceptively important and (ii) the mapping has to be implemented in a precise and consistent way, rather than in a piecemeal, ad hoc fashion. Ultimately, to determine if a particular visualization makes a task easier for a type of user in a given context, it is necessary to carry out proper user studies and evaluations (e.g. currently we do not always understand when 3D is more effective than 2D [7]).

The designer of medical systems who plans to propose a new IV technique or apply existing ones to a new task should thus keep up to date with research aimed at providing IV design guidance (e.g. van der Heyden et al.'s [26] study is aimed at understanding better the issues involved in presenting magnetic resonance images on a computer screen) and also be familiar with the wide spectrum of techniques routinely used in human–computer interaction for studying users and evaluating systems.

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