ICONOGRAPHIC DISPLAYS FOR VISUALIZING MULTIDIMENSIONAL DATA*

Ronald M. Pickett
Department of Psychology

Georges G. Grinstein
Department of Computer Science

University of Lowell
One University Avenue
Lowell, Massachusetts 01854

Steeply increasing amounts and complexity of scientific data demand improved capability to display data graphically. A powerful new graphic technique for displaying multidimensional data is explained and illustrated. The basic approach is to represent each datum by a graphic icon, the visible features of which are under control of the multiple measures on each datum. When the icons are displayed *en masse*, densely stacked into a two-dimensional array, statistical structure in the data is perceived in the form of texture contours or gradients of texture variation over the display. This approach is illustrated with weather satellite imagery data. Five channels of multispectral data are combined into one picture, in which each pixel is an icon. We also describe how large statistical data bases like medical epidemiological data or census data might be visualized iconographically.

Introduction

As the volume of complex scientific data continues to grow, the need for improved graphical data displays grows increasingly acute. A recent National Science Foundation Workshop Report [1] highlights the problem and recommends an intensive national effort to rectify it. We report here on the accomplishments and the future direction of a program to improve the display of large banks of multidimensional data. The basic approach is to transform each datum into a graphic icon, the visible features of which are under data control. The icons are displayed *en masse*, densely stacked into two-dimensional arrays that analysts can visually browse, sensing structure in the data in the form of gradients and contours in the visual texture of the array.

Applications of the iconographic approach are foreseen in the analysis of two main categories of data. One is multispectral imagery data, such as that generated by earth resources satellites, or in medical settings by magnetic resonance imaging systems. In this same category are other spatially or temporally coherent data bases such as those generated in simulations of fluid flow or in seismic sensing. The second is large data bases, such as those generated in census taking or in medical epidemiological studies. In this paper we provide an illustration in the first of these areas and discuss how the technique could be extended to the other.

The current approach for merging multispectral imagery data into an integrated display is to have the pixel values for each channel control the intensity of a primary color, and thereby to integrate the pictures, for up to three channels, in a single full-color image [2]. Our iconographic approach offers a powerful new way to extend the display of multispectral images well beyond three channels, and it has the additional advantage that the data from the individual channels are visually conserved in the icons, whereas they are lost in the color integration.

The conventional approach to displaying large statistical data bases is to employ a scatter-plot display. Though immensely effective, the scatter plot has the obvious limitation that it permits examining data in only two or three dimensions at a time. Our iconographic approach provides a rich domain of ways to raise the dimensionality of such displays. Each point becomes a data-controllable icon, and data structure can be perceived not just in the clustering of points, but in other perceptible properties related to the texture of icon clusters.

Rationale of the Iconographic Approach

The critical requirement of an effective graphic display is that it stimulate spontaneous perceptions of structure in the data, i.e., that finding the structure not require deliberate cognitive analysis. The immense utility of the scatter-plot display in analyzing a large data base is that it is a potent stimulator of a natural and spontaneous perceptual capacity to sense the clustering of points in space. The primary rationale of our iconographic approach is that it allows us to exploit another such spontaneous perceptual capacity—the capacity to sense and discriminate the texture of a complex image.

To stimulate a visual texture perception, many small but discriminable elements must be displayed over a relatively small area. Such an image is experienced, for example, when one examines a slice of bread. With deliberate visual analysis, one can obtain specific kinds of information about the shapes, sizes, and positions of particular holes, but one also receives, without any deliberate inquiry, a strong and informative impression of the overall texture of the slice. It is just such natural impressions of texture, and the capacity for them to change as the statistical properties of the elements change, that we seek to harness in the iconographic approach. The icons become, as it were, the holes in the bread, and as their individual characteristics of shape, size, and spacing change under data control, so too will the analyst's spontaneous impressions of texture change and thereby signal one or another kind of statistical structure in the data.

*This work was supported under a grant from Digital Equipment Corporation.

CH2556-9/88/0000-0514 $1.00 © 1988 IEEE

The challenge, of course, is to create icons that stimulate highly distinctive texture perceptions when their statistics shift from one area of the array to another. Research on texture perception has provided some good leads on the kinds of icon geometries that will do that. Indeed, the stick-figure icon used in the illustration for this paper was chosen on that basis. But, even so, whether a given design works to reveal the structure in a particular body of data probably depends on how its particular geometry resonates with that particular structure. We envision that an analyst might need to apply different icons in perhaps a large series of trial-and-error examinations before he finds one that does the job. As a start on developing such a facility, we have developed not just one stick-figure icon, but actually a family of twelve, each with a distinctively different geometry that will potentially resonate better with some kinds of data structures than with others. We envision that a comprehensive facility might have several such families, each family with its own generically distinctive geometry.

Prior Work

Prior relevant work is in three main areas: developments in graphical data analysis; research on visual texture perception; and developments in computer graphics.

Developments in Graphical Data Analysis

Two developments in particular have promoted an intense and growing interest in graphical data analysis. One has been the seminal work, over several decades by Tukey [3], promoting the technique of exploratory data analysis. Tukey has argued that we should put much more effort into looking at data and not be so blindly dependent on numerical analysis. He states in the preface of his book that "the greatest value of a (data) picture is that it forces us to notice what we never expected to see." Over this same period, those who had data to analyze were no doubt getting a sense of being drowned in what the NSF Workshop report has colorfully described as "fire hose" flows of data, and that data overload has concurrently spurred an intense interest in visualization techniques. Wainer and Thissen [4] provide a comprehensive review of numerous attempts to use emerging computer graphics capabilities to meet these growing needs. Pickett and White [5] presented perhaps the first iconographic data display, using arrays of triangles whose shape, orientation, and tilt in a stereographic display graphically conveyed a 7-dimensional data base. Chernoff [6], using arrays of tiny faces, displayed data in as many as eleven dimensions. These early efforts were mainly aimed at illustrating the general idea of an iconographic image. The particular icons and icon features under data control were chosen arbitrarily, and no pretense was made that those particular graphic codes were the most visually effective. Knowledge of what codings would be best was only then beginning to be gathered in research on visual texture perception.

Developments in Visual Texture Perception

The study of visual texture perception goes back to pioneering work by Gibson [7], but large strides in research came only after the availability of computer graphic techniques for generating artificial textures with precise control over the shape and placement of the texture elements and overall texture statistics [8,9]. By the early 70's, knowledge of what kinds of texture elements and what feature variations stimulated the most discriminating perceptions of texture began to emerge [10,11,12]. Linear texture elements and variation in orientation were identified as key texture codings. In general, those icons are best in which variations of the elements can be sensed peripherally, i.e., out of the "corner of the eye," or as expressed in more recent explanations, which can be sensed preattentively, i.e., without requiring deliberate focus of attention and cognitive analysis [13]. This knowledge provides some good leads for the choice of effective icons, but the continuing development of iconographic displays will need to include empirical explorations of alternative icon codings, to find those that work best. Important supporting developments in computer technology, in addition to graphic capabilities, per se, are those that will facilitate such exploration.

Developments in Computer Graphics

Three basic developments in computer graphics underlie our present efforts to explore and develop iconographic displays and to apply them in data analysis.

The initial critical developments were those that extended the resolution, bandwidth, and drawing speed of graphic displays to the point where large numbers of finely drawn elements could be displayed *en masse* to form a computer-controlled texture display. Much of the early basic research on texture perception and the early illustrations of iconographic displays awaited those initial developments in the 1960's.

Systematic studies of iconographic displays and research of the kind we describe in this paper, however, had to wait longer—for the availability of workstations that had not only high resolution and drawing speed, but also the capability to support the software tools that could make such explorations practically feasible. Development of the modern workstation with pointing device, high resolution bit-mapped display, and graphical user interface, all within a distributed environment happened in the 1970's, but then it took over a decade more for the cost to drop enough to make such workstations commonly available on desk tops [14,15]. Other recent developments in User Interface Management Systems and windowing have also been critical in making our present research feasible.

Further developments that have come only in recent years now permit broadening our horizons from pure research on these techniques to applications in real world scientific settings. Networking capabilities, for example, provide for the distributed environment needed to develop and share software and data bases across different systems. One can now access remote data bases, handle the potentially immense data processing required for iconographic images on other remote modes, and locally just display the resulting images.

Applications

We illustrate application of an iconographic display in the analysis of some multispectral imagery data, and discuss ways it could also be applied in analyses of data in the other general category of large statistical data bases. We need first, however, to describe the particular icon used in our illustration and how data are mapped to it. We need also to describe the general logic of using this particular icon, and others of its twelve-member family, to conduct a comprehensive visual exploration of any given data base.

Stick-Figure Icon and Logic of Its Application

The basic icon used in our illustration is a stick figure consisting of five connected line segments. One of the segments is the body of the icon. The other four are the limbs. The icon family we have created (see Figure 1) consists of twelve members, each defined by the manner in which the limbs are attached to the body or to each other. In one member of the family (see 1, Figure 1) all four limbs are attached directly to the body, giving it essentially two arms and two legs. In another member (see 12, Figure 1), and indeed, the one used in our illustration, all four limbs are attached to one end of the body, giving it one long, three-jointed arm. The other ten family members provide for attaching the limbs in one or the other of all the remaining possible sequential and parallel combinations. Our assumption is that each of these members has the potential of resonating to a different type of data structure and that among them, a very wide spectrum of data structures may be detected.

The numerical data to be analyzed are mapped onto the icon by having each measure on each datum control the angle of one of the limbs of the icon to which that datum is assigned. Thus, data in up to four dimensions can be displayed with any one of the members of this particular family of icons, and a fifth dimension can be displayed if we let it control orientation of the body.

The logic of conducting visual explorations of a data base with an icon family like this is that one would take multiple looks. One would not necessarily know which icon family member would be most informative of structure potentially present in the data. For example, the structure might be such that it would be most sensitively revealed by the icon with one long arm, or perhaps by the one with independently connected arms and legs. Nor would one know necessarily in advance which particular mappings of data dimensions to icon features would be most informative. It might be that the structure of the data pops out in the display only when dimension 1 is mapped to the first of the line segments in member 12. The logic is such, then, that one would like to have the facile capacity to look at the data with each of the family members and, with each, to look at all the possible mappings of data dimensions to icon features. In this situation such a thorough exploration would require looking at up to $12 \times 5! = 1440$ pictures. Such is the spirit of this kind of unbridled visual exploration. Its feasibility derives from the fact that it relies on effortless, spontaneous perceptions of textures in the array. With appropriate computer support that automates the exploration, the observer would ideally be watching a kind of movie, stopping the show when some interesting structure flicked into view. In our illustration, of course, we show only one of those views.

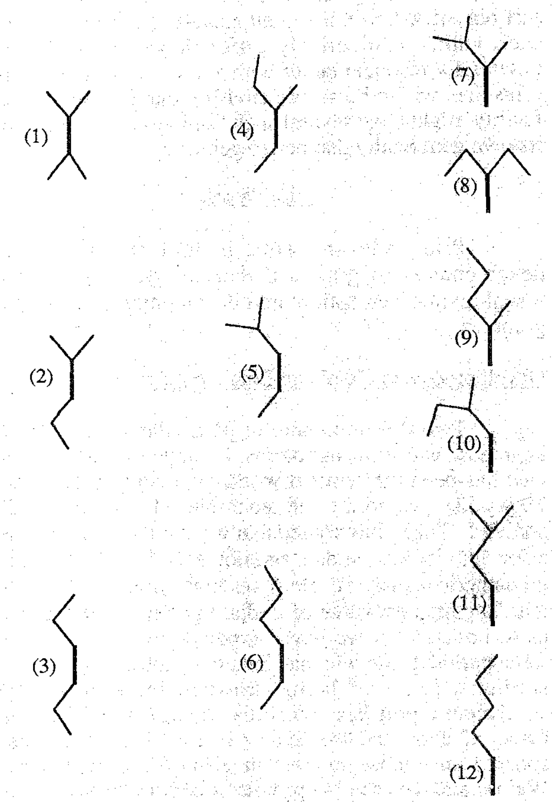

Figure 1. A stick-figure icon family. Each member has four limbs, the orientations of which are under data control. The different patterns of attachment of the limbs make each member potentially suitable for conveying different types of data structure.

It is also important to mention, before proceeding to the illustration, that we will not attempt to explain what new and interesting things the picture actually shows. It would not be appropriate to seek evidence that the iconographic approach works or does not work on the basis of whether this particular display shows some new and striking information that would not otherwise have been retrieved from conventional numerical or graphic analysis. The primary intent here is to illustrate how the technique translates into an actual, concrete display, and to ve some feeling for what such displays look like. The imate proof of whether such displays work to convey new kinds of information has to depend on the results of much wider testing. We can only say that this picture provides a view of these particular data that would have been impossible to achieve by other available graphic techniques.

<u>An Iconographic Picture of Five Channels of Weather Satellite Data</u>.

We show in Figure 2 an integrated picture of five channels of data from the NOAA-7 AVHRR satellite. As may be evident to readers familiar with the geography, depicted is a geographical area covering all of the western end of Lake Ontario and part of the eastern tip of Lake Erie in North America. The lower center of the picture is roughly over Niagara Falls. This picture used icon family member 12, from Figure 1. The particular mappings are such that one of the visual channels controls orientation of the body. The remaining visual channels control orientation of the two limb segments closest to the body. The two IR channels control the outer two segments.

We chose this particular member of the icon family, and this particular mapping of data channels to limb segments because the combination seemed to yield the strongest differentiation among the geographical regions of the display we knew were there.

On the whole, a rather strikingly well-structured picture emerges in the total absence of gray scale coding. This picture nicely demonstrates how strongly one can differentiate regions in an array of icons on the basis of texture differences.

In actual applications, one would, of course, typically be looking for regions one did not know were there. What those might be, we could only speculate about. They could be regions defined by some higher order interaction among the channels. We were curious, for example, whether one or another of the potential interactions among the channels that the iconographic picture could show might have revealed a plume from the outflow of the Niagara River into Lake Ontario. No plume is visible in the individual pictures, nor is there any clearly apparent plume in the iconographic picture, but that illustrates the kind of discovery that these displays might permit.

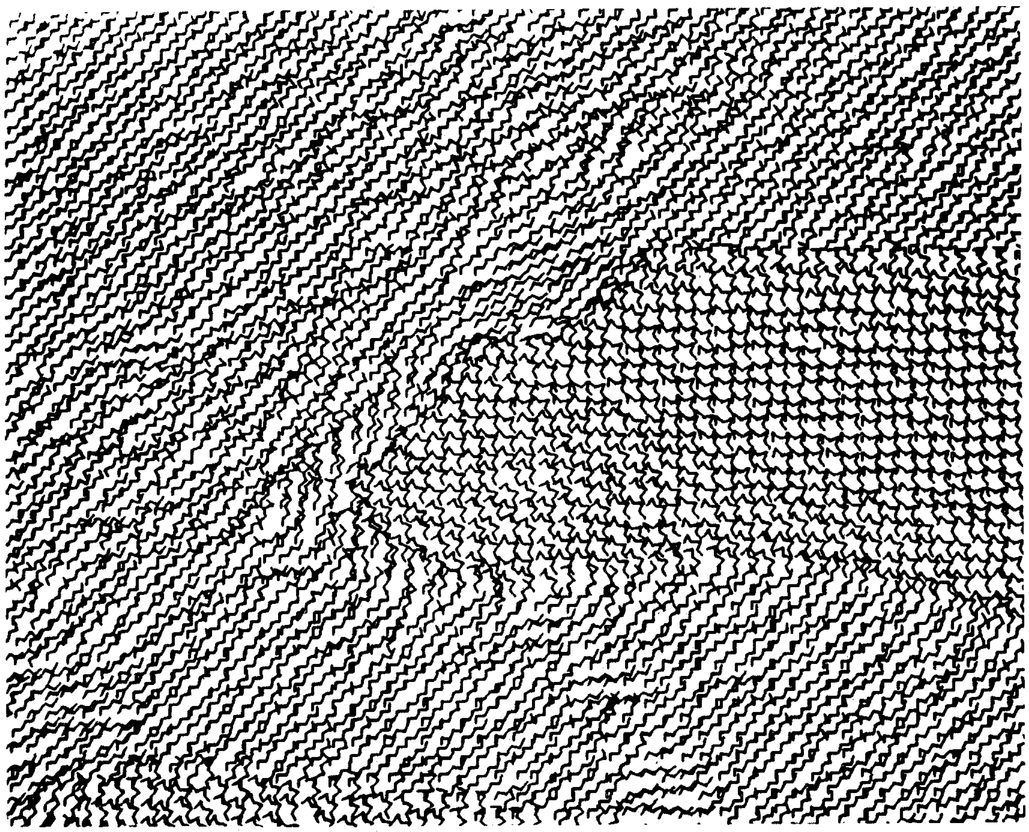

Figure 2. An iconographic display of multispectral imagery data from the NOAA-7 AVHRR weather satellite. Five channels of data control the orientations of the limbs in the stick-figure icon that forms each pixel.

Applications to Other Types of Data

The iconographic approach is most directly applicable to spatially coherent data such as multispectral imagery data or temporally coherent data of the kind created in simulations of fluid flow or in seismic sensing. Its application in the analysis of large statistical data bases will typically be more problematic, but still promising.

One basic problem is that there is much less of an imperative for choosing which variables should control the location of the icons in the array, and sometimes there may not be two continuous variables on which the data are reasonably evenly and densely distributed to do the job at all But even in those situations the value of an iconographic display is not all lost. One approach could be to break the array up into subregions, say quadrants, and assign icons to the quadrants depending on whether they fall above or below a threshold on two key variables. Locations of the icons within each quadrant could be random, but texture differences among the quadrants could still be informative.

How to have qualitative variables drive icon features is another problem that will be much more frequently encountered in analysis of large statistical data bases. The dilemma is that if one arbitrarily assigns qualities to particular degrees of variation on a continuously variable icon feature, it invites the invalid visual interpretation that the driving data are ordered. A valid solution here can often be achieved by slicing the data into two categories to drive a binary variation in the icon. Despite these complexities, we think the iconographic approach will be useful in many situations for analyzing large statistical data bases. We also envision that for some very large data bases, displays approximating those of the multispectral imagery will be achievable.

Implementation

We have given much thought about how best to design a system that can support our activities in research on these techniques as well as in various possible applications of them for actual data analyses. From a design philosophy perspective, the largest concern is to facilitate management of the various tasks—first in exploring alternative icon codings, and second in using those that work to explore data.

The flexibility of object-oriented programming for creating and modifying icons has been attractive. Software tools and systems like the X Window System* were also deemed important to facilitate the development of user interfaces and of application software capable of working in a variety of computing environments.

We chose the X Window System because, from our experience with it on other projects, this seemed a natural environment for it. Here were tools to build extensible user interfaces. Here was a package capable of running on a variety of workstations, and not necessarily from the same vendors. X provided for most of the functionality needed for extensible windowing systems [16].

Since we intended to interactively and dynamically add new icon families, the code had to be extensible in an obvious and natural way. Object-oriented languages and environments were the obvious choice. However, the X Window System had only a C library. Our preference in object-oriented languages, C++, was to come later. We decided, therefore, to write the software in an object-oriented manner.

The objects we are defining are called object icons. We have focused in our work on associating a physical view with the logical view of the data records. This is often called mapping the logical part of an object, or meaning of a object record, graphical or non-graphical, to the physical part that is displayed [17]. Manipulation of the icons after the mappings have been defined is similar to image processing. The purpose is to increase the informativeness of the data. All the manipulations of the logical to physical mappings of the icons, and of the browsing controls, are accomplished through the user interface. These manipulations include:

- Select icon family
- Map data fields to icon features
- Display icons in partitions
- Cycle through mappings
- Suppress icon features

The valid object operations are defined along with each object within the program.

We have designed an interface format so that any data base may be used as data input. Thus, once a data base is selected, an icon family chosen, and parameters mapped to the icon features, browsing may begin.

Direction and Scope of Future Work

As the complexity of issues raised in this paper suggests, getting from conception and illustration to practical application will require considerable ingenuity, extensive effort, and abundant computer graphics resources.

Our immediate goal is to continue the effort represented in this paper of explaining and illustrating this approach. The first main step is clear. We need to develop a general purpose system that can facilitate further exploration, development, illustration, and testing of iconographic displays. We need also to improve the user interface. Here the X Window System will play a central role. The next main step is to develop exportable systems for field applications by scientists and engineers now facing those "fire hose" flows of data. These applications packages would probably be built around three or four well tested icon families, with good user interfacing to permit rapid and flexible visual

*The X Window System is a trademark of M.I.T.

explorations of data and with strong supporting documentation and user manuals [18].

We are also intrigued with possibilities of dynamic icon coding, i.e., where the icon features under data control are dynamic properties. Structure in the data may become much more salient as the data driving the icons cause them, e.g., to "dance" or "swim" on the display. Also intriguing is the possibility of having such dynamic icons interact with each other, or of giving the user capabilities to interact with them. Moreover, it may also be of value to implement all of these capabilities in 3D. These implementations will require workstations with substantial computational power. These may seem rather radical steps to consider in light of the many uncertainties of how best to proceed and how best to exploit even what little we now have up and running. But we are convinced that capabilities of display technology are running far ahead of our abilities to exploit them, and that such far fetched explorations are well justified.

References

[1] B.H. McCormick, T.A. DeFanti, and M.D. Brown (eds.), "Visualization in Scientific Computing—A Synopsis, 1987" IEEE Computer Graphics and Applications, pp. 156-177, July 1987.

[2] R.P. d'Etremont, and L.W. Thomason, Interpreting Meteorological Satellite Images Using a Color-Composite Technique, Bulletin American Meteorological Society, 1987, 68, 762-768.

[3] J.W. Tukey, Exploratory data analysis, Reading, Mass.: Addison-Wesley Publishing, 1977.

[4] H. Wainer, and D. Thissen, "Graphical Data Analysis," in M.R. Rosenwieg and L.W. Porter (eds.) Annual Review of Psychology, Palo Alto, Calif.: Annual Reviews, Inc., ch. 32, pp. 191-241, 1981.

[5] R.M. Pickett, and B.W. White, "Constructing data pictures," Proceedings of the Society for Information Display Seventh National Symposium, 1966, pp. 75-81. Information Display,-vol. 3(5), p. 57, September/October 1966.

[6] H. Chernoff, "The use of faces to represent points in k-dimensional space graphically," Journal of American Statistical Association, vol. 68, pp. 361-368, 1973.

[7] J.J. Gibson, The perception of the visual world, Boston, Mass.: Houghton Mifflin Co., 1950.

[8] R.M. Pickett, "The perception of a visual texture," Journal of Experimental Psychology, vol. 68, pp. 13-20, 1964.

[9] R.M. Pickett, "Response latency in a pattern perception situation," Acta Psychologica, vol. 27, pp. 160-169, 1967.

[10] R.M. Pickett, "Visual Analyses of Texture in the Detection and Recognition of Objects," in B.S. Lipkin and A. Rosenfeld (eds.), Picture Processing and Psycho-Pictorics, New York: Academic Press, 1970, pp. 289-308.

[11] J. Beck, "Similarity grouping and peripheral discriminability under uncertainty," American Journal of Psychology, vol. 85, pp. 1-19, 1972.

[12] J. Beck, "Relations between similarity grouping and peripheral discriminability," Journal of Experimental Psychology, vol. 102, pp. 1145-1147, 1974.

[13] A. Triesman, "Preattentive Processing in Vision," Computer Vision, Graphics, and Image Processing, vol. 31, pp. 156-177, 1985.

[14] G.E. Pake, "Research at Xerox PARC," IEEE Spectrum, vol. 22, pp. 10, 54-61, 1985.

[15] T.S. Perry, and P. Wallich, "Inside the PARC," IEEE Spectrum, vol. 22, pp. 10, 62-74, 1985.

[16] G.G. Grinstein, Windowing Techniques and Tools—Summary Report, X3H3.6/87-09, February 1987, American National Standards Institute.

[17] S. Chang, "Visual Language: A Tutorial and Survey," IEEE Software, pp. 29-39, January 1987.

[18] G.G. Grinstein, A GKS Manual, John Wiley & Sons, in preparation.