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Background knowledge and the construction of a situational representation from a diagram

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Comprehension of a diagram requires viewers to construct from its graphic constituents a mental representation that captures the situational entities and relationships referred to by the diagram. However, this implies viewers possess appropriate background knowledge concerning the depicted situation. Meteorologists' and non-meteorologists' mental representations were investigated using a three-stage card sorting task during which subjects generated hierarchical groupings of the graphic elements of an Australian weather map diagram. Cluster analysis indicated that the two subject groups differed fundamentally in the basis of their sorting behaviour. Subjects' justifications of the groupings suggested that non-meteorologists' mental representation of the diagram elements was primarily based upon domain-general, visuo-spatial characteristics whereas in meteorologists' representations, these characteristics were subservient to a domain-specific, situational interpretation of the graphic array. The findings indicate that background knowledge deficiencies may make it difficult for learners beginning study of a domain to construct suitable mental representations from domain-related diagrams.

Introduction

Many of today's instructional materials place great emphasis on pictorial presentation of their subject matter. Although this is partly a reflection of society's increasing adoption of visually-oriented communication media in general, it also reflects the apparently widespread conviction in the educational community that pictorial presentation has some sort of privileged instructional effectiveness. This is exemplified by the pronounced tendency among designers of educational materials to treat illustrations as if they were unproblematic aids to instruction.

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The research reported here investigated the basis of the way students process pictorial materials, in particular the type of specialised depictions that characterise scientific and technical domains. It is part of a programme of studies designed to develop a detailed characterisation of how diagrams are mentally represented on the assumption that the nature of such mental representation is fundamental to the processing involved in their interpretation. Evidence is emerging that a knowledge-related effect somewhat similar to that found for text also occurs when individuals with high and low levels of knowledge in a particular subject domain are confronted with a domain-related diagram. In this situation, it seems that a general capacity to process everyday pictorial material would be insufficient to deal with the specialised content found in such diagrams. Rather, specialised background knowledge would be required in order to build an effective mental representation of the situation depicted in the diagram. A clear understanding of the way different influences predominate at different levels of domain-specific background knowledge is essential in order to develop instructional strategies that can help beginning students in technical domains use highly abstract domain-relevant diagrams more productively. Given this understanding, an instructor's task could then extend beyond merely including such diagrams as part of a learning resource to a point where diagrams were embedded in an instructional context that deliberately supported the learners' construction of effective mental representations. This support would address differences in the influences that determine the way that mental representations of diagrams are constructed by students and their instructors.

While there is a substantial body of research showing that illustrations can facilitate desirable learning outcomes (Willows & Houghton, 1987), much of this has focussed upon pictorial material in the role of a text adjunct. Until quite recently, there has been comparatively little detailed study of the way individuals interact with illustrations in their own right. However, there is increasing awareness that the successful interpretation ("reading") of some of the types of illustrations used for instructional purposes may be a more demanding processing task than has been previously realised (Blystone & Dettling, 1990; Gillespe, 1993). This is particularly likely to be the case with highly abstract and specialised illustrations such as diagrams (Constable, Campbell, & Brown, 1988; Kindfield, 1993; Lowe, 1988).

Although the great majority of educational research dealing with illustrations has been concerned with instructional outcomes (rather than the mental processes that contribute to these outcomes), the mental processes involved in the perception and comprehension of pictorial materials are the subject of increasing interest (e.g., Larkin & Simon, 1987; Mandl & Levin, 1989; Schnotz & Kulhavy, 1994; Winn, 1991; 1993). Developing an effective interpretation of a diagram requires a viewer to deal with its contents and expression in a way that appropriately captures the situation referred to in the diagrammatic depiction. In highly abstract diagrams designed to reveal key relationships in the subject matter (rather than provide explicit information about its appearance), this means going well beyond the visuo-spatial characteristics of the graphic marks that comprise the diagram. The viewer needs to be able to build a mental representation that expresses accurately the situational entities and relationships implied by the arrangement of graphic entities in the diagram. This construction process can be considered to result in an internal representation that has been described as a mental model or situational model of the depicted subject matter (Glenberg & Langston, 1992; Mayer & Gallini, 1990). The advantages that diagrams can have over text in helping individuals deal with complex content have been linked to distinctive aspects of the information structure of diagrams that facilitate their processing compared with informationally equivalent text (Larkin & Simon, 1987; Winn & Li, 1989). On this analysis, the effectiveness of a diagram as a means for a particular individual to develop an appropriate understanding of a diagrammed situation should very much depend on that individual's capacity to use the diagram's information structure effectively. In the following section, it will be suggested that an important aspect of this capacity is the level of domain-specific knowledge that an individual possesses regarding the subject matter of the diagram.

Knowledge and Processing

In studies of text processing, it has been established that a high level of background knowledge in a particular domain facilitates effective processing of domain-related text (e.g., Fincher-Kiefer, Post, Greene, & Voss, 1988; Spilich, Vesonder, Chiesi, & Voss, 1979). This domain-specific knowledge appears to assist high knowledge individuals in building a useful mental representation of the situation described in a presented text (that is, a situational representation; Kintsch, 1986). In an instructional context, the consequences of a student not building an appropriate mental representation from a set of presented information can be that understanding and problem solving performance are compromised. With some types of subject matter, this issue goes beyond whether a student reaches the stage of building some sort of situational representation from the given information. It is critical that the nature of the situational representation constructed is suitable for dealing with concepts that are fundamental to effective functioning within the domain from which the information is drawn. Individuals beginning their studies in scientific and technical domains may be particularly at risk in this regard. For example, it has been found that novices in physics tend to represent the information given in physics problems in terms of its superficial characteristics (such as the objects and types of arrangements presented in the problem) rather than according to the deeper structure of fundamental physics concepts used by physics experts (Chi, Feltovich, & Glaser, 1981; Larkin, 1983).

Evidence of the role of background knowledge in visual processing emerged some years ago from the work of a number of researchers who investigated expertise in chess. For example, Chase and Simon (1973) found that domain-specific knowledge was a key factor in the superior performance of chess experts over novices in a cognitive task involving non-random configurations of pieces on a chess board. The experts' greater capacity to deal with this visual information was attributed to their possession of knowledge that allowed them mentally to chunk the configurations into groups of pieces that were bound together by domain-specific relations. Similar chunking behaviour based upon domain-specific knowledge has also been found with more diagrammatic displays such as electronic circuit diagrams (Egan & Schwartz, 1979), architectural drawings (Akin, 1986) and baseball play diagrams (Allard & Burnett, 1985). In the next section, the various types of meaningful relations that may be used to bind together the individual elements of a diagram will be discussed.

Representing diagrammatic information

Work by Mayer and his colleagues (e.g., Mayer, 1989; Mayer & Anderson, 1992; Mayer & Gallini, 1990) indicates that diagrams can help learners to develop effective mental representations of scientific systems by facilitating the cognitive processes required to connect information about a system into a coherent structure bound together by meaningful relations. These processes include the building of internal connections between ideas that are part of the presented material and the building of external connections between these ideas and the learner's existing knowledge. Where a combination of visual and verbal information is presented to the learner, the building of referential connections between the learner's visual and verbal representations needs to be considered. Mayer and colleagues' research suggests that these various construction processes can be enhanced by instructional design strategies that give proper consideration to the cognitive challenges involved. These strategies include using diagrams as concrete models to foster systematic thinking, presenting diagrammatic material in a way that emphasises component behaviour as well as system typology, and coordinating the combination of diagrammatic and verbal information in ways that maximise spatial and temporal contiguity.

However, even with carefully designed instruction, it may still be difficult for students to build an instructionally useful mental representation of a system from a diagram if that diagram is very abstract. This is likely to be the case when the diagram's subject matter or depictive conventions are far removed from the students' everyday experience. Daily, we deal successfully (and in an apparently effortless way) with a barrage of external visual information. Underlying this continual visual processing is a range of highly generalisable capacities for handling the visuo-spatial characteristics of our everyday surroundings. Our extensive world knowledge about everyday situations and events allows us to interpret such information in an appropriate manner. This knowledge base helps move our mental representation of the information beyond a visuo-spatial level to a more useful situational level. While these generalised visuo-spatial capacities equip us very well for making sense of the wide range of everyday visual information we encounter, their very domain-general character may limit their usefulness in more specialised situations where we lack a relevant knowledge base.

Winn's (1993, 1994) analysis of the perceptual and semantic grouping processes involved in dealing with materials such as diagrams emphasises the importance of this knowledge component and also raises the issue of whether the two types of grouping processes support or counteract each other. This latter aspect can be illustrated with the weather map diagrams that are the focus of the present research. Figure 1 shows a typical weather map consisting of a land mass outline (Australia) covered by an assortment of meterological markings. An example of perceptual and semantic grouping processes supporting each other occurs with the heavy barbed lines near the south east corner of the map (cold fronts). These are both perceptually arresting because of their bold visuospatial characteristics and meteorologically significant because of what they mean for the temperature in their region.

However, most of the markings in Figure 1 are isobars (lines joining locations with the same atmospheric pressure) and these provide an example of how perceptual grouping may counteract semantic grouping. In the south west corner of the map's border, there are three quarter-closed isobars which perceptually tend to be linked into one coherent group because of their particular visuo-spatial characteristics (proximity and similarity in shape). Similarly, in perceptual terms, the three distant peaked isobars in the south east corner of the map together appear to constitute another distinct group. In other words, the perceptual effect is that intermarking relations within each of these groups are strong but between the two groups these relations are weak (or possibly non-existent). However, despite these perceptual effects induced by the visuospatial characteristics, there are in fact strong semantic relations between isobars in the separate groups. For example, the middle isobar in the south west group and the top isobar in the south east group are actually both parts of the same continuous isobar. The link between them is the segment of this continuous isobar that is not shown on the map because it runs to the south of the lower border.

This meteorological example raises the more general case of an individual who knows very little about a particular knowledge domain encountering an abstract diagrammatic depiction of an aspect of the domain's subject matter. Such a situation might face a beginning student of a scientific or technical discipline encountering an explanative diagram intended to focus sharply on the very essence of its topic in a powerful and economical way. Although the person's basic capacities for handling visual information would allow her or him to construct a domain-general visuo-spatial mental representation of the diagram's constituents, it seems unlikely that s/he would be able to progress to a domain-specific mental representation that appropriately captures the situation that the diagram stands for.

Weather map diagrams

The present research is concerned with characterisation of meteorologists' and non-meteorologists' mental representations of weather map diagrams. This particular choice of diagram type has no special significance of itself; it simply provides a suitable illustrative example of the features that are common to a wide range of highly abstract diagrams that are used in scientific and technical domains. Levin, Anglin and Carney (1987) categorise the functions of pictorial materials within instructional settings into five broad classes; decoration, representation, organisation, interpretation and transformation. A major proportion of the diagrams that characterise scientific and technical domains are intended to fulfil the interpretation function.

This typically involves visual explanations that aim to clarify specialist subject matter, present abstract concepts in an accessible manner, and make difficult material more comprehensible. These explanative diagrams typically use a highly parsimonious treatment of their subject matter that dispenses with all but its most central aspects in order to make the key information clear, accessible and simple. Weather maps provide an excellent example of this more demanding type of diagram because they present our world in terms of formal scientific abstractions that are depicted via a highly conventionalised system of symbols. They therefore contrast with more concrete representatives of this category of pictorial materials such as the diagrams of pulley sets, pumps and brake mechanisms that have been used other researchers in this field.

The reason for using meteorologists and non-meteorologists as subjects is that their great difference in domain expertise parallels the gulf that usually exists between (a) a teacher who is knowledgeable in his or her technical domain and (b) beginning students of that domain. In such an instructional situation, teachers frequently make use of diagrams on the assumption that this form of presentation is essentially transparent to beginning students. Because meteorologists and non-meteorologists have greatly differing levels of background knowledge and expertise with respect to the domain depicted in weather map diagram (meteorology), differences in their capacity to develop an appropriate mental representation of such diagrams would be expected. When presented with a weather map diagram, meteorologists should be able to construct mental representations from the display's graphic elements that are not limited to a visuo-spatial characterisation of the diagram's information structure. Although *domain-general* visuo-spatial characteristics are likely to play some role in the constructed mental representation, this role would be expected to be quite subservient to the domain-specific meaning that such characteristics have in the field of meteorology. In contrast, non-meteorologists' lack of domain-specific meteorological knowledge would be expected to limit them to the construction of an impoverished and largely visuo-spatial mental representation from the diagram. Clearly this type of mental representation would not be an effective way to capture the meaning of the meteorological situation depicted in the weather map.

Previous studies have indicated that *relations* are central to differences in the mental representation of weather maps by meteorologists and non-meteorologists (Lowe, 1989, 1993, 1994). It seems that for meteorologists, relations involving meteorological regularities, generalisations and principles are fundamental to the way weather map information is processed. Relations between the entities explicitly portrayed by markings in a given weather map as well as wider relations between these given entities within the weather map border and entities expected beyond the border both appear to be important. There was also evidence that indirect relations between the given markings which are based upon these latter wider relations exerted a strong structuring influence on the way the meteorologists performed a quite diverse range of weather map tasks. However much less evidence was found in these previous studies for the influence of meteorological considerations on the weather map processing of non-meteorologists. Rather, their processing reflected a mental representation of weather maps that seemed to be primarily based upon generally applicable visuo-spatial considerations. In addition, it appeared that non-meteorologists did not typically invoke external relations with the wider spatial and temporal context of a weather map to support their processing of information explicitly portrayed within the boundaries of that particular map.

Evidence that non-meteorologists have a largely visuo-spatial (rather than meteorological) basis for the mental representation that underlies their weather map processing should be reflected in the way they mentally characterise (a) the *entities* that make up the map, (b) the *relations* that are used in the mind to bind individual weather map markings into groupings, and (c) the way these entities and relations are *qualified* to add specificity to their representation. This last aspect of qualification is concerned with the attributes of entities and relations and includes elaborations such as the specification of the shape of an entity or the closeness of a spatial relation. Of these three aspects (entities, relations and qualifiers), the relations are of particular importance because of their central role in determining the *structure* of mental representation. The existence of groups of markings within the mental representations of both meteorologists and non-meteorologists is strongly indicated by the studies referred to above. However, the bases upon which these groupings are constituted appears to differ. Direct investigation of the relations involved in these groupings should provide more detailed information about what sorts of influences shape the structure of the mental representations that are built from highly abstract diagrams.

The main purpose of the present study was to determine the nature of the relations between the entities that comprised subjects' mental representation of weather maps. However, the investigation of relations inevitably entails consideration of the entities involved in those relations and the qualifiers that help to improve the definition of both the entities and relations. This study required subjects both to identify groupings of elements existing at a number of levels and to give detailed, explicit explanations about the relations that were the basis of those groupings.

It was expected that meteorologists would group weather map markings primarily on a meteorological basis, justifying their groupings according to relations that included spatial and temporal constraints beyond the scope of the given map. Relations involving the visuo-spatial characteristics of markings would form part of their justification only to the extent that they were set in the context of the meteorological significance of those markings. Thus an hierarchical mental representation that contained qualitatively different types of information integrated across different levels would be indicated. In contrast, non-meteorologists were expected to group the markings primarily in terms of their visuo-spatial characteristics, justifying their groupings according to relations that were confined to the explicit graphic content of the given map. Although there may be some references to meteorological aspects, these would not set the map in a wider meteorological context and would be indicated as a relatively minor characteristic of the non-meteorologists' mental representations.

Method

Subjects

Eight meteorologists were forecasters in the Perth office of the Bureau of Meteorology who had from 3 to 30 years' of professional experience in their field. Eight non-meteorologists were university graduates from a variety of disciplines who were studying for a Diploma of Education. These subjects were without specialist training in meteorology and reported that their main experience with weather maps came from viewing television weather presentations or from the weather section of newspapers.

Materials

The weather map on which this study was based was the same as that used in a previous study (Lowe, 1993). Although the map was modified to the extent that numerical information concerning isobaric values was omitted, in all other salient respects it corresponded to a standard synoptic chart of the type routinely used to present weather information about the Australian region. It was comprised of an outline of Australia together with a set of meteorological markings that were characterised as consisting of 34 individual graphic components belonging to nine figural or conceptual categories. These graphic components consisted of an assortment of lines as well as crosses, triangular barbs and alphabetic symbols. For the purposes of the research task, 34 cards each measuring 12.5cmx7.5cm and all bearing identical copies of the weather map in the form of a black and white line diagram were prepared. On each of these cards a different graphic element was highlighted by marking it in red, as shown in the examples given in Figure 1 (in which highlighted elements are indicated by the heavy gray outline). Hence the full set of highlighted cards together contained marked versions of all the 34 map elements.

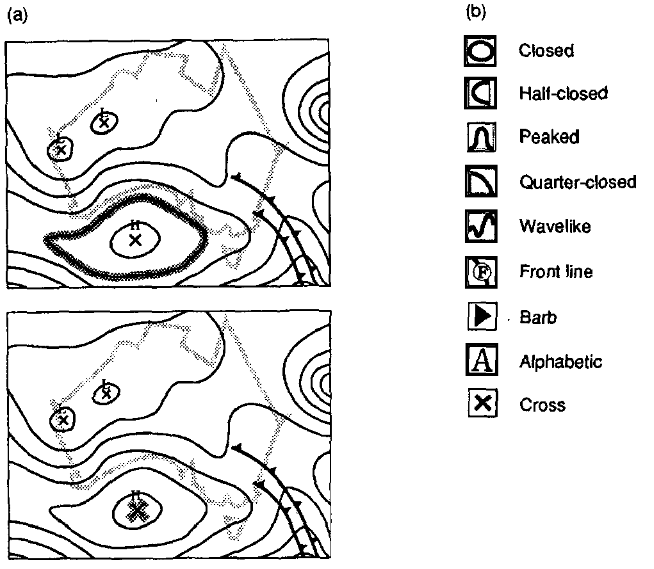

Figure 1. (a) Examples of maps with different markings highlighted as used in card sorting task; (b) Nine figural or conceptual categories of components

Procedure

The procedure used in the study was developed as a modification and extension of the card sorting task described by Chi, Feltovich, and Glaser (1981). It required subjects to sort a set of cards, each of which displayed the same weather map diagram but with different elements highlighted. Each subject undertook a progressive card sorting task individually with the experimenter. This task involved sorting the weather map cards in three successive stages that will be described as the primary sort, the subdivision sort and the combination sort respectively. In the primary sort, the 34 cards were spread out randomly on the table in front of the subject who was then asked to sort them so as to form groups in which the elements highlighted on the cards belonged together in some way. Subjects were told that they could use as many or as few groups as they considered necessary and were asked to sort the cards according to what immediately occurred to them as the most natural groupings. It was made clear to subjects that it was their personal reaction which was required and that there were no "right" or "wrong" answers. Once the subject was satisfied with the groupings, s/he was asked to explain the reasoning underlying the choice and membership of groupings. To give additional focus to this explanatory process, the subject was asked to reflect upon what held the elements in each group together and what distinguished each group from the other groups formed. In addition, the subject was asked to produce a brief descriptive title for each group which could be used to identify that group clearly and economically. The grouping reasons and group titles were recorded by the experimenter and the suitability of these records checked with the subject.

In the subdivision sort, the subject was asked to subdivide, where possible, any of the primary sort groups into smaller groups (with the constraint that new groups should be formed only if there was a clear and natural basis for the subdivision). After formation of the groups, the subject's explanations for grouping and descriptive titles were recorded as before.

In the combination sort, the original groups that the subject produced in the primary sort were re-established. The subject was then asked to combine any of the groups that s/he wished to form a smaller number of more inclusive groups. Once again, explanations for grouping and descriptive titles were recorded.

Data Analysis

It was assumed that within each of the subject groups, the extent to which any two graphic elements were likely to be mentally represented as related to each other was indicated by the overall frequency with which they were associated during the card sorting task. Thus the more often two particular graphic elements were placed together in a category by the members of a subject group, the more strongly those elements were assumed to be associated within mental representation. Using the categorisations produced by each of the subject groups during the three stages of the sorting task, the frequencies with which elements shared the same category were determined for all possible pairings of the 34 elements. These frequencies were used as the distance metric in a cluster analysis procedure in which frequency was inversely proportional to the relational distance between the elements in a pair. Separate cluster analyses (complete linkage) were performed for the meteorologist subject group and the non-meteorologist group. In addition, a qualitative analysis of statements that combined the reasons for groupings with group titles was made to characterise the nature of (a) the entities constituting the groups (b) the relationships used as a basis for those groupings and (c) aspects of the explanations that acted to qualify these entities and relations.

The following hybrid description has been constructed from statements made by both meteorologists and non-meteorologists. It illustrates the various types of information that were typically contained in subject responses.

> *"These curved lines are symbols for the closed isobars that are tightly arranged around a cyclonic low pressure cell in the Pacific".*

The subject descriptions of weather map information can be characterised in terms of the types of *entities* (such as isobars, low pressure cell and the Pacific) from which they are constituted and the *relations* between those entities (such as the surrounding of the low pressure cell by the isobars or the location of that cell in the Pacific). Precision and specificity may be added to the basic descriptions of both the entities and their relations by the addition of elaborative *qualifiers* (such as the closed nature of the isobars and the tight arrangement of isobars around the low pressure cell). Within this description, different classes of entity, relation and qualifier can be identified. For example, in addition to the isobars and other clearly "meteorological" entities that have been discussed above, the line is just as clearly a "graphics" entity that has a very much wider domain of application than in this particular map. Similar distinctions can be drawn among the various relations that occur between entities. This is illustrated in the example given above in which the relation involving the isobar and the low pressure cell occurs between two meteorological entities whereas that involving the low pressure cell and the Pacific is between a meteorological entity and its geographic context. These two types of relation can be distinguished according to the nature of the components involved in the relation. The former can be characterised as a *spatial* relation involving the arrangement of variable components of the map. Entities such as isobars and low pressure cells can both legitimately occur in a particular spatial arrangement relative to each other irrespective of their absolute position within the map border. For example, they can be close to each other or distant, directly adjacent or separated by other markings or arranged so that either one or the other is uppermost. In contrast, the latter is a *positional* relation involving the location of a variable component with respect to the unchanging interpretative framework provided by the geographic context. There can also be different types of qualifiers used to elaborate upon the entities and relations described. For example, the qualifier used to refine the description of the line is concerned with its shape (visuo-spatial) whereas that used to elaborate upon the low pressure cell is concerned with its meteorological status.

A coding scheme based upon entities, relations and qualifiers was developed to analyse the responses subjects produced when asked to give reasons for their grouping of the 34 weather map elements. These three main coding categories were further subdivided to allow for the presence of different types of entities, relations and qualifiers as discussed above.

Table 1 lists the 18 individual coding categories developed. The large Entities group was broken down into two subgroups of domain-specific entities and domain-general entities to reflect the degree to which the categories applied specifically to the meteorological domain. This breakdown of the Entities group has been done mainly for convenience. Similar distinctions can also be made for the Relations and Qualifiers groups but the split is not as even as it is in the entities group so these will be referred to during the discussion of results. The bold face letters indicate the abbreviations used for these categories in subsequent figures.

Table 1
Statement description coding categories

Entities			
Domain-specific	Domain-general	Relations	Qualifiers
Broad-scale F**e**ature	**U**ndefined **E**ntity	**U**ndefined **R**elation	**M**et. **Q**ualifier
Composite F**e**ature	**C**omposite **G**raphic	**S**patial **R**elation	**S**hape **Q**ualifier
Single F**e**ature	**G**raphic	**P**ositional **R**elation	**E**xtent **Q**ualifier
Meteorological **E**lement	**S**pecific **G**raphic	**P**art-**W**hole Relation	**O**ther **Q**ualifier
	Other **E**ntity	**O**ther **R**elation	

Within the Entities category, the major subdivisions are meteorological and non-meteorological (mainly graphical) with each of these being further subdivided to produce a set of hierarchically related sub categories. In the Relations category, a distinction was drawn between those occurring between an entity and its components (part-whole), between various entities (spatial relation) and between an entity and the interpretative framework in which the entity was located (positional relation). In the Qualifiers category the three main sub categories covered specifically meteorological description as well as the more general characteristics of shape and extent. A coding manual containing detailed specifications for all categories was devised as the basis for analysing the descriptive statements. All 372 descriptive statements (171 from the non-meteorologists and 201 from the meteorologists) were combined into a single set that was then randomly sorted so that the origin of each statement was hidden. Each statement was then analysed by the experimenter according to the specifications given in the coding manual to determine the number of times information fitting each of the coding categories occurred per statement. After this blind analysis, a mean score per statement on each of the categories was calculated for the two subject groups. To assess the reliability of this process, a second coder trained in the categorisation procedure independently coded a random sample consisting of 25% of the total statements set.

Results

This section begins with an examination of the patterning of the markings as revealed by cluster analysis of the card sorting data. Next, results from the analysis of statements produced by subjects as they explained the basis of their card sort groupings will be reported. Although these two types of data are reported separately, they should be treated as complementary.

Cluster Analysis

Figures 2 shows the top two levels of element clustering that emerged from the cluster analysis. These specify the most inclusive and second most inclusive groupings of elements produced as a result of this analysis procedure.

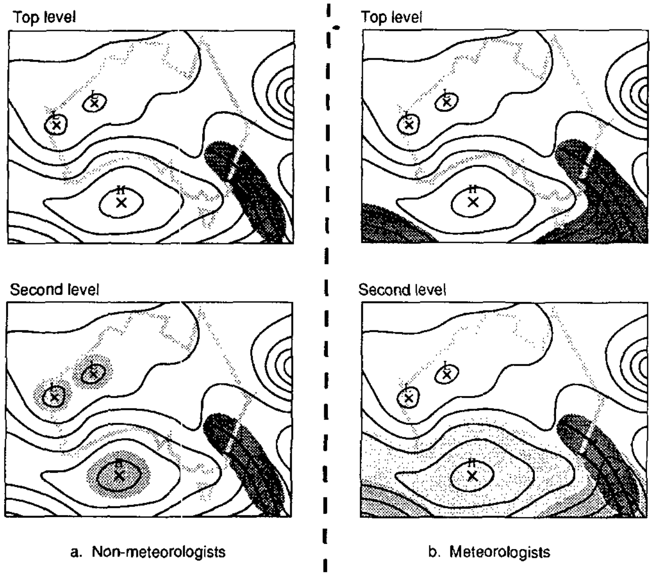

Figure 2. Top levels of element clustering for (a) non-meteorologists and (b) meteorologists

At the uppermost level, the analysis for both the meteorologist group and the non-meteorologist group distinguished the two frontal symbols as major components of the map. However, although the result for the non-meteorologists distinguishes these features as separate from all other markings on the map, the meteorologists' result includes the two sets of isobars in the south west and south east corners of the map in the same group as the two fronts. At the second level of the analysis, the clustering produced for each of the two subject groups becomes far more distinctive. For the non-meteorologists, the non-frontal map elements split into two subgroups. The smaller of these subgroups is comprised of the inner regions of three pressure systems. Each is made up of a central cross, an appropriate alphabetic symbol ("H" for high or "L" for low) and a single closed isobar. The larger subgroup consists of a variety of peripheral isobars that are not themselves central parts of complete closed circulations. For the meteorologists, the second level clustering distinguished the set of two fronts as a group and identified three subgroups among the non-frontal map elements. One of these was comprised of the two sets of isobars in the south west and south east corners of the map that were associated with the fronts in the superordinate cluster mentioned previously. The other two subgroups were (a) all the markings in the northern half of the map (plus a single curved isobar fragment on the south east border of the map) and (b) a set of markings located in the Great Australian Bight. In contrast to the non-meteorologists' second level clustering, these subgroups could not be divided simply into either central or peripheral parts of pressure systems. The northern subgroup contains markings indicating low pressure areas while the Bight subgroup constitutes a region of high pressure.

Figures 3a and 3b use a different format to show further selected details of the clustering patterns produced in the analysis. These tree diagrams emphasise hierarchical aspects of the clustering patterns. They were derived from groups that emerged up to and including the fourth level of clustering and were selected so as to show only larger groupings of elements (groups containing less than four elements are not presented). The cluster labels used on the two diagrams were derived from the major trends in grouping reason explanations and group titles produced by the particular subject group concerned.

The non-meteorologists' clustering reflects an organisation based around a primary distinction between markings that comprise fronts and markings that do not. These non-frontal markings are further subdivided into those that constitute pressure centres and those that surround these centres. These surrounding markings are distinguished according to whether they are associated with the high centre or the pair of low centres.

The meteorologists' clustering reflects a different basis for the organisation of elements on the map. As with the non-meteorologists, there is a clear indication that pressure centres provide some of the structuring for the organisation of map elements. However, there is not the same simple division of the map into frontal and non-frontal elements. There are three major divisions of the map region according to broad latitude zones (the extreme south, the mid latitudes and the tropical region in Australia's north).

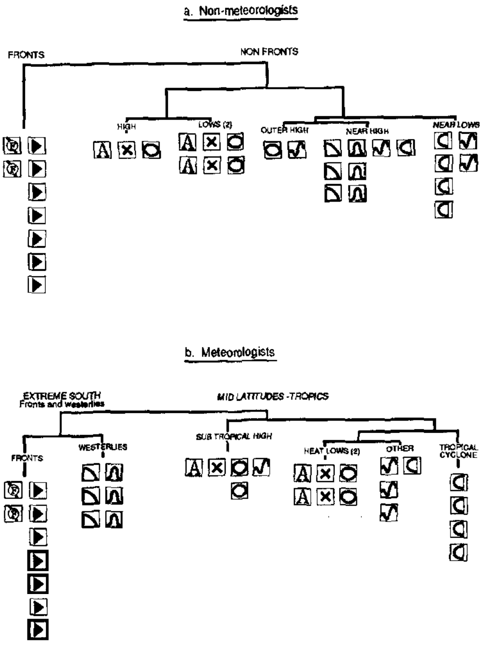

Figure 3. Tree diagrams showing further details of (a) non-meteorologists' and (b) meteorologists' element clustering patterns

In the extreme south, two quite different types of elements constitute the group. Comments recorded during the card sorting task indicated that the meteorologists considered the isobars in the south west corner and in the south east corner of the map to both be fragments of the same continuous westerly flow that runs across the southern region. The other part of this southern group is the pair of cold fronts. These are conceptually different from isobars because they mark the positions of air temperature discontinuities rather than regions with the same atmospheric pressure.

In the mid latitudes, the major feature mentioned is a high pressure cell in the Bight. In contrast to the pattern found for the non-meteorologists, this high is not merely composed of the central cross, alphabetical symbol and inner-most isobar. Instead it is extended so that as well as these inner elements, it is also comprised of the two other outer isobars that surround the central region.

In the northern region (tropics), the two heat lows in the north west and the Pacific cyclone were the main focus of description and explanation. Once again the meteorologists differ from the non-meteorologists in that the markings comprising the grouping extend beyond the central region of each of the low pressure systems. However, in this northern region, the extension is not as clearly defined as it is for the high in the mid latitudes.

Exceptions to this clear latitudinal grouping over the map occurs in the case of the single half-closed isobar that is present on the south eastern boundary of the map and in the case of the single wandering wave-like isobar that travels across the centre of the map. These elements were frequently characterised by the meteorologists as being in their "own" groups. The south east boundary isobar was reported to be a retreating high cell that was a continuation of the subtropical ridge. The wandering central isobar was mainly seen as marking the division between the warmer low pressure areas in the northern half of the map and the cooler high pressure areas in the southern half.

Explanatory Statements

For the 25% sample of statements categorised by both coders, the correlations for the frequencies with which statement components were assigned to categories were 0.92 and 0.93 for the meteorologist and non-meteorologist groups respectively. Table 2 compares the mean number of descriptive references per statement made by meteorologists and non-meteorologists within each of the three broad groupings used to categorise these responses (entities, relations and qualifiers). For each of these three groupings, the meteorologists produced significantly more descriptive references per statement than the non-meteorologists, although this difference was much more pronounced for the entities and relations groups than for the qualifiers group.

Table 2

Mean references per statement in entity, relation and qualifier categories

Grouping	Subject group: Meteorologists		Subject group: Non- meteorologists		$t(370)$
Entities	4.60	(1.86)	3.23	(2.02)	6.77**
Relations	2.80	(1.75)	1.75	(1.24)	6.56**
Qualifiers	1.64	(1.58)	1.33	(1.31)	2.06*

Note. ** $p<.0001$; * $p<.05$; standard deviations in parenthesis.

Based on median values, a typical statement by one of the meteorologists can be characterised as containing four references to entities, three to relations and one to qualifiers. On a similar basis, a typical non-meteorologist statement typically also contained one qualifier but only three entities and two relations. It should be noted however that these numbers do not necessarily represent different instances from within the same grouping because they generally include repetitions of one or more aspects of the descriptions (see example statements below). The relative numbers of entities and relations is consistent with the expectation that the number of relations would be smaller than the number of entities linked by these relations. When the entities grouping was broken down into domain-specific and domain-general subgroups, the mean number of domain-specific entities per statement produced by the meteorologists was significantly greater than that produced by the non-meteorologists (Mmet=3.05, SD=1.45; Mnon=1.17, SD=1.21; $t(370)=13.44$, $p<.0001$). For the domain-general subgroup, the situation was reversed (Mmet=1.54, SD=1.72; Mnon=2.68, SD=1.89; $t(370)=6.00$, $p<.0001$).

Figure 4 shows the mean overall frequency with which descriptive comments were made in each of the 18 categories. The three most commonly used categories were (a) the domain-specific Single Feature category (b) the Positional Relation category and (c) the Extent Qualifier category. This reflects the frequent description of markings across both groups of subjects in terms of the identity of individual markings, their location relative to other information on the map and the number of markings of each type.

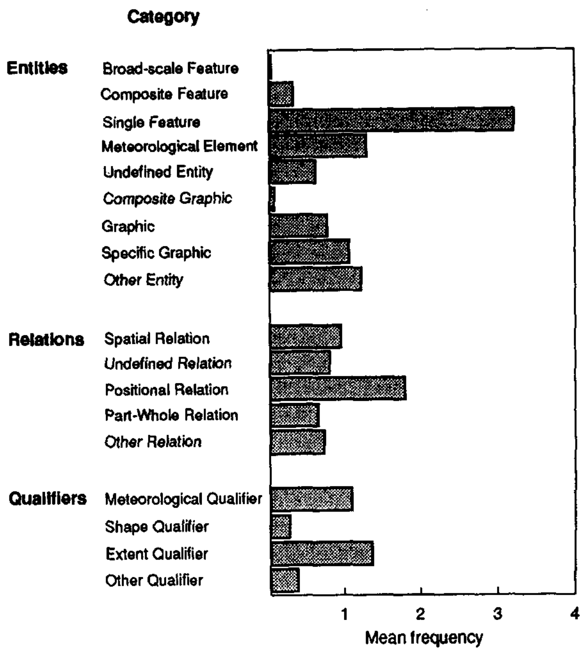

Figure 4. Use of statement categories by all subjects

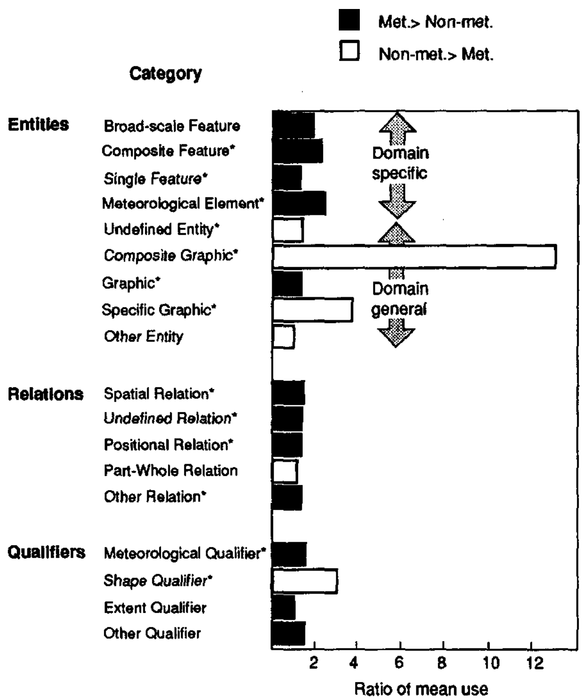

Figure 5. Relative use of statement categories by meteorologists and non-meteorologists (* indicates $p<.05$)

Figure 5 shows which of the two types of subject tended to make more use of descriptions belonging to each of the 18 categories. It is based upon the same data as was used for Figure 4 (mean number of descriptive references made per statement) but displays these data in terms of proportions. Where this reference frequency was greater for the meteorologists, the ratio meteorologists/non-meteorologists is shown. For purposes of display in Figure 5, where the reference frequency was greater for the non-meteorologists, the inverse ratio has been used. Within the entities category, the ratios for the domain-specific subgroup indicate that the meteorologists tended to produce all categories within this subgroup more frequently than the non-meteorologists. However, for the domain-general subgroup, the reverse was the case for all categories except the "graphics" category. This category differs somewhat from the other categories within this subgroup because it covers entities that are rather more abstract and generic. In the relations grouping, the relative frequency with which the non-meteorologists used individual categories was lower for all categories except Part-Whole Relation where it was higher. In the qualifiers grouping, the relative frequency for the non-meteorologists was lower for all except the Shape Qualifiers category, where it was higher than for the meteorologists. In all other cases, the relative frequency with which the categories in these two groupings were used was greater for the meteorologists.

An examination of some individual statements that subjects used to describe their card-sort groupings will help to show the origin of the general trends reported above. The selected statements given below are drawn from a variety of levels in the card sorting task (primary, subdivision and combination) and are intended to be illustrative rather than representative. The bold superscript letters in parenthesis that follow each of the descriptive fragments within the statements refer to the coding category to which these fragments were assigned.

Non-meteorologists' statements:

"Information**(U)** about what appears to be a series of concentric lines**(CG)** that follow the same pattern**(CG)** down in the south east corner**(PR)** of the map**(OE)**; south east corner**(PR)**, part of**(PW)** a concentric pattern**(CG)**."

"The cold**(MQ)** front**(F)**; threatening**(OQ)** lines**(SG)** that move across**(PR)** at right angles to**(SR)** the other lines**(SG)** of pressure**(OE)**; only two**(EQ)** so put together**(UR)**; lines**(SG)** of cold**(MQ)** fronts**(F)**"

"Curved**(SQ)** lines**(SG)** or a second**(EQ)** circle**(SG)** outside**(SR)** an inner**(SR)** circle**(SG)**, such as number 18**(OE)** or 22**(OE)**; wavy**(SQ)** lines**(SG)** or circular**(SQ)**"

Entities: The first statement lacks any reference to specifically meteorological entities but does mention two types of more generally applicable entities (Composite Graphics and Other Entities), whereas the second contains a mixture of both domain-specific and domain-general entitie (Features, Specific Graphics and Other Entities). In the third, again there are no specifically meteorological entities mentioned (Specific Graphics and Other Entities – in this case the other entities refer to two of the other cards used in the card sorting procedure).

Relations: In the first statement, the same Positional Relation is mentioned twice and a reference is made to a Part-Whole relation involving two levels of graphic information. In the second, Positional Relations, Spatial Relations and Undefined Relations categories are represented. Although there are several different types of relations in this second example, it should be noted that they are largely concerned with low level visuo-spatial aspects of the display and could just as easily apply to a display from any other domain. In other words, they are not in any sense specific to the meteorological nature of the material they describe. A similar situation exists in the third statement with the use of the terms "inside" and "outside" in a way that is not domain specific.

Qualifiers: Although there are no qualifiers in the first statement, the second contains examples from the Meteorological Qualifiers, Other Qualifiers and Extent Qualifiers categories. However, the nature of these qualifiers is such as to put them in the realm of everyday experience rather than in a specifically meteorological domain. In the third example, Shape Qualifiers are used extensively to help describe the visuo-spatial characteristics of the entities with an Extent Qualifier used to help identify which of the lines is being referred to in the course of the description.

In summary, these examples illustrate how for entities, relations and qualifiers, the non-meteorologists tended to produce descriptive material that was domain-general rather than specific to the meteorological domain. Although some meteorological terms did appear, the emphasis was on the more superficial graphical information in the display and how it was arranged.

Meteorologists' statements:

"Associated(UR) with a high(F) in the Pacific(PR) to the south(SR) of the tropical(MQ) cyclone(F); related to(UR) weather system(U) not appearing on(SR) the weather map(OE); Tasman(PR) high(F)"

"Isobars(E) showing(OR) the trough(CF) in which(SR) the fronts(F) are embedded(OR); frontal(MQ) trough(CF)"

"Symbol(G) that defines(OR) the location(PR) of the centre(PW) of a high(F); location(OQ) symbol(G) rather than isobar(E) or label(G); high(F) centre(PW) location(PR)"

Entities: The first statement contains two different types of Single Features (high and cyclone) as well as an Undefined entity (weather system) and an Other Entity (weather map). In the second statement, three different levels of meteorological description co-exist. The isobars (Meteorological Element) are at the lowest level, the trough (Composite Feature) at the highest level and the fronts (Single Feature) between these two. The third statement mixes two different varieties of Graphic entities (symbols and labels) with the meteorological entities (Elements and Single Features) represented by these graphics.

Relations: Various relations specified in the first statement locate entities with respect to each other and with respect to the weather map region (Spatial Relations and Positional Relations) with Undefined Relations mentioned as involving these entities. The second statement uses Other Relations and a Spatial Relation to specify the way the low-level entities (isobars) collectively delineate the high-level entity (trough) that contains the mid-level entity (front). Relations used in the third statement describe the role of a graphic element in representing aspects of the meteorological entity it depicts (Other Relation), specify the function of the graphic element in indicating the position of a particular region of that entity (Positional Relation) and indicate that this region is part of a larger structure (Part-Whole Relation).

Qualifiers: Both the first and second statements use Meteorological Qualifiers to provide a more detailed description of meteorological entities. In the first statement, this has the effect of describing the origin and nature of the entity (tropical) while in the second, it helps define the hierarchical relationship between the various entities mentioned in the statement. The only qualifier (Other Qualifier) present in the third statement simply acts to clarify the function of the graphic symbol and its place in the notational system relative to other possible entities.

In summary, these examples illustrate how for entities, relations and qualifiers, the meteorologists tended to produce descriptive material that was highly domain-specific. When they did refer to general matters, they did so in the context of an overarching meteorological characterisation of the material being described. A clear distinction was made between graphic level information and the meteorological content that it was used to depict. Many of the relational terms used and some of the qualifiers helped to establish the idea of hierarchical structuring of different levels of meteorological information, both within the map boundary and beyond it. There is also evidence suggesting that graphical information was linked with this meteorological hierarchy in an organised and integrated manner.

Discussion

As expected, the card sort clusters produced from the non-meteorologists' data can be explained largely in terms of overall visuo-spatial characteristics. More specifically, the non-meteorologists' clusters were formed from elements which had one or more of the following characteristics: they were (a) visually distinctive, (b) in close proximity, (c) similar in their graphic properties or (d) part of the same visuo-spatial pattern. These characteristics of the non-meteorologists' clusters are evident from the arrangements shown in the cluster analysis diagrams (Figures 2 and 3) and from the analysis of the comments that subjects made during the card sorting process. This latter analysis showed not only that the non-meteorologists gave less extensive descriptions of their groupings than the meteorologists (especially of entities and relations), but also that those descriptions had a qualitatively different emphasis. Within the broad Entity grouping, the non-meteorologists had a strong tendency to use domain-general, visuo-spatial terms to describe the groups of elements they produced, while the meteorologists' descriptions emphasised terms that are essentially specific to the domain of meteorology. Similar effects, although less pronounced, were seen in the way the non-meteorologists emphasised visuo-spatial matters in the Relations and Qualifiers groupings.

The results of the cluster analysis will now be used as a framework for a more detailed consideration of what information the subjects' descriptive statements indicate about the characteristics of their mental representations of weather maps. Although the analysis for both subject groups singled out the visually-distinctive cold fronts in one of the two high level clusters, only the meteorologists linked these features to the isobar fragments in the south west and south east corners of the map. The set of peaked isobars in the south east corner could reasonably be associated with the fronts because they cut across these features. Hence they can be linked by the very generalised visuo-spatial characteristics of proximity and intersection. However, the quarter-closed isobar group in the south west is so distant from the front lines that in a visuo-spatial sense it seems quite unrelated. So while a visuo-spatial explanation may account for the association of the south east isobars with the front, that explanation breaks down for the south west set.

Nevertheless, there is a sound meteorological reason why the fronts, south east and south west isobars can be considered to be closely related (despite their apparent independence from a visuo-spatial perspective). The two sets of southern isobar fragments are part of a more extensive band of isobars associated with the general westerly flow at this latitude (responsible for the strong winds in this region known as the "westerlies"). Within these westerlies are embedded a series of troughs with associated fronts and it is highly probable that meteorologists' knowledge of this meteorological subsystem accounts for the way they linked together the southern isobars and fronts. However, it seems likely that the non-meteorologists may simply have singled out the fronts as a major cluster on the basis of their distinctive visuo-spatial characteristics. Not only do the front markings consist of much thicker lines than the other markings, they also have a distinctive array of spikes distributed along them and cut across the path of the isobars. Among the several other types of markings spread across the map (lines, circles, crosses and alphabetical symbols), these frontal symbols are unique and intrinsically highly visible because of their particular graphical treatment and orientation. The interpretation given here for this illustrative example is consistent with the general type of description the non-meteorologists tended to use when giving reasons for groupings in the card sort task.

In the second level of clustering produced, there is further evidence that visuo-spatial considerations are fundamental to the way that the non-meteorologists mentally represent weather map information. Sets of discrete visual "objects" comprising circles (closed isobars), crosses (pressure centres) and alphabetical letters (pressure level designations) in close proximity appear to constitute one cluster of information for these subjects. All the other lines (isobars and isobar fragments) seem to form another. Despite this strongly visuo-spatial orientation, the comments made by the non-meteorologists suggest that their mental representation of weather maps is not entirely lacking in a meteorological dimension. Although a large proportion of the descriptive material they produced in their statements about grouping reasons is quite domain-general, there were often several meteorological terms mixed in with the fundamentally visuo-spatial description. Isobars, fronts, highs and lows were mentioned quite frequently by the non-meteorologists but their statements containing these references generally focussed on the visuo-spatial characteristics of these entities. Although in some cases, dynamic properties were attributed to these entities, these were highly simplistic and overgeneralised. It appears from the evidence discussed above that it would be a mistake to characterise the non-meteorologists' mental representation of weather maps as being entirely visuo-spatial. It may be more appropriate to regard it as involving a rudimentary and coarse-grained model of the components, structure and dynamics of weather systems. For example, such a model might be composed of a major visuo-spatial dimension which is linked in a rather haphazard way to fragments of meteorological knowledge.

The meteorologists' second level of clustering and the relevant statements they produced to describe the patterns that emerged identified several major zones running across the map that had distinctive meteorological characteristics which varied according to the latitude of these zones. The positions of these zones suggests that the meteorologists mentally represent them as part of the large scale meteorological phenomena that are associated with global atmospheric circulation. Each of these zones is characterised as being populated by different types of meteorological entities that have different origins, different properties and different meteorological effects. Some of these entities mentioned by the meteorologists in their comments on grouping reasons occur over a relatively broad scale, for example troughs and ridges. These broad-scale entities were described as generally containing a number of lower level features such as fronts and pressure cells. The various pressure cells themselves were further subdivided into entities such as isobars from which they were constituted and finally the graphic symbols that were used to depict these lowest level meteorological entities.

It seems that both the meteorologists and non-meteorologists attach importance to pressure cells and fronts as major structural components of a weather map. Both groups made a clear distinction between high pressure cells and low pressure cells. However, what needs to be considered is the place that each of these components occupies in the *overall* mental representation of weather map information and the way they are related to other components. Further, it is important to understand the way these components are linked to other types of information, such as that concerned with the visuo-spatial characteristics of the map and the map's wider spatial-temporal context. With the non-meteorologists, there appears to be little distinction between conceptually different types of information. However, there is evidence that as far as the markings are concerned, the meteorologists draw a clear qualitative distinction between *graphical* information about markings and *meteorological* information with the former being strictly subservient to the latter. This type of distinction seemed to be part of a well-organised overall coordination of different types and levels of information. In contrast, the non-meteorologists showed little discrimination between different information types and levels. Neither did they appear to have an extensive hierarchy of information levels.

The results of the present study indicate that meteorologists represent mentally a specific weather map as a particular instance of much more generalised meteorological phenomena. It appears that the specific array of markings on particular map that is under consideration are set in the context of a spatially and temporally extended representation of the Australian weather map region. Meteorologists seem to link an individual map to a series of broad-scale meteorological influences and patterns that apply over a much wider geographic area than is depicted on the map itself. It is likely that this connection of the given map information to the extended area allows them to impose an overarching structure on the map's markings. This would have the advantage of allowing them to represent the set of markings as variants on an on-going theme rather than as completely novel patterns. An additional dimension to the representation would be added by setting the particular map in the context of the regular seasonal changes that are the ultimate source of the marking patterns comprising the weather map. Once again, a knowledge of the typical characteristics expected for different seasons could have representational advantages in terms of seeing a specific map as a variant of a typical stage within a larger cyclic pattern of changes.

However, the non-meteorologists seem to lack this larger contextual framework within which to set a specific weather map. Their behaviour suggests that their mental representation of a given weather map is an isolated construction which owes a minimal amount of its constitution to the broader meteorological context. They processed the map's markings in a manner that suggested a superficial visuo-spatial representation of this information and one which essentially ended at the boundary of that particular map. It seemed that their mental representation was not one that normally allowed for the meteorological systems depicted to be considered as parts of larger spatial or temporal patterns. It was almost as if nothing existed beyond the boundaries of the map (reminiscent of ancient mariners who believed that if they sailed beyond charted regions of the Earth, they would sail off the edge of the world) or that the time scale for meteorological change that the non-meteorologists considered extended little more than a few days.

Conclusion

The mental representation constructed from a diagram is a basis for the cognitive processes involved in understanding and remembering the information it deals with, as well as for solving problems within the subject domain addressed by the diagram. It follows that unless students can take advantage of a diagram's potentially beneficial information structure to build an appropriate situational model, they would be unlikely to make effective use of that diagram as a learning resource. The highly abstract diagrams that tend to characterise scientific and technical domains present particular challenges to beginning students of those domains. These students lack the domain-specific knowledge that is possessed by their instructors and which is required to "fill out" the parsimonious depictions given in such diagrams. A fundamental goal of instruction is to help students develop the capacity to deal with information in a particular domain in a manner that accords with the way their instructors deal with that type of information. For a diagram to support this development, its study should result in the construction of a suitable mental representation (that is, a representation reflecting the same basic principles of content and structure that would be expected for an instructor). The clear differences in the mental representation of a diagram by individuals with different levels of domain-specific knowledge found in the present research indicate that it is unlikely that a highly abstract diagram could, of itself, produce such a result.

If, as indicated by the research reported here, a lack of domain-specific background knowledge can largely preclude the construction of an appropriate situational model from a highly abstract diagram, then specific instructional support for beginning students appears necessary to help them become skilled readers of certain domain-relevant diagrams. Merely including such diagrams to accompany text in learning materials would be insufficient. These results contrast with findings from other research in which diagrams were found to aid the building of situational models (presumably because the processing requirements they imposed were not as demanding as those of the abstract diagrams used in the present study). Using the detailed information about differences in mental representation that emerged from this study, a number of suggestions can be made about possible ways to provide support for effective diagram processing. These address questions related to text design, diagram design and strategies to optimise the processing of information presented in both these sources. If the broad findings are generalisable to similarly abstract diagrams in other domains, it appears appropriate to provide students with explicit supporting information for diagrams that serves to compensate for their lack of background knowledge. In effect, the roles conventionally assigned to text and diagrams would be reversed. Instead of treating a diagram as a "transparent" facilitative adjunct to text, supporting text could be used to elaborate the diagram with the specialised information necessary to construct a situational model based upon concepts central to the domain concerned. This support should go beyond the usual (and necessary) practice of explaining the symbols and their individual meanings because of the important role that explicit and implicit relationships between those symbols appears to play in construction of an appropriate situational model.

However, because much of the important diagram information that may be missed by students is likely to be visuo-spatial, instructional strategies should not be limited to verbal support. Visual support should also be provided to help students locate and understand important relationships. Ideally, diagram designers should arrange the visuo-spatial characteristics of the graphic-level information so that those which tend to be noticed by domain novices correspond to salient aspects of the depicted domain. However, this is not always possible since there will sometimes be relationships that, while not strongly cued in visuo-spatial sense, are nevertheless of key importance in building an effective mental representation from a diagram. Where there is this lack of correspondence in the diagram between perceptual conspicuity and the domain-relevance of information (as occurs with various subtleties in the way elements are related), compensatory cueing such as shading or marking off particular areas could be used to draw students' attention to productive ways to chunk the graphic elements. Although the value of helping students use various relationships to connect graphic entities into meaningful chunks has been emphasised by other researchers, the present study highlights the importance of relations *between* different levels of information as well as those *within* the same level. This indicates that the broad goal of instructional strategies should be to help the beginning student to build from a diagram a more heirarchically structured mental representation in which qualitatively different forms of information are usefully coordinated across its various levels. Because many technical diagrams represent only small subsets of much broader situations, the strategies used to help students progress beyond a superficial treatment of a diagram could also include explicit elaboration of its spatial and temporal context.

This study was confined to a domain that, while highly abstract, does use symbols that are have some passing familiarity to most people. It therefore invites use of this type of investigation for diagrams in other domains, especially those in which the symbols, diagram type and content are even less familiar. For example, would the same general visuo-spatial categories appear for such diagrams? Research is also required to investigate the extent to which instructional support of the type suggested above is able to improve the efficiency and effectiveness with which students develop the capacity to construct appropriate mental representations from diagrams. The findings presented here question the widespread and uncritical assumption that illustrations in general are necessarily effective instructional aids for beginning students of a domain. They also suggest that with highly abstract diagrams depicting unfamiliar content, the facilitative effect that other types of diagrams have been found to provide for the building of situational models may be counteracted by the powerful constraint imposed by deficiencies in domain-specific background knowledge. While an elegantly simple diagram may be seen by teachers as capturing the essence of its subject matter, to their students it may appear as a decontextualised assortment of graphic symbols that are difficult to combine into a meaningful whole.

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La compréhension d'un graphique exige du sujet qu'il construise, sur la base de la représentation figurale, une représentation mentale des éléments du graphique et de leurs relations. Cela suppose, de la part du sujet, des connaissances adéquates déjà constituées à propos de *la situation représentée par le graphique. Les représentations mentales de météorologues et de non-météorologues ont été comparées à la faveur d'une tâche de sélections successives (trois étapes) d'éléments d'une carte météorologique qu'ils devaient regrouper en fonction de leurs relations et selon une catégorisation hiérarchique. Une analyse en clusters a mis en évidence des différences très nettes dans les principes des classifications appliquées par les deux groupes de sujets. Les justifications fournies ont révélé que les non-météorologues fondent leur représentation mentale des éléments du graphique sur des caractéristiques générales et visuo-spatiales du domaine; les météorologues s'appuient sur une interprétation spécifique et située de l'information apportée par le graphique. L'inadéquation des connaissances antérieures gène l'acquisition dans des domaines nouveaux où le sujet doit construire des représentations appropriées à partir de représentations graphiques du domaine étudié.*

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Most relevant publications in the field of Educational Psychology:

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Lowe, R.K. (1994). Selectivity in diagrams: Reading beyond the lines. *Educational Psychology, 14*, 467-491.