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ABSTRACT

This paper describes how visual media technologies have been used to support research into the way technical diagrams are represented in people's minds. Two groups of subjects participated in this research, individuals with either a high or a low level of expertise in meteorology, specifically professional meteorologists and non-meteorologists. Two general types of visual media technologies--computers and video--were used to investigate the mental representation of diagrams. Two main types of data were collected by the computer and video methodologies: (1) process data, the actions subjects perform as they work through a task; and (2) product data, the outcomes (drawings) of copying, recalling, or completing a weather map. Examples of the way process and product data were handled during analysis are presented. The strength of video technology is that it provides for the capture of highly detailed visual data. However, it also presents problems with the time-consuming nature of transcribing the data into a form suitable for statistical analysis. In contrast, computer technology can directly monitor some aspects of a subject's performance and save the generated data in files that are suitable for statistical analysis, although it is not currently capable of directly providing (for reasonable cost and effort) the type of facilities for dealing with visual data that are available with video. Recent merging of the two technologies with the advent of digital video is opening up new possibilities for research. (Contains 15 references.) (AEF)

USING VISUAL MEDIA TECHNOLOGIES TO INVESTIGATE COGNITIVE REPRESENTATION OF TECHNICAL DIAGRAMS

by
Richard Lowe

This paper describes a selection of ways that visual media technologies have been used to support various aspects of research into the way technical diagrams are represented in people's minds. Its purpose is to demonstrate how such technologies can address some of the difficulties inherent in conducting research in this area. The research programme for which the techniques described here were devised has the broad goal of understanding how learners deal with instructional diagrams.

While illustrations in general can be included in instructional materials for a range of different purposes (Levie & Lentz, 1982), a central role of diagrams of the type used in technical domains is to explain some aspect of the subject matter (Levin, Anglin & Carney, 1987; Lowe, 1993). To date, much investigation of expository illustrations such as diagrams has focussed upon their instructional outcomes, rather than upon the processes by which these outcomes are generated. However, the rise of information processing approaches to the study of thinking and learning in recent years has highlighted the need to understand mental processes in trying to improve instructional outcomes. With this has come an increasing interest in the mental processes involved in the comprehension of pictorial materials such as diagrams (e.g. Winn, 1991). Fundamental to these mental processes is the way in which the information upon which they operate is represented in our minds. Consequently, before we can fully understand how diagrams are processed, we need to know about the mental representation that people develop for the graphic elements which are the fabric of those diagrams. Unfortunately, a person's mental representation of a diagram is not directly accessible to us for the purposes of study (unlike the outcomes of a diagram-based instructional task) and so its characterization presents a considerable research challenge. As a result, the methodologies involved in such diagram research of necessity rely on indirect approaches that aim to provide fine-grained data from which inferences can be made about mental representation. This requires that these approaches are not only robust and powerful, but also that they are appropriate to use with pictorial material.

A fundamental consideration in designing research methodologies for this area arises from the nature of the materials to be investigated. Diagrams and similar explanatory visual materials typically are used because they are considered better suited to the presentation of the subject matter than verbal formats (written or spoken text). It now seems clear that aspects of the information structure of diagrams can provide them with cognitive processing advantages over text (Glenberg & Langston, 1992; Larkin & Simon, 1987; Winn & Li, 1989). However, the great majority of research into the way people mentally represent information involves the use of verbal materials and verbally-oriented methodologies. There has been considerable development in the collection of detailed verbal data in recent years and approaches to analysis such as those discussed by Ericsson and Simon (1984) are well established. However, the direct adoption of such methodologies for the investigation of the way people deal with visual materials would require visual-to-verbal translations, so compromising their intrinsic visual character. In other words, collecting *verbal* data about the processing of *visual* material (for example, think-aloud protocols generated by a subject performing a diagram processing task) would be of dubious value on its own (although it may be a valuable source of supplementary data). What is required instead are approaches that properly acknowledge the visual nature of these materials and deal with them without the need for any translation. So for an investigation of the way people deal with diagrams, it is not sufficient to confine the visual aspect of the procedure to the stimulus materials. It is important that the outputs that subjects produce should also be visual as should any intervening manipulations of the materials they perform. The need to use a consistently visual approach across the various aspects of investigation guided the development of the methodologies described in this paper. This development was informed by the approaches used by researchers in the investigation of cognitive aspects of various visually-oriented domains such as chess (Chase & Simon, 1973), architectural drawings (Akin, 1986), and electronic circuit diagrams (Egan & Schwartz, 1979).

Before dealing with specific aspects of the methodologies that have been developed for the current research program, some general considerations regarding this type of research will be discussed. For a methodology to be useful for fine-grained investigation of the way people interact with diagrams, it needs to be able to:

1. Display the diagrammatic material effectively to the research subjects,

2. Provide appropriate ways for the subject to interact with the diagram,

3. Capture detailed information about subject-diagram interactions,

4. Characterize these subject-diagram interactions with appropriate measures,

5. Permit generated data to be analyzed in a meaningful way,

6. Deal with static and dynamic components of the investigation.

As will be illustrated below, a suitable combination of the capacities of video and computer technology can address these types of needs in a variety of ways. In addition, the capacity of these technologies for dealing with dynamic data gives them a distinct advantage over more conventional (static) approaches to the reporting of results from this type of investigation.

Diagrams and Subjects

All the methodologies described here were applied to the study of how weather map diagrams are mentally represented. However, it should be noted that weather maps were used purely as illustrative examples of the type of diagram commonly used for instructional purposes (there was no interest in the investigation of weather maps *per se*). A discussion of the advantages of using weather maps for this purpose appears elsewhere (Lowe, 1990). In principle, the methodologies are applicable to a variety of diagram types from a wide range of technical disciplines. The two groups of subjects who participated in this research were individuals with either a high or a low level of expertise in the domain of meteorology, specifically professional meteorologists and non-meteorologists. Because it involved comparison of two groups with greatly differing levels of domain expertise, this research approach can loosely be described as fitting within the "expert-novice" paradigm (Chi, Glaser, & Farr, 1988). However, because the meteorologists were competent practitioners rather than acknowledged expert performers in their domain, the expert-novice characterization should be treated with some caution.

Data Collection

In the following sections, the use of two general types visual media technologies (computers and video) for the investigation of the mental representation of diagrams will be discussed. Although these approaches were specifically developed for use with very abstract diagrams of a technical nature, there is no reason in principle why they could not be adapted for various other types of graphically-simple pictorial materials that are used as instructional illustrations.

Computer Technology

The computer-based methodology described here is an adaption and extension of an earlier manual technique that has been reported in detail elsewhere (Lowe, 1989). In general terms, the methodology was used to investigate a subject's mental representation for weather map diagrams by monitoring the way the subject explored an unfamiliar example of such a diagram which was initially hidden from view. This monitoring relied on the diagram having been segmented so that the subject's exploration across individual regions could be followed. A superimposed 6 x 5 grid divided the weather map into 30 square pieces (the diagram consisted of a map outline and its meteorological markings). When a subject began the experimental task, the display was completely covered with squares that were blank except for the map outline (i.e., no meteorological markings). During the task, the subject gradually revealed parts of the display by removing the covering squares from the display one at a time. This allowed determination of the order in which the selected regions of the display were inspected. However a condition of the task was that the subject was permitted to expose a total of only one third of the whole display (10 of the grid squares) and told that from this limited amount of information, she/he would later be required to complete the display.

In the computer implementation of this technique, the experimental task involved the subject interacting with a screen depicting a blank weather map of Australia and divided into 30 squares by a grid as described above (the map and grid were drawn in black on a white background). The subject was prompted through the required interactions by appropriate instructions provided in a side bar on the screen. To reveal what was under a particular square, the subject moved the computer's mouse pointer onto that square and clicked once, upon which the square turned black to signal that it had been selected. The subject was then able to either confirm the selection with a second click on the blackened square, or select a different square by clicking on it instead. The second (confirmatory) click on a square caused the hidden meteorological markings on that part of the weather map to be revealed. For any square exposed in this way the background was changed from white to grey so that the subject could easily tell that it had already been revealed (this was necessary since not all of square segments comprising the map actually contained weather map markings). As this revelation process continued, the instruction side bar gave the subject updated information about how many of the quota of 10 squares remained available for selection. Once all 10 of the allowed squares had been revealed, the subject's map showing the exposed meteorological markings was printed off. The subject then attempted to complete the whole weather map by drawing in any further meteorological markings that were thought to exist in the remaining 20 grid squares.

Because the interactions just described are somewhat involved, each subject was trained in the necessary operational processes before moving on to the experimental task. The sequence of presentation was as follows. After an introduction to basic processes such as moving and clicking the mouse, the subject was given preliminary training in the technique of revealing information by clicking on squares. This was done using a simple four-square grid (Figure 1).

Next, these skills were applied to a graphic display of a familiar scene (a simple house and its surroundings) following the same procedures that would be required for performing the experimental task with the weather map. The subject began with a bare outline of the house divided by a grid of 30 squares (Figure 2) then by using the procedure described above for the experimental task, clicked on 10 squares in sequence to reveal one third of the house's details (windows, doors, etc.).

For this practice task, the subject's response was not printed off for completion. After this practice, the subject carried out the experimental (weather map) task with weather map. During the experimental task, the computer program recorded the identity of the squares chosen and the sequence in which they were selected. Finally, a screen dump of the subject's partly completed map (showing the 10 revealed squares) was printed off for the subject to complete (Figure 3).

This computer version of the original manual method was developed in Hypercard so that it was able to run on even low-end black and white Macintosh computers, thus making it suitable for use in a wider range of situations. Although some aspects of the methodology (such as the training segment) were altered to make the technique less dependent on the experimenter, the course of the experimental task remained fundamentally unaltered. The computer-based version has a number of benefits over the original procedure such as the automatic collection of data regarding which squares were chosen by a subject and their order of selection. It also has the potential to be used for displays other than weather maps as will now be explained. In the weather map version described above, the map outline constitutes one level of information (provided for the subject) and the set of markings that depict meteorological information constitutes another (to be provided by the subject). However, since the computer program is essentially a shell into which a particular display is fitted, the method could easily be adapted for investigating the way subjects search other diagrams that can be characterized in terms of two levels of information. For example, in the area of biology, subjects could be presented with an outline of an unfamiliar animal's body and the way they searched for hidden details of the animal's digestive system studied. Similarly, in the area of electronics, subjects could search for information about the components present in a hidden section of a circuit diagram.

Video Technology

The methodology described here was developed to obtain finer details about the mental representation of weather map diagrams than could be obtained from the technique described above. In addition, its basic approach to data collection was fundamentally different, thus providing the opportunity for triangulation. A video recorder was used to capture the sequence of actions performed by subjects in carrying out tasks involving a previously unseen Australian weather map. A major part of the process involved subjects drawing a copy of the map's meteorological markings onto a blank map. However, the weather map they were to copy was not continuously visible. Instead, subjects could only view the stimulus map while they were pressing a button with their drawing hand. This meant that they could either take a look at the stimulus map or draw markings onto the blank map but not continuously view and draw at the same time. Hence, subjects were forced to alternate viewing and drawing in a succession of discrete actions. An indicator light was switched on when the viewing button was pressed and remained illuminated for the duration of each viewing period (i.e., as long as the viewing button was depressed).

The subject carried out the experimental tasks at a specially constructed table that had a glass window inserted into its top with a mirror set beneath the window at an angle of 45 degrees. A video recorder aimed at the mirror allowed each subject's drawing behavior to be recorded from below without obstruction (the response sheet containing the blank map was made from tracing paper so that the subject's drawing was visible from below). The viewing indicator light was positioned so that it could be included in the area being recorded by the video and the camera was fitted with a counter that marked each frame with elapsed time. Thus in addition to recording the subject's drawing of each meteorological marking, the length of each viewing period was automatically recorded on videotape. As well as drawing a copy of the weather map, subjects later drew what they could recall of the map's markings. Video records of this process were also made to enable comparison of the intake of diagram information (during copying) with its output (during recall).

Data Analysis

Two main types of data are collected by the techniques that have been described. The first are *process* data which come from the actions subjects perform during an investigation as they work through a task. Of particular interest here are the temporal order in which the meteorological markings are processed, the location of those markings, and the durations of various stages that comprise the processing. The second type are *product* data such as the outcomes (drawings) of copying, recalling, or completing a weather map.

Analyzing each type of data presents its own challenges, some of which concern practicalities such as how to carry out particular measurements while others concern more fundamental theoretical issues involving the choice, treatment, and interpretation of those measurements. Some examples of the way process and product data were handled during analysis will now be presented.

Process Data

A number of assumptions were made here. First, it was assumed that the temporal order in which the meteorological markings were processed was in some respects influenced by the nature of the mental representation of the weather map information. This assumption parallels that made by Taylor and Tversky (1992) in their investigation of the mental organizations of environments. As these

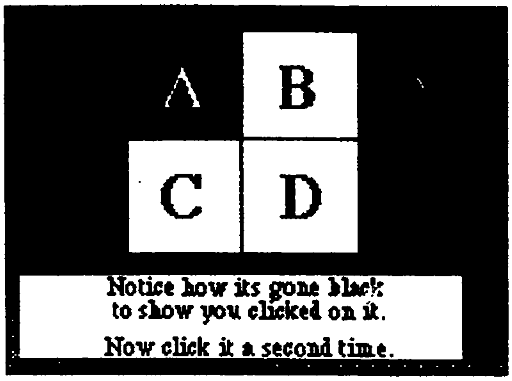

Figure 1.
Grid used for training subjects in procedure for selecting squares (black indicates square 'A' has been clicked once; a further click would reveal what was under this square).

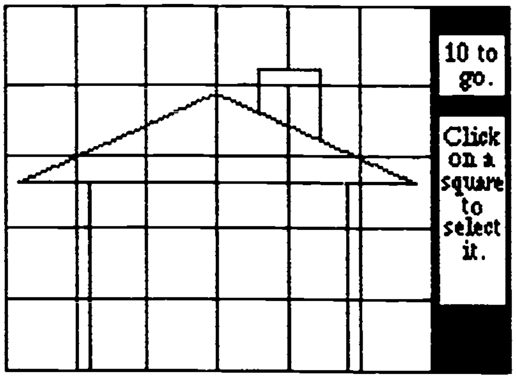

Figure 2.
Practice task graphic showing outline within 30 square grid. Note instructions to subject in side column.

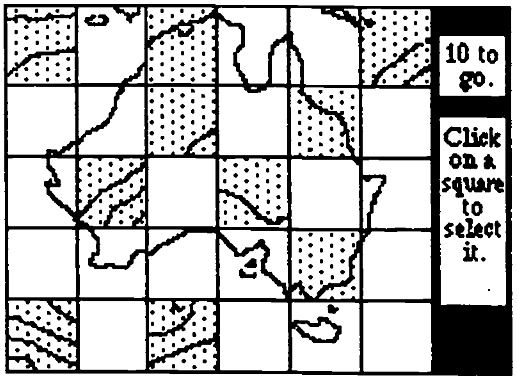

Figure 3.
Screen dump showing markings on a subject's 10 selected squares. Subject would next attempt to complete the map' markings.

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authors have observed, one of the research difficulties in using drawings as data is how to score them. Taylor and Tversky used the order in which elements of a map are drawn as an index of organization on the assumption that the clustering of items in a recall sequence occurs because those items are closely related in some way. In the video-based weather map investigations referred to in the present paper, this type of clustering assumption was made about the sequences produced during the copying of items as well as during their recall. In the computer-based investigation mentioned earlier, assumptions about clustering were made from the order in which the 10 squares were selected for revelation. Depending on the particular task a subject was performing, the structure of these sequences may provide an indication of matters such as the effects of established habits of perceiving and drawing, the extent of visual impact (in perceptual terms) of different types of markings, the tendency of subjects to group the markings because of similarities in their visuospatial characteristics, the ease with which markings of different types were processed or the relative meteorological importance attached to different markings.

The second assumption was that the relative durations of particular aspects of processing (such as the lengths of viewing periods) were of significance. In the current context, this assumption concerns only the video-based investigation described above. On most occasions during the copying task, subjects viewed the stimulus diagram using a series of relatively short glimpses. After each glimpse, a subject typically drew one or more marks. However, at various stages during the process of copying the stimulus diagram, the subject would spend a much longer time gazing at the diagram before changing to drawing. These longer viewing periods were interpreted as indicating the start of a new phase of processing in which the subject's attention shifted to a different group (or chunk) of graphic elements within the stimulus diagram. This interpretation permitted each subject's processing sequence to be used to identify subsets within the complete set of graphic elements comprising the diagram. By examining the constitution of these subsets, inferences could be made about inter-element relations that might be involved in the subject's mental representation of the diagram as a whole. For example, it appeared that the non-meteorologists structured the mental representation of information in the diagram on the basis of relations involving the visuospatial characteristics of the markings themselves whereas the meteorologists' structuring was based upon relations that reflected the meteorological significance of these markings.

A major disadvantage of the process aspect of the video-based investigation was the time consuming and labour-intensive nature of the data transcription required. The raw data consisted of a videotape record of each subject's viewing and drawing behavior in which each videotape frame was marked with the time elapsed since the start of the task. In addition, the videotape of the copying task also contained records of the periods during which the viewing indicator light was switched on and switched off. Transcription of the videotape involved locating precise frames at which (a) the viewing indicator light was switched on or was switched off and (b) the subject's pencil just began to draw a mark or just finished drawing that mark. The elapsed time for each of these frames was transferred manually to build up a table that set out each subject's viewing and drawing behavior. In addition, each of the marks drawn on the map was labelled with its position in the overall drawing sequence. In contrast to the video-based investigation, the computer-based investigation described earlier automatically collected process data about the identity of the 10 squares that a subject revealed and the order in which they were selected. These data required no pre-treatment after collection and were ready for immediate transfer to a statistical analysis program. However, the computer-based approach did not offer the same opportunities for collecting the subtle types of data that can be captured by the use of video. Clearly an integration of the capacity of video technology to collect detailed visual data and the automatic data collection capacity of computer technology would be the ideal combination.

Product Data

Map markings drawn by subjects and the larger graphic structures formed by the conjunction of drawn and existing markings can be characterized by various measures. These measures allow a range of comparisons to be made including those between (a) the markings on the stimulus materials and those produced in the subjects' responses, (b) different classes of subject (such as experts and novices) and (c) products generated at different stages of an investigation (such as copied and recalled markings). Measures of position, size, shape, and orientation are useful to characterize the properties of individual markings both in terms of their basis visuospatial properties and in terms of the meteorological significance of those markings. For example, the sizes and relative positions of markings in of a set of concentric closed isobars that together constitute a cyclone not only show the physical extent of that feature, they also indicate its likely severity. As well as making measurements of each marking on its own, it is important to characterize larger composite structures made up of two or more markings which constitute meteorologically significant assemblies.

A fundamental matter to be resolved in developing an analysis procedure is the definition of what constitutes a discrete entity for the purpose of analysis. In cases where a marking consisted of a single graphic stroke or a set of physically connected strokes, this generally did not constitute a problem since it was usually quite clear that a single entity was intended. However, for other markings such as a cold front symbol, physically connected but geometrically distinct markings were considered as separate entities because pilot studies showed that these different components were drawn by subjects as a number of separate subgroups (in the case of a cold front, a line plus a group of triangular barbs).

Once individual graphic entities have been defined, the next problem is in making measurements of the position, size, shape, and orientation of each entity. Recent developments in image analysis computer software have greatly simplified this measurement task. These programs process an image that has been converted to digital form and then use various algorithms to characterize properties of the image. In the case of the weather map diagrams used for the research referred to here, the image was captured by means of a flatbed scanner to form a disc file (in a format such as PICT). Some preliminary treatment using image enhancement software was usually necessary to clean up the scanned image and to prepare it for analysis. For example, regions bounded by particular sets of lines might be filled with "paint" to isolate them so that the image analysis program can later identify them as distinct features to be measured (each such region is typically described as a "blob"). Once the prepared image is loaded into the analysis program, the user can then specify the desired measurements and select the blobs of interest. Simple measures of distance (such as length or perimeter) and area are made by counting pixels which are then converted into more familiar units. The position of a blob is based upon its center of gravity while a variety of measures such as symmetry, roundness, and the ratio of the axes of the best fitting ellipse help to characterize its shape. For orientation, a measure of the inclination of the longest axis of the best fitting ellipse can be used. Data from these measurements are readily transferred to statistics packages for further processing.

Reporting Results

A combination of the capacities of computer and video technologies has enabled the findings obtained from the types of investigations described above to be displayed in a manner that is more appropriate than conventional methods. This is particularly well demonstrated in the case of results obtained from analysis of the process data where the nature of the subjects' performance over time was of special interest. For example, a computer animation program was used to produce dynamic summaries of essential differences in how those in the meteorologist and non-meteorologist subject groups built up the meteorological markings as they copied a weather map. These summaries collapsed the individual marking sequences produced by subjects within these two groups into an overall sequence for each group as a whole. In addition, the animation greatly compressed the time scale so that the broad temporal patterns present in the sequence became much more apparent. Once prepared, the animated sequence for each of the subject groups was transferred to videotape for easy presentation and distribution. This animated form of the results captures process aspects of the subjects' performance far more faithfully than is possible in a static figure of the type typically used to report the findings of an investigation. Further, complex results of the type generated in this investigation appear to be considerably more accessible if presented in an animated format than if presented in a more conventional manner.

Conclusion

This paper has dealt with several illustrative examples of how video and computer technology can be used to support basic research into the way diagrams are represented in people's minds The approaches that have been developed can address a variety of challenges that face the researcher in this field, ranging from those of presenting the initial stimulus material to subjects through to reporting the research findings in an appropriate manner. In common with other research methodologies, in order to make use of these approaches effective, sufficient attention must be given to theoretically significant aspects of data collection, analysis, and interpretation. The strength of video technology is that it provides for the capture of highly detailed visual data. However, it also presents problems with the time-consuming nature of some aspects of transcribing the generated data into a form suitable for statistical analysis. In contrast, computer technology can directly monitor some aspects of a subject's performance and save the generated data in files that are suitable for analysis by a statistical package without further processing. Unfortunately, it is not currently capable of directly providing (for reasonable cost and effort) the type of facilities for dealing with visual data that are available with video. However, the recent merging of video and computer technologies with the advent of digital video opens up exciting possibilities for developing a whole range of new research tools that can be used to increase our understanding of the way people deal with visual information.

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