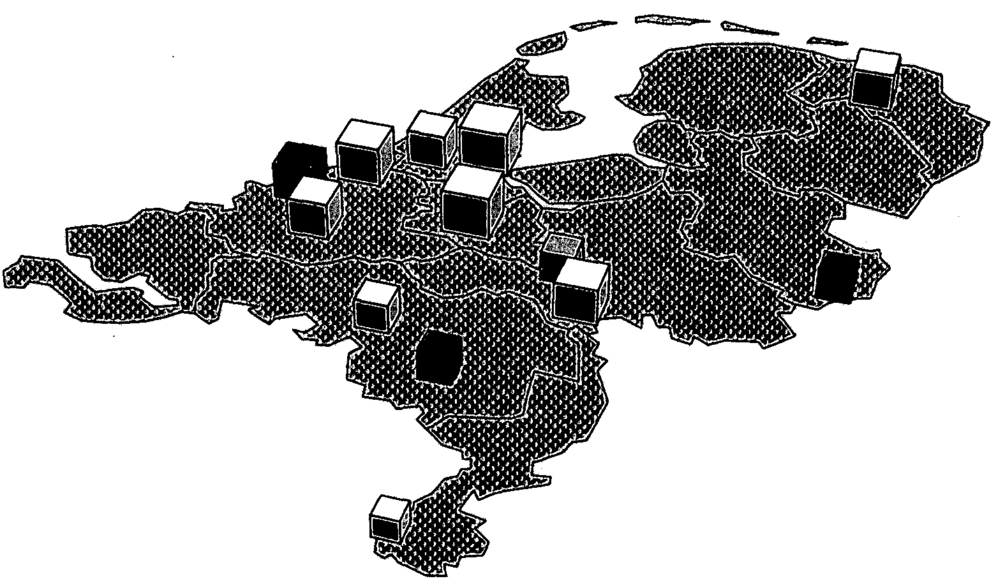
computer-assisted cartographical three-dimensional imaging techniques

m.j. kraak



COMPUTER-ASSISTED CARTOGRAPHICAL THREE-DIMENSIONAL IMAGING TECHNIQUES

COMPUTER-ASSISTED CARTOGRAPHICAL THREE-DIMENSIONAL IMAGING TECHNIQUES

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR AAN DE TECHNISCHE UNIVERSITEIT DELFT, OP GEZAG VAN DE RECTOR MAGNIFICUS PROF. DRS. P.A. SCHENCK, IN HET OPENBAAR TE VERDEDIGEN TEN OVERSTAAN VAN EEN COMMISSIE DOOR HET COLLEGE VAN DEKANEN DAAR TOE AANGEWEZEN, OP DONDERDAG 27 OKTOBER 1988, TE 14.00 UUR

DOOR

MENNO-JAN KRAAK

GEBOREN TE VAASSEN (GEM. EPE)
DOCTORANDUS

Delft University Press/1988

Dit proefschrift is goedgekeurd door de promotoren:

Prof. Dr. Ir. M.J.M. Bogaerts & Prof. Dr. F.J. Ormeling

Published by:
Delft University Press
Stevinweg 1
2628 CN Delft
the Netherlands
(015) 783254

CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Kraak, M.J.
Computer-assisted cartographical three-dimensional imaging
techniques / M.J. Kraak. - Delft: Delft University Press. -
Ill. Proefschrift Delft. - Met lit. opg. - Met samenvatting
in het Nederlands
ISBN 90-6275-463-5
SISO 519.3 UDC 912(183)+[681.3:528.9](043.3)
NUGI 674
Trefw.: drie-dimensionale kaarten / computergebruik in de cartografie.

cover: Three-dimensional point symbol map of the Netherlands, showing the type (yellow=ordinary; green=agricultural; blue= technical) and size (smallest cube represents 3,200 students, and the largest 26,000 students) of Dutch universities.

Stellingen bij het proefschrift 'Computer-assisted cartographical three-dimensional imaging techniques' door M.J. Kraak.
Delft, 27 oktober 1988.

1. De fransman Bertin omschrijft de kartograaf als de 'mathematicus' van een niet-mathematisch systeem van tekens [Bertin, 1983, pp .286], waarmee hij doelt op een systematische ordening van het grafische beeld. In het hedendaagse informaticatijdperk geldt voor de kartograaf die zich bezig houdt met onderzoek dat de aanhalingstekens in Bertin's omschrijving weggelaten kunnen worden.

2. Om te communiceren beschikt de mens over gesproken en geschreven taal en daarnaast over beeldtaal. Het vermogen om zich van deze drie communicatievormen te bedienen wordt in het engels omschreven als respectievelijk articulacy, literacy en graphicacy [Robinson, 1984, p. 3]. De vervaardigers van beelden moeten ook over beide andere communicatie faculteiten beschikken indien zij de computer bij de produktie toepassen: het lezen van de handleiding(en) en gesprekken met collega's zijn onvermijdelijk.

3. Het is niet altijd eenvoudig de gemiddelde kaartvervaardiger te overtuigen van de noodzaak de kartografische grammatica te gebruiken om tot een goed kartografisch produkt te komen. Kartografische tradities en conventies kunnen dit zelfs tegenwerken. De kaart waarin het relief door de traditionele hypsometrische tinten (groen/geel/bruin - van laag naar hoog) is weergegeven is hiervan een voorbeeld [dit proefschrift].

4. De traditionele permanente kaart is een voorbeeld van zowel een goede gegevens- en opslagstruktuur als van een goede presentatievorm van ruimtelijke gegevens. De tijdelijke kaart (de beeldschermkaart) is nog slechts een voorbeeld van dit laatste [dit proefschrift].

5. De ontwikkeling van de computerkartografie in samenhang met de ruimtelijke informatiesystemen heeft ertoe geleid dat de kaart zowel in oude als nieuwe gedaanten een grotere verspreiding heeft gekregen, hetgeen de kartograaf moet toejuichen. Veel van deze nieuwe kaarten worden echter vervaardigd door niet-kartografisch geschoolde kaartmakers. Dit is de belangrijkste reden om de ontwikkeling van kartografische kennissystemen sterk te stimuleren.

6. De extrapolatie van de trends die hebben bijgedragen tot het aanvatten van het onderzoek dat aan dit proefschrift ten grondslag ligt, doet verwachten dat ontwikkeling van de drie-dimensionale kartografie in veel opzichten dynamisch zal verlopen [dit proefschrift].

7. De permanente kaart met de gemiddeld kortste levensduur is de kaart afgebeeld op postzegels. Een uitzondering hierop vormen de postzegelkaarten die in bezit komen van een karto-filatelist.

8. '..... Seen it on the map! Huck Finn, did you reckon the states was the same color out-of-doors as they are on the map?'
'Tom Sawyer, what's a map for? Ain't it to learn you facts?'
'Of course'
'Well, then, how is it going to do that if it tells lies?...'
Deze conversatie tussen Tom Sawyer en Huck Finn [Twain; Tom Sawyer abroad, 1894, pp.42-43] geeft een voorbeeld van het gezag dat een naïeve kaartgebruiker aan een kaart toekent. Wordt de kaartinhoud opgeslagen in een bestand dan blijft de invloed van het gezag niet beperkt tot naïeve gebruikers. Door velen wordt, geheel onterecht, een grote autoriteit toegekend aan wat door de computer wordt getoond, waarbij de kwaliteit van de oorspronkelijke gegevens wordt genegeerd.

9. Wanneer het door het Ministerie van Onderwijs en Wetenschappen gelanceerde plan, het aantal lesuren aardrijkskunde drastisch te verminderen onverhoopt mocht worden uitgevoerd, dan kan het effect hiervan worden verminderd door in de algemeen vormende vakken die de aardrijkskunde moeten gaan vervangen een onderdeel op te nemen dat het gebruik van de grafische beeldtaal stimuleert.

10. In de wetenschap bestaat er een verband tussen de frequentie van het gebruik van nieuwe vaktermen, zoals bijvoorbeeld kennissystemen en geografische informatie systemen, en de van overheidswege beschikbare subsidies voor onderzoek.

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Colour illustrations

Between the pages 20-21, 52-53, 84-85 and 126-127 colour illustrations can be found representing some of the three-dimensional maps used during this research. They are reproductions of maps originally presented on a colour screen. It has been tried to reproduce the screen colours as closely as possible, but due to difference in nature of the colour systems used (additive - RGB - system on screen and the subtractive - CMY - system on paper) this was not possible. Also some hardware patterns used in the maps presented on a screen could not be reproduced in their original appearance. Some of the illustrations presented can be viewed in stereo, however they will have to be removed from the book to be able establish a proper eye-base.

The list below describes the illustrations. The number between the brackets corresponds to question and illustration numbers in Appendix III and IV.

ACKNOWLEDGEMENTS

That this study is finished, is partly due to both my promotors, Prof. Dr. Ir. M.J.M. Bogaerts and Prof. Dr. F.J. Ormeling, whose enthusiastic, encouraging and critical comments stimulated me after every discussion. Their efforts are also responsible for providing me with an almost ideal working environment.

I am also very grateful to Prof. G. McGrath who, during his sabbatical leave in Delft, has reviewed the english text of this thesis; however, any mistake left is my sole responsibility. We also had some fruitful discussions with respect to the contents of this work, and he suggested some improvements.

During the progress of the work student assistants I.C.A. Kuijlaars, R.L.G. Lemmens and R.E. Molendijk have been most helpful in preparing the necessary software, in guiding the students who participated in the computer-assisted map user test, and with processing the test results.

My special thanks go to T.M.P. Tijssen who not only assisted me with my normal work, but also contributed with constructive criticism. My colleagues A.H. Fonk and M. Struyk also helped me with my daily work, and were still willing to answer difficult questions. Also thanks are due to colleagues M.G.G.J. Jutte, who has drawn many of the illustrations, to A.B. Smits, responsible for the photography, to A.J. van Dam who printed the colour illustrations and the cover of this book, and to E.M. Seintra-Fendel who read the final texts.

The Faculty of Geodesy provided the facilities needed for this research project. The study contract between the Faculty, unit Land Information & Cartography, and IBM has to be mentioneded separately, since it supplied the necessary computer hard- and software.

Last but not least I have to thank my parents who provided the base of my education, my late grandfather who stimulated my interest in maps, and most of all Marijke and Eelke, for without their endless patience this study would not have been possible.

CHAPTER 1. INTRODUCTION

Cartographers are concerned with the information transfer of spatial distributed data by means of maps. For centuries mainly manual techniques have been used to design and produce maps. In mapping phenomena related to the earth the three-dimensional real world has to be projected onto the paper's plane surface, for long the most important carrier of cartographic information. In some maps the cartographer was trying to represent the three-dimensional world as closely as possible. This was a difficult and laborious undertaking.

Since the sixties, however, the importance of the computer as a cartographic tool has increased. The use of the computer made some laborious manual techniques, like scribing and lettering superfluous. The application of computer graphics techniques, that is the creation, storage and manipulation of models of objects and their pictures via computer, introduced new aspects to cartography. It also made the practice of cartography change considerably, but the basic principles remained relatively unchanged [Morrison, 1986, p.5].

Developments in the field of computer graphics led to an increased use of these techniques in many disciplines [Foley & Van Dam, 1984]. The use of the computer makes the presentation of research results more flexible then before. The application of three-dimensional graphics seems to contribute especially to the evolution of disciplines such as molecular biology (a better understanding of the DNA structure), architecture (a better perception of the plan) and engineering (CAD/CAM, interactive design; robotics & kinematics). A look at recent literature on computer graphics [SIGGRAPH, 1985] confirms this impression.

Is such a trend also apparent in cartography? Can the application of three-dimensional computer graphics help to solve some of today's cartographic problems? In several subfields of the discipline cartographers struggle with the third dimension, for example with map projections, relief representation and the display of spatial data models. For some of them more or less satisfactory solutions have been found [Imhof, 1965] while others use less successful or laborious methods.

The relation between cartography and computer graphics is schematically displayed in Figure 1-1. The result of the cross section can be seen as part of computer-assisted cartography. Computer-assisted cartography applies to all aspects of cartography where the computer is used as an aid. Many developments in computer graphics are directly or indirectly applicable to cartography. There are also similarities in both disciplines, technical (the use of the same equipment) as well as theoretical aspects (the interest in a good communicative image).

Despite this close relation computer-assisted cartography has developed in a direction different from other disciplines using computer graphics techniques. This is due to the nature of the data the cartographer has to work with: geographical data. Geographical or spatial data have characteristics which differentiate them from other data. Each element has an unique location in space (a metric representation). These definitions of location tend to be complex, since they exist in complex and irregular patterns, while many spatial relations are possible [Peuquet, 1984, p.73].

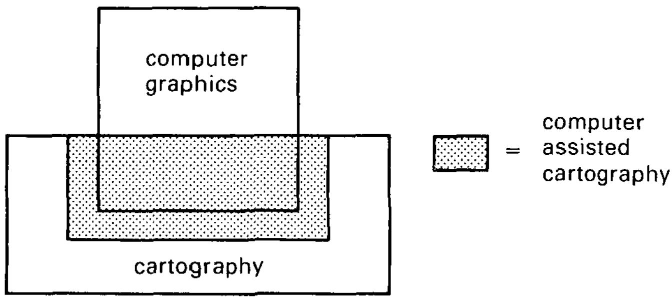


Figure 1-1. Relation cartography, computer assisted cartography and computer graphics.

To answer the question which was raised at the beginning of this chapter a closer look at three-dimensional cartography by combining knowledge of cartographic theory, three-dimensional perception and computer graphics using new technological developments is necessary. The following observations indicate an interest in three-dimensional cartography [Kraak,1986, p.54].

1. Computer technological developments

Looking at developments in computer technology, it can be seen that computer systems are becoming smaller while their capacity increases. The personal computer of tomorrow will be able to handle the job of the mini computer of yesterday. In addition to the increase in capacity there are the decreased prices of equipment. A similar trend is seen when looking at the peripherals. New storage techniques can handle more data than before and more and more displays in use have advanced colour screens. Computerized data handling, input, storage, manipulation and output become easier. These developments make the technology become more generally available and all disciplines can benefit from it. For cartography it may facilitate possibilities for sophisticated map presentation [Marble, 1987, p.101].

2. Developments in computer graphics

Since many computer graphics applications involve the display of three-dimensional objects and scenes, techniques were developed to display them on two-dimensional screens [Newman & Sproull, 1981, p.293]. These techniques deal with questions such as how depth, the third dimension can be displayed on a screen and how the three-dimensional world should be modelled in the computer so the images can be generated.

3. Developments in computer-assisted cartography

The introduction of the computer as a cartographic tool made cartographers change their approach to the discipline. It has already penetrated many subfields of cartography. In a decade, in most developed countries the prefix 'computer-assisted' will become superfluous, since the computer will be a tool in all fields of cartography. An overview of its introduction, its nature, and its advantages as well as disadvantages can be found in Monmonier [1985], Morrison [1980] and Rhind [1980]. Looking at today's cartography several trends can be distinguished.

- Automation of the mapping and charting process

  In several nations the mapping and charting programme is being automated, while others have plans to do so [Young, 1987]. For new maps data are collected in a digital form. Surveying, photogrammetric and remote sensing techniques are used. Existing maps are converted from analog into digital form using digitizing techniques. For most topographic maps and charts the data capturing is in x-, y- and z-coordinates. The purpose of these maps is to represent the three-dimensional reality as closely as possible. Very often the z-coordinate is used to depict height or depth contours and selected spot elevations or soundings. In trying to introduce more realism the cartographer is held up by visualization problems [Castner & Wheate, 1979, p.77]. A more realistic view of the topography can possibly be obtained by the graphical representation of a digital terrain model. This is a numerical representation of terrain characteristics. When dealing with the altimetric aspects only they are called digital elevation models. When the term digital terrain model is used in this thesis it refers to its graphical representation;

- The production and use of thematic mapping software

  An increase can be seen in the number of software packages which can produce thematic maps. These can be packages fully oriented to cartography [Noranha, 1987]. They can also have a different origin, for instance oriented to statistical analysis and extended with a cartographic component [Carter, 1987]. Many of these products have facilities for three-dimensional images such as prism maps. The use of this software, however, will not always result in good communicative images. This is mainly because cartographers were not involved in the design and production of software. Based on the increase in the number of licenses issued for software packages such as for instance GIMMS, the last decade has shown a distinct increase in the use of cartographic software;

- The interest in the cartographic component of Geographical Information Systems. Geographical Information Systems are tools for an effective utilization of large volumes of spatial data. They represent the intersection of disciplines such as surveying, remote sensing, geography, geology and cartography [Brassel, 1983]. Burrough [1987, p.6] describes these systems as 'A powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes. This set of tools constitutes a Geographical Information System'. For planners, market researchers and policy makers it is possible to approach their problems in a integrated fashion. Due to the character of the problems to be solved there is a need for sophistication in data analysis, manipulation and presentation. The system's success heavily depends on its cartographic component, which presents its results;

- The interest in the development of cartographic expert systems. The number of non-cartographers working with software which can produce maps increases, particulary with geographical information systems becoming commonplace. To make sure that those map makers can produce their own, but cartographically correct, maps they may need some help. Here a cartographic expert system might provide a solution [Mackaness, 1986];

- An interest in 'new' cartographic products. The computers creates opportunities for the cartographer to work on map types which are, without the use of the computer difficult or laborious to produce [Taylor, 1984]. This is certainly valid when the third dimension is involved. A greater interest in map types such as prism maps and digital terrain models can now be seen.

The combination of these observations instigated this research project: computer-assisted cartographical three-dimensional imaging techniques. Its objective is to see what characterizes three-dimensional maps and determine whether indeed three-dimensional maps produced by computer-assisted cartography give the map user a better understanding of the mapped phenomena. To be able to test this it is necessary to know what role the three-dimensional map plays in the cartographic communication process.

Using this type of maps in the process of spatial information transfer is not always the most obvious solution. During occasions such as the annual film and video show at the SIGGRAPH conference on computer graphics [SIGGRAPH, 1985] it can be seen, especially in applications such as the advertising and entertainment sectors that they are used probably just because they are impressive and pleasant to look at. In most cases a two dimensional map could transfer the message as well. But if, from a cartographic point of view, there are no objections against presenting information this way there is no problem in using the map as an eye-catcher.

In specific applications the use of three-dimensional maps can be very effective in explaining spatial relations. For instance when mapping the earth's surface digital terrain models can give an understanding insight into its forms. Using the possibilities to look at the terrain in an interactive environment, by changing view angle and azimuth, the sometimes difficult interpretation of a topographic map or chart contour lines can be avoided [Griffin & Lock, 1979]. The height information-can be combined with for instance land use information. Looking at the urban environment three-dimensional maps can be helpful for planners and architects [Joosten, 1986].

Maps portraying statistical surfaces, such as the prism map, were originally used in classifying statistical data from which choropleth maps have to be produced [Jenks & Coulson, 1963]. But they can function independently and offer dramatic views of the mapped phenomena and will for long be remembered by the map user. The influence of the extreme statistical values in the area becomes notable.

It should be noted that most attention in this study has been focussed upon the final impact of the three-dimensional map. For instance no real attempt has been made to provide an efficient data structure, although a production system for these maps is given. To be able to come to conclusions on the research project's objective it is structured as presented in Figure 1-2. Each square in the scheme corresponds to a chapter in this dissertation.

A short description of the theoretical approach to cartography as a framework of this research project is given in Chapter 2. Definitions and descriptions of specific terminology used in this project are given and explained here. Three-dimensional maps are classified according to the technique used to produce them. Four map types/applications are chosen to illustrate ideas throughout the project.

A survey of current cartographic theory is given in Chapter 3. This is necessary since it is the base on which the three-dimensional approach in chapter 5 is built. Cartographic communication theory, cartographic information analysis and the principles of the (carto)graphic sign system are combined.

Chapter 4 will examine how humans see and perceive the three-dimensional world around them. From this knowledge elements can be obtained to add to the three-dimensional map to improve it, and let the map user truly perceive it as three-dimensional. The chapter will also take a closer look at expedients which can be used to enhance the appearance of the three-dimensional images.

In Chapter 5 a synthesis of the previous three chapters is given. Knowledge from cartography and three-dimensional perception are combined to see whether they strengthen or weaken each other.

Chapter 6 describes the program developed to produce the three-dimensional maps. A procedure to construct the maps is discussed. The basic principles in the three-dimensional map production system are after data collection and processing the pre-display of the map, its manipulation and the final step in creating the map.

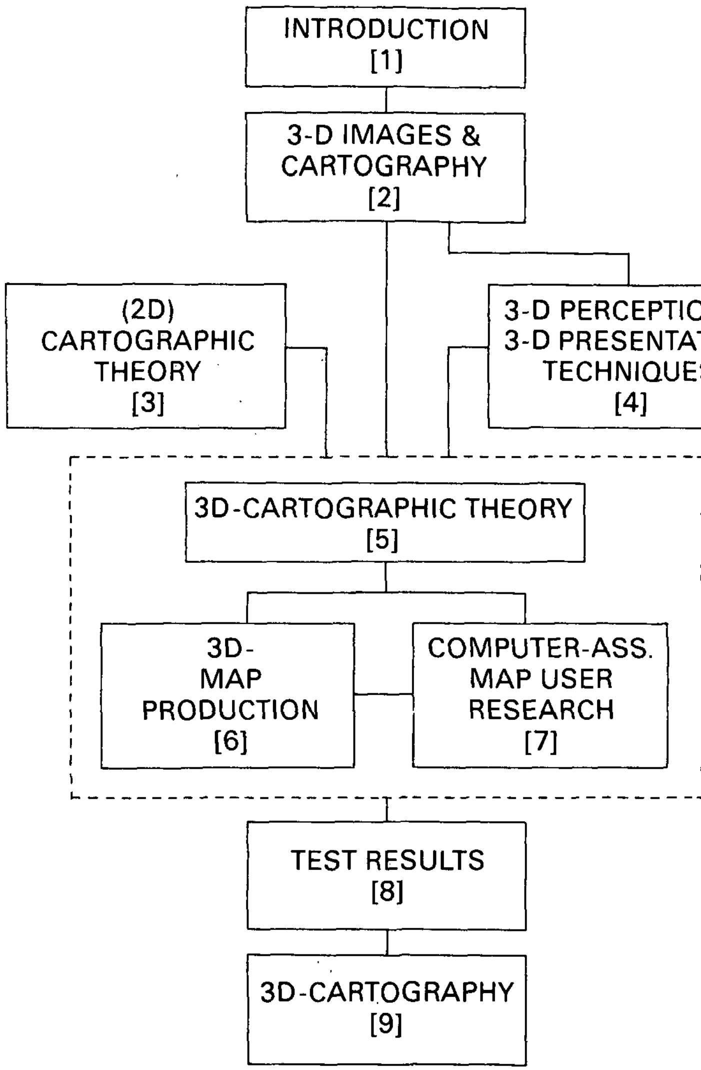


Figure 1-2. The structure of the research project; the number between brackets indicates the chapter number, and the chapters within the dotted square represent the main topics of this study.

The pre-display and the manipulation of the map are an explicit necessity when producing three-dimensional maps. Because there will always be dead ground in these maps information will be lost. To keep this loss to a minimum an ideal image position will have to be found, keeping the purpose of the map in mind. A computer-assisted map user test in which map users are confronted with the three-dimensional maps is discussed in Chapter 7. This to find answers to assumptions made, and questions raised in Chapter 5. Attention is given to the subjects, the test environment, the test map characteristics, the questions asked and the test procedure.

Chapter 8 discusses the test results and tries to formulate some general rules for three-dimensional maps. The final chapter, Chapter 9, draws the conclusions.

CHAPTER 2. THREE-DIMENSIONAL IMAGES AND CARTOGRAPHY

2.1 Introduction

The purpose of this chapter is to place the three-dimensional map within the framework of the cartographic discipline. A short description of the cartographic discipline including definitions and views, is followed by definitions of the three-dimensional terminology to be used. In a survey of the use of the third dimension in the map the Spatial Map Image concept is introduced. Examples of this non-orthogonal three-dimensional map are used as illustrations and test material throughout the research. Four applications, represented by a Spatial Map Image, are described in this chapter's last section.

2.2 The cartographic discipline

Together with written and spoken languages people use graphics to communicate ideas and concepts. As soon as a spatial component is included in the graphic image, cartography comes into focus. This spatial graphic image is called the map. No means of communication other than maps can give such a clear insight in this spatial component. Cartography deals with all aspects involved in the design, production and use of maps.

A more detailed definition of cartography can be found in the 'Multilingual dictionary of technical terms in cartography' [ICA, 1973, p.1]. Here it is stated that 'Cartography is the art, science and technology of making maps, together with their study as scientific documents and as works of art'. Since this definition was formulated the impact of the computer on cartography has been enormous. Because of this the traditional definition quoted above is now overdue for revision [Morrison, 1986, p.2].

The literature provides several more recent definitions of cartography, but the only common feature is that cartography has something to do with maps [Olson, 1983, p.263]. In a report of ICA's Commission C Guptill and Starr [1984, p.2] provide the following definition, which is adapted to the information age: 'Cartography can be described as an information transfer process that is centered about a spatial data base which can be considered, in itself, a multifaceted model of geographic reality. Such a spatial database then serves as the central core of an entire sequence of cartographic processes, receiving various data inputs and dispersing various types of information products'. To this definition should be added that the purpose of the information products, the maps, is to be an efficient means of communication and as such they should provide an understanding of geographic reality.

For a computer-assisted cartographic environment a definition such as that from Guptill and Starr is satisfying. However, there will be cartographers who have some difficulties with this approach. Should there exist a new universally accepted definition, cartographers would still have different views of cartography [Robinson et al, 1984, p.11]. Some focus upon its technology to produce the maps, while others focus upon the geometry behind the cartographic model or upon the artistic qualities of the maps. Concentrating on the theoretical approach to cartography, Robinson [1960] and Imhof [1963] were among the first to explore this in more detail. Four main schools of thought emerged in the period from the end of the sixties onwards [Ormeling, 1982, p.38].

1. Cartography as a 'communication science'
In this approach cartography is seen as the process of transferring spatial information by means of maps. It was initiated by the work of Board [1967], Kolácny [1970] and Ratajski [1973]. The map is seen as a means of communication and is built on the cartographer's perception of reality. The map content is processed by the map user and results in the map user's perception of reality. The cartographer's and map user's perception are not necessarily identical.

2. Cartography as a part of semiology
Cartography is presented here as a part of semiology or as the science of sign systems. The syntax of semiology is emphasized, that is the main attention is focused upon the inter-relations between symbols, and on their relative position in the image. This theory was the first to systematize the relation between data characteristics and their graphical representation. This approach was stimulated by the French cartographer Bertin [1967].

3. Cartography as a 'formal science'
The Austrian cartographer Arnberger [1966] saw cartography as the science of logic, methodology, and technique of map construction and map interpretation. According to his view cartographers should establish forms, methods and rules to represent spatial data correctly in maps. The objective of this view is cartographic representation. They are the sematic aspects of the map which are emphasized.

4. Cartography as 'cognitive science'
This approach considers cartography as a method to study geographical patterns. A strong advocator of this view was the Russian cartographer Salichtchev [1970]. In his ideas the objective is the representation and analysis of spatial systems of different complexity by cartographic modelling.

Since they were first presented these four schools of thought have been criticized negatively as well as positively. They have influenced each other and adaption has taken place. The view of cartography as a communication science has found most supporters, and is practiced on all continents, while the last two views mentioned have only found local support. In some places aspects of two or more views have been combined. Examples can be found in Ratajski [1973], Freitag [1979] and Ormeling & Kraak [1987].

The concept of cartography adhered to, as a guideline, in the approach to three-dimensional cartography is based on a combination of the communicative and semiological approaches. The spatial information to be transferred is analyzed and represented according to the rules of the graphic sign system. The next chapter will explain this approach in more detail.

2.3 Three-dimensional terminology and the map

The previous section dealt with the cartographic discipline. Whatever definition or view is discussed, the map is the common denominator. A definition of the map is necessary in order to continue.

In the 'Multilingual dictionary of technical terms in cartography' [ICA, 1973, p.7] a map is defined as 'a representation, normally to scale and to a flat medium, of a selection of material or abstract features on, or in relation to, the surface of the earth or a celestial body'. This, similar to the dictionary's definition of cartography, is a traditional approach. In contemporary literature several other definitions can be found.In the 'Nature of maps' [Robinson & Petchenik, 1976, p.16] a map is defined as 'a graphic representation of the milieu'. This definition covers all graphical representations of spatial relations, however landscape drawings and paintings should be excluded. It is this definition of the map that is used in this thesis. This definition may look vague when compared to that in the ICA-dictionary, but it encompasses the various map types to be dealt with in this research. Another advantage is that it is not affected by the computer's impact on the map. This in spite of the introduction of a new state of display of the map, the temporary map [Riffe, 1970]. This new map exists next to the permanent and the virtual map.

The **permanent map** is a map in a form familiar to most people. It is the traditional map presented mainly on paper, but also the globe and relief model belong to this category.

The **virtual map** is the map in the mind. Two types can be distinguished. The first is a unique personal map image. An example is the mental map, shaped by one's knowledge and perception of the environment, for instance a mental route map used while going from A to B. It is seen by the 'inward eye' [Gould & White in Robinson & Petchenik, 1976, p.16], and therefore can not be seen by others. An other example of this type of virtual map is the map image which results from the interpretation of maps, such as a relief or city map. The second is the map shaped in the mind when an expedient such as a stereoscope is used. This can be seen by more people at one time. For this last type it should be stated that it refers to the non-interpreted map.

The **temporary map** is the map which can be seen on a screen. It is produced by computer-assisted cartography and originates from a spatial database. In this map blinking and moving symbols are introduced. Moellering [1983, p.54] sees the temporary map also as a virtual map. He distinguished three kinds of virtual maps, based on the map characteristics of permanent tangibility and direct viewability.

Returning to the definition of a map a question to be raised is 'Does it contain information on the dimensional aspects of spatial phenomena?'. It can be seen that they are not specifically mentioned. Three-dimensional maps are not included, but they are not excluded either. A fundamental question to raise now is 'What distinguishes them from two-dimensional maps and what are the characteristics of three-dimensional maps?'.

Maps are models of reality. They provide information on spatial phenomena existing in reality. They are constructed by a process of generalizing and structuring data from reality. Most spatial phenomena have a three-dimensional distribution, but by modelling them onto the two-dimensional map the third dimension is often not conveyed to the user. Sometimes it is omitted deliberately. For many applications this is not a problem since the map user is very well able to understand the model. For instance, when a map user visualizes the information retrieved from a city plan, a three-dimensional virtual image will be the result. This reduction from three to two-dimensions is often required for a pragmatic reason; most maps are presented on a flat medium. The absence of information on a spatial phenomena's third dimension qualifies the map as two-dimensional.

If the cartographer wants to preserve the third dimension, the construction of the map becomes more difficult. Even though the computer can be used to help in its construction, most permanent and temporary maps are still presented on a flat medium. Extra stimuli have to be added to let the map user perceive the map as three-dimensional. By some these maps are called two-and-a-half dimensional instead of three-dimensional, since the third dimension is not tangible.

Viewing examples of three-dimensional maps some will copy a cartographic interpretation of Orwell's statement [Orwell,1974]: 'all animals are equal, but some are more equal than others'- all three-dimensional maps are equal but some are more equal than others. For instance a map user will immediately approve of the three-dimensional qualities of a permanent map such as a tangible relief model. He or she will also consider a virtual map created by the use of anaglyph or holographics to be three-dimensional. Jensen [1978, p.130] would like to reserve the term 'three-dimensional' for only these map categories. The permanent and temporary maps presented on paper or screen respectively will only be seen as three-dimensional if they contain the proper stimuli. The perceptual aspects of these maps are covered in chapter 4.

In this thesis a map, considered as a graphic representation of the milieu, is said to be three-dimensional when it contains stimuli which make the map user perceive its contents as three-dimensional.

2.4 Three-dimensional maps

2.4.1 Three-dimensional presentation techniques

To create three-dimensional maps several techniques are available. Figure 2-1 presents a classification of these techniques. Not all techniques mentioned are regularly applied to cartography and combinations of different techniques are possible. In the diagram the presentation techniques are related to the possible map states of display: the permanent, temporary and virtual map.

They are divided into two main categories. Those resulting in a real three-dimensional representation, e.g. the third dimension is tangible, and those resulting in suggestive representations in which the third dimension is non-tangible. The globe, the relief model and the tactual map can be found in the first category. The second category is further divided into sub-categories, depending on the number of images needed to create the three-dimensional map.

Examples of the first sub-category, the one-image representations, are maps presented on a two-dimensional medium, but with the necessary stimuli to let the map user perceive it as three-dimensional. Also images created by movement parallax, as well as mental maps belong to this category. The second sub-category of three-dimensional suggestive maps, the two-image representations, has to be looked at using a special device to perceive it as three-dimensional. The techniques mentioned in the last sub-category need several images to create a three-dimensional map. A more detailed approach to the principles of the techniques can be found in chapter 4.3 and 4.4.

The final result of the presentation techniques has to be considered when referring to the possible map state of display in the right half of the scheme. For instance, the two separate images used to create a three-dimensional map using a stereoscope can be two permanent paper maps, but the result is considered to be a virtual map. Referring to the scheme again, it can be seen that most realistic representations and the suggestive one-image representations are permanent maps. This last category can also be temporary, that is presented on screens. The temporary maps also include all other suggestive representations, although not necessarily presented on screens. Virtual maps are all suggestive two- or more-image representations as well as mental maps. These last maps will not be treated in this research.

The choice and usefulness of one of these presentation techniques depends on the interaction of three factors. These are:

- human skills.
  These can have a physiological as well as a psychological character. For instance a small percentage of people are not able to see depth in a stereoscopic image, which might limit the use of this technique. And people who suffer from colour blindness can have trouble with anaglyph maps;

- purpose of the three-dimensional image.
  Depending on the nature of the information to be transferred by the map and the character of the map's target group, the level of detail and realism to be included in the map image may vary. Some of the presentation techniques are more suitable for a very detailed image than others;
- technical opportunities.
  The choice of a technique may be limited by pragmatic reasons, since not all cartographers will have all necessary equipment and materials available needed for a specific application.

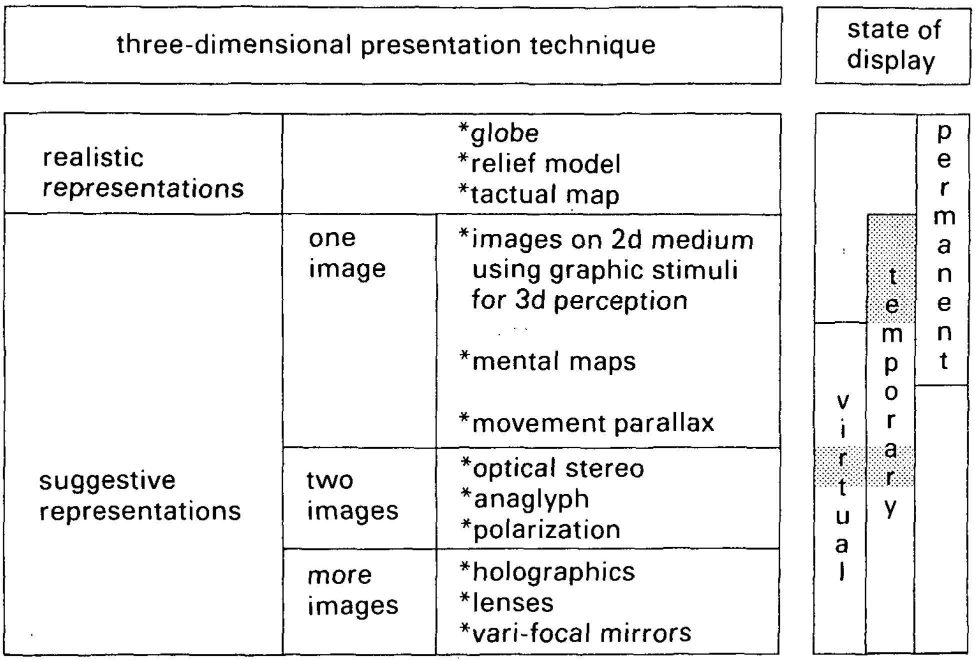


Figure 2-1. Classification system of three-dimensional presentation techniques in cartography. The patterned areas indicate the categories to which the three -dimensional maps studied belong.

2.4.2 Use of the thrid dimension in maps

This paragraph presents a survey of the use of the third dimension in maps. A guideline in this brief survey are the three phases Keates [1982, p.73] distinguished in the cartographic process to represent reality. These are: 1) a transformation of the locational structure from a geographical graticule coordinate system to a two-dimensional coordinate system; 2) a transformation of three-dimensional phenomena to two dimensions (the representation of the earth's surface); and 3) the generalization of the two-dimensional map content as a consequence of scale. This last phase falls outside the scope of the study and is therefore not covered here.

The main objective of the first phase of transformation is a conversion of the curved surface of the earth to the plane surface of the map. Only a few map projections try to preserve the earth's three-dimensional appearance [Ormeling, 1984]. Since the earth is an oblate spheroid, a map projection always results in known distortions and when the purpose of the map is known an appropriate map projection can be found. For the mathematics and problems involved in this process Richardus & Adler [1972], Maling [1973] and Snyder [1985] give thorough accounts. This thesis will not deal with map projections in more detail, since the earth's curvation can be neglected in the examples used.

For some maps, however, the first transformation phase does not take place. A map projection is not necessary when producing a globe, since there will be no distortion of the spheroid. Since globes were first produced [Muris & Saarmann, 1961] some producers have tried to omit the second phase [Briesemeister, 1957].

In another realistic representation of the three-dimensional map, the relief model, the second phase can be left out. This is because its objective is to present a scale model of earthly phenomena. In addition to relief, the urban environment can be the object of these models. Relief models originated in a military environment, but are now also in use for educational and touristic purposes. Computer-assisted cartography is also used to produce them [IGN, 1986 and Kraak, Van de Broek & Vergeest, 1986]. In this thesis the realistic representations (see Figure 2-1) will not be treated in more detail.

Keates' second phase refers to the transformation from three dimensions to two dimensions, and always results in an approximation of reality. In referring to this phase in this survey it is emphasized that the cartographer has tried to preserve three-dimensional information in the map image during this transformation. Computer-assisted cartography has changed the approach to this second phase. The permanent map not only functions as an image to transfer spatial information, but it is also an excellent analog data model and a perfect medium to store large quantities of spatial data. In the temporary map, introduced by computer-assisted cartography, these functions are separated. The map image which transfers the spatial data is separated from the data model and data storage (see also the definition on cartography in section 2.1). This gives the cartographer the opportunity to store all of the original three-dimensional data, and selectively perform phase two to produce a permanent or temporary map. Another advantage of the temporary map is, that it, in some situations, does not exhibit some of the permanent map's drawbacks such as difficult data manipulation and data updating.

Results from the second phase transformation are best known from the representation of topography, but also in thematic mapping results of this transformation can be found. Topography can be considered as visible and can be divided into natural features, such as relief, and man-made features, such as the urban environment. To map the correct two-dimensional position of topographic features on a map a orthogonal projection is most commonly used (Figure 2-2). This projection tries to preserve the existing relations between the x and y coordinates.

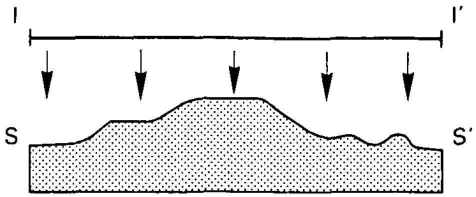


Figure 2-2. The orthogonal projection.

In mapping relief cartographers have employed many graphical techniques. The oldest relief maps portray the terrain with simple symbols [Arnberger & Kretschmer, 1975, p.249]. The mountains were drawn in aspect or sketched (Figure 2-3). Relief mapping further developed via hachuring which omitted three-dimensional stimuli, to a systematic hachuring, later followed by shading to enhance the relief impression. An example of the systematic hachuring can be found in Figure 2-4 which shows part of the swiss Dufour-Karte. Figure 2-5 shows relief shading by the swiss cartographer Imhof.

Imhof [1965] introduced the 'Luftperspektivische Gelände Darstellung' to represent relief. It is based on the natural effects of atmospheric colours in the mountains and is seen as one of the best methods to map relief in an orthogonal map while still preserving the third dimension. The shading is printed in tints of violet, and to the slopes facing to a fictitious light source a yellowish tint is added. The relief impression is further enhanced by adding more contrast in the higher areas. This technique is employed in the Swiss topographic maps. Since this method of relief representation is a skilful, and as most other relief representation methods, a laborious activity, cartographers have tried to employ the computer to solve this problem. A study of automated relief mapping can be found in Peucker [1974], Sprunt [1975] and Horn [1982]. Figure 2-6 shows an example of analytical relief shading.

Other relief representation methods have been proposed by Raisz [1931] and Tanaka [1950]. Raisz' method is based on a geomorphological approach, while the Japanese cartographer Tanaka based his method on the illumination of contours. Yoeli [1983] applied the computer to this last method. A survey of most relief representation techniques is given by Brandes [1983] and Brandstätter [1983], while a historical overview is given by Schwarz [1987].

A different approach to relief mapping is given by representations such as block diagrams [Lobeck, 1958] (see Figure 2-7), perspective views, panorama maps [Berann, 1986] (see Figure 2-8) and digital terrain models. In these maps the third dimension is not projected on an orthogonal base map. Imhof named these

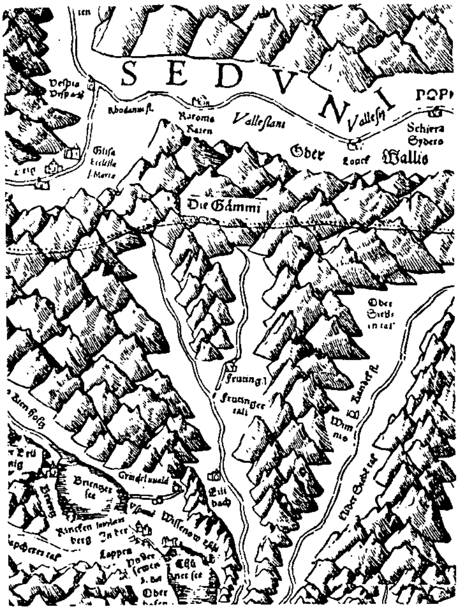


Figure 2-3. Aspect relief mapping Example from Tschudi, A.: 'Nova Rhaetiae atque totius Helvetiae descriptio (1538/60) [Kretschmer et. al, 1986, p.249].

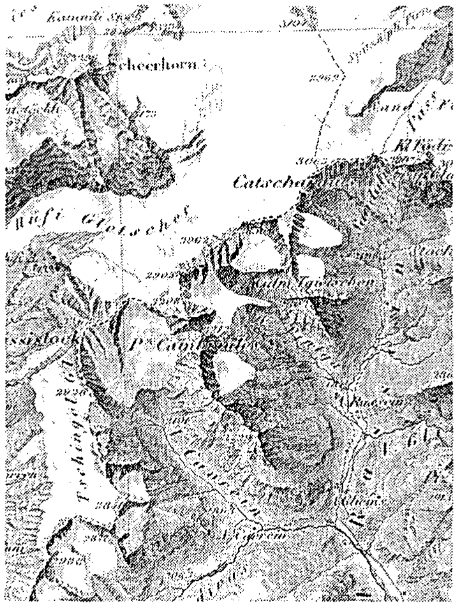


Figure 2-4. Systematic hachuring. Example from Swiss Dufour-Karte sheet no.14, 1889.

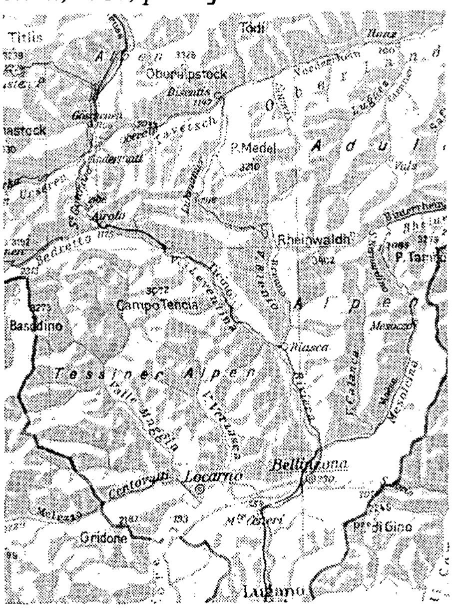


Figure 2-5. Imhof's relief shading [Schweizerische Weltatlas,1981, p.15].

Figure 2-6. Analytical relief shading [Peucker et al,1975,p.196].

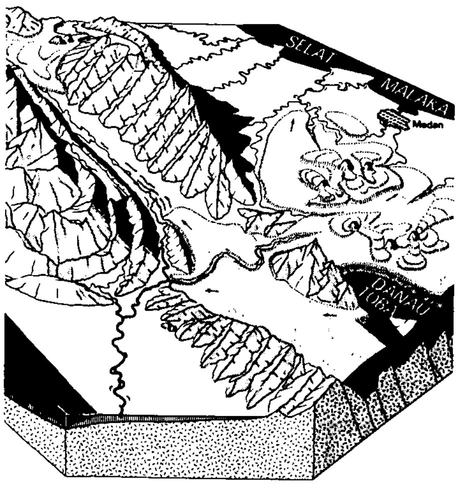


Figure 2-7. Block diagram, example N. Sumatra [Alphen, 1983, p.285].

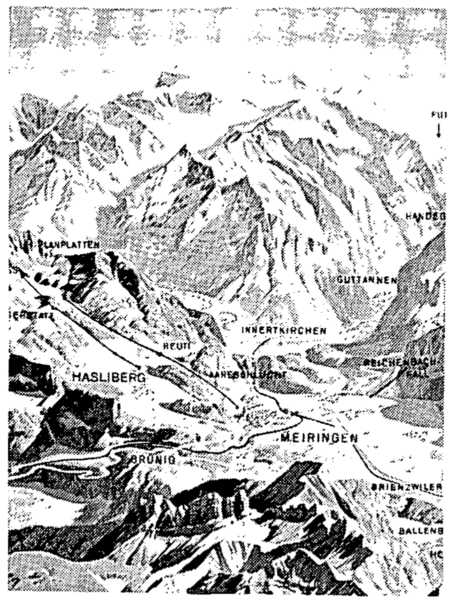


Figure 2-8. Panorama map Meirungen, Switserland [Berann]

cartographic product 'Kartenverwandte Darstellungen' (map-related representations). In his article in the International Yearbook of Cartography [1963] he explores most possibilities. A more recent survey of these maps is given by Hermann and Kern [1986], which also includes alternatives produced computer-assisted cartography.

In mapping the urban environment cartographers have long applied non-orthogonal representations. One of the first cities mapped in perspective was Amsterdam by the Dutch cartographer C. Anthonisz [Koeman, 1983, p.116]. Figure 2-9 shows a fragment of this map. Bollmann's Bildkarten [Hodgkiss, 1973 and Bollmann, 1986] is today's exponent of this approach (Figure 2-10). A computer-assisted approach can be found in the planning and architectural environment [Laurini, 1984].

In thematic cartography the cartographer works with continuous or non-continuous phenomena such as climate and population. Maps presenting information on such phenomena may or may not be in an orthogonal format. In this last case this can result in maps displaying three-dimensional point symbols (Figure 2-11) or statistical surfaces. One of the first to map statistical surfaces was Robinson [1961]. Statistical surfaces can be thought of as a representation of a mathematical continuous distribution of a phenomena consisting of a series of points, with x, y, and z characteristics. The x and y indicate the planimetric location and the z is

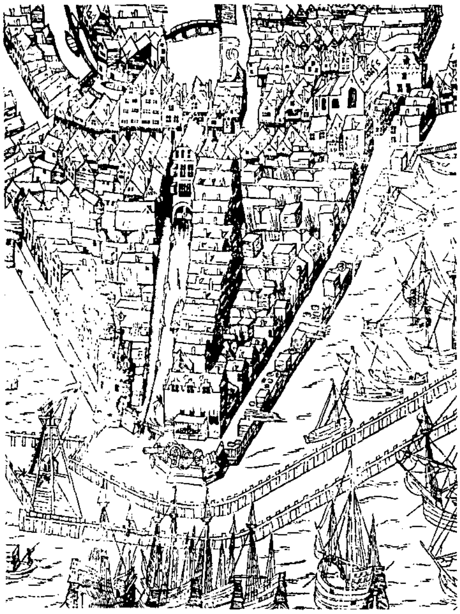


Figure 2-9. C. Anthonisz' map of Amsterdam, 1544, [Koeman, 1983, p. 116].

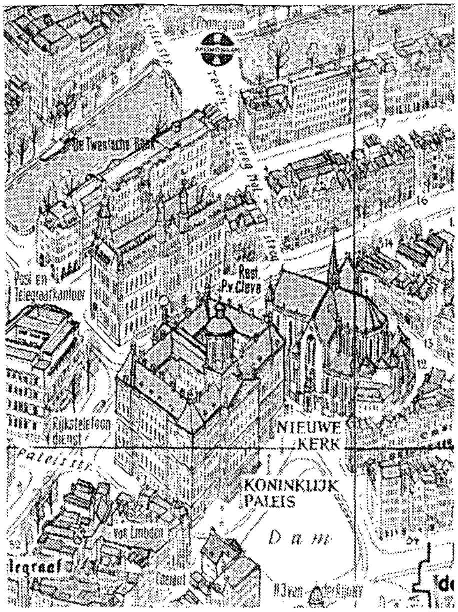


Figure 2-10. Bollmann's map of Amsterdam [map no.14,195?].

the point's statistical value expressed in a relative height above a horizontal datum. Two types of statistical surfaces can be distinguished, the smooth and the stepped statistical surface. This last type is shown in Figure 2-12. Jenks and Coulson [1963] introduced the statistical surface as an aid in the data classification process for choropleth mapping.

To enhance the three-dimensional impression of the above maps, three-dimensional presentation techniques such as the anaglyph and stereoscopics have been used since the middle of this century [Graf, 1943 and Carlberg, 1949]. In more recent literature Jensen [1978 & 1980] and Egels [1986] also explore these techniques. The French 'Atlas des formes du relief [Cholley, 1956] presents some fine examples of these techniques.

It is the non-orthogonal three-dimensional cartographic product which is interesting in this information age. The computer provides the cartographer with the opportunity to manipulate and experiment with its full three-dimensional map data set. These are also the products which Taylor [1984] had in mind when discussing the products of the 'new' cartography. These maps, those with a topographic as

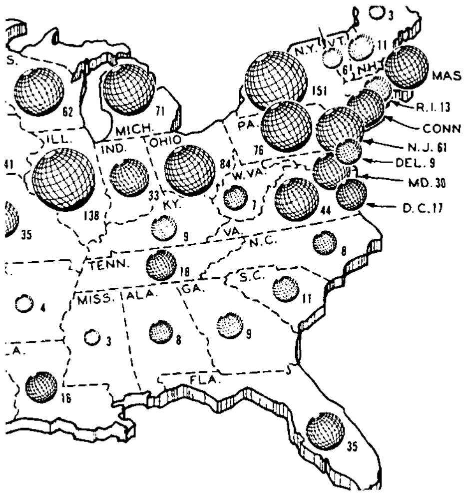


Figure 2-11. Three-dimensional point symbol map of the United States [Schmid, 1983,p.148].

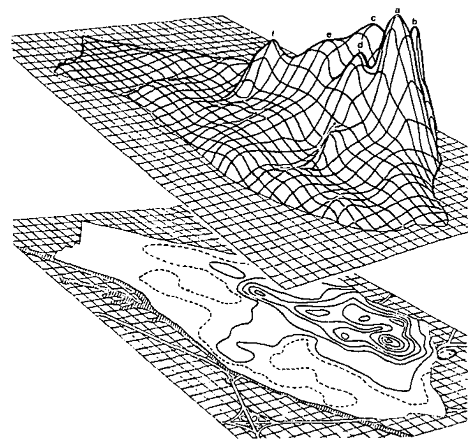


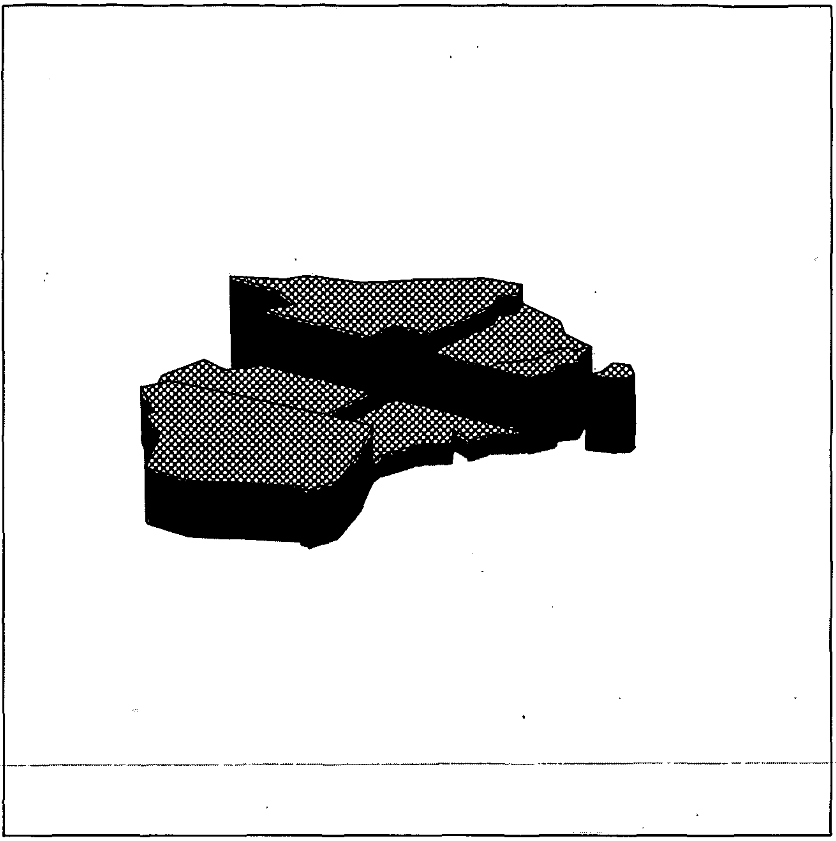
Figure 2-12. Smooth statistical surface of Utrecht [Th.C.M.van der Heijdt in Ormeling & Kraak, 1987,p.108].

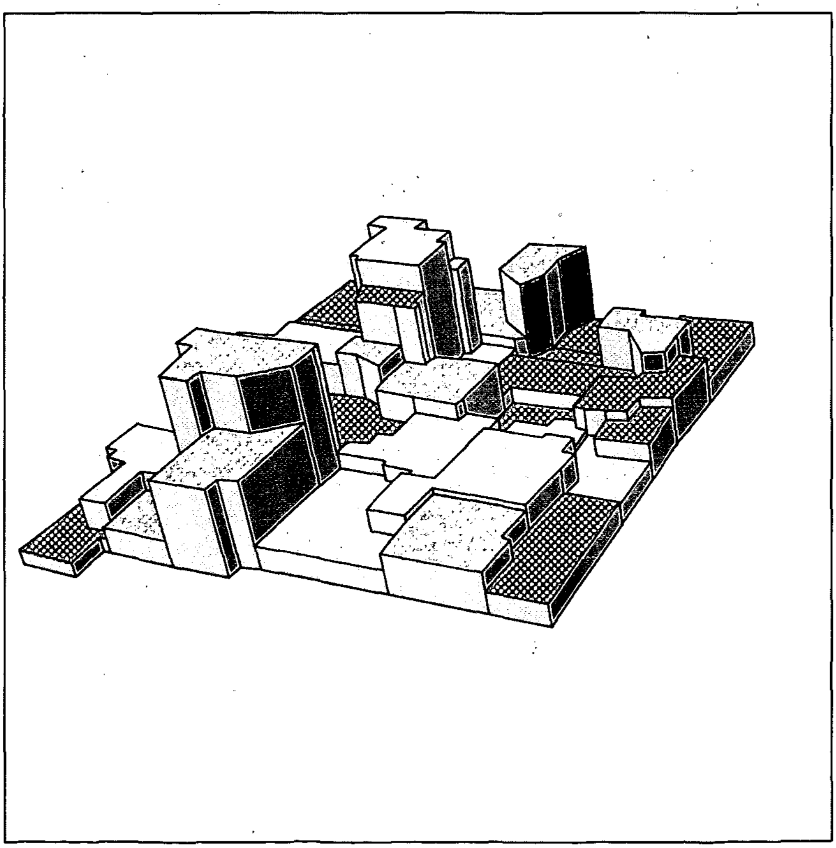
well as a thematic nature will be referred to as Spatial Map Images and are studied in this research project. Section 2.5 and 2.6 will explain this in more detail.

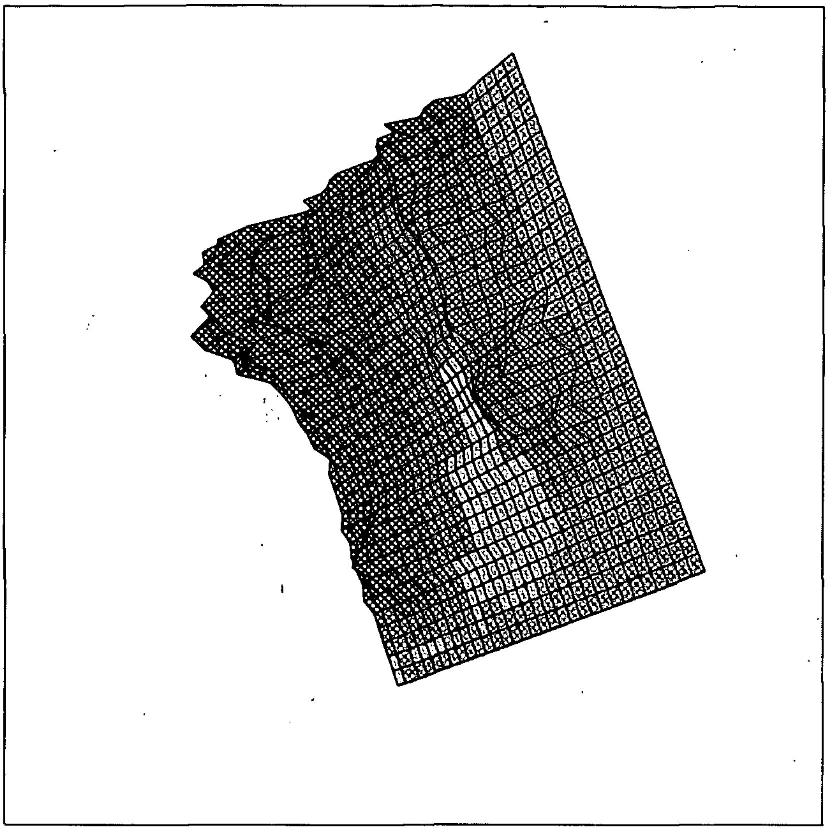
2.5 The research approach

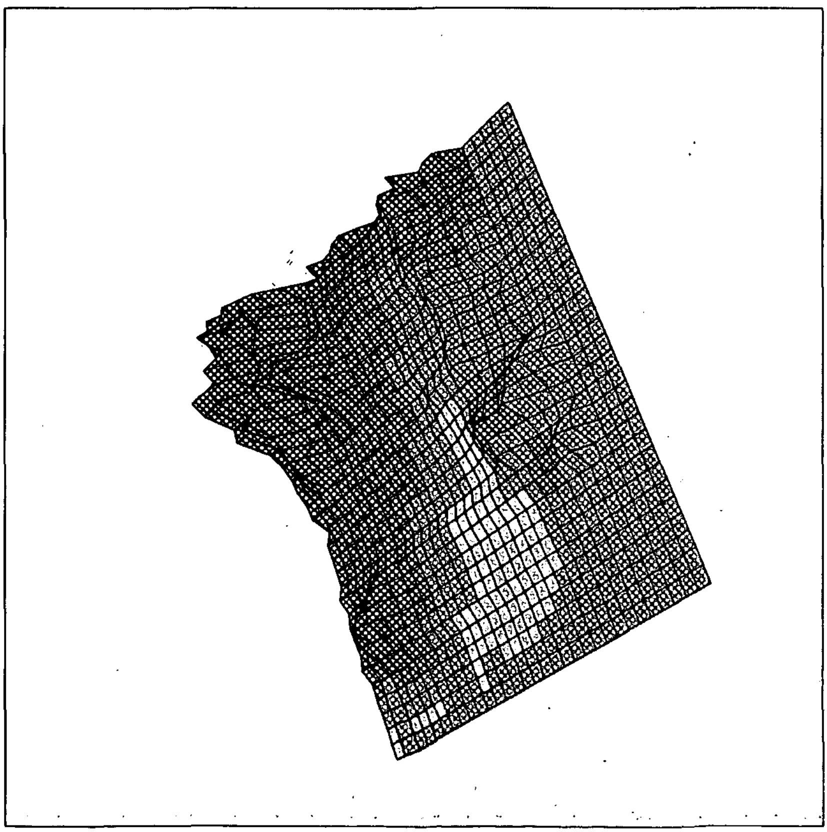
To find out whether three-dimensional maps do indeed provide the map user with a better understanding of the mapped phenomena, it is first necessary to define the specific characteristics of these maps and place them within the cartographic approach briefly described at the end of section 2.2. In the next chapter this view will be explained in detail, and in chapter 5 the placement of the three-dimensional map within this view takes place in combination with knowledge of depth perception, itself described in chapter 4.

Since it would be too ambitious to include the whole concept, which is a combination of cartographic communication theories and the cartographic sign system, the research will be focused on parts of the approach. These will be the cartographic information analysis, the syntax of the sign system and the perception of the maps. This approach via computer-assisted map user tests will reveal the specific characteristics of the three-dimensional map, relate the graphical variables









to the stimuli for depth perception, and indicate the effect of the use of a stereoscopic expedient.

It will be the non-orthogonal three-dimensional maps, or Spatial Map Images, that function as test material and illustrations in the research. Section 2.6 will provide more details on these test maps. They will be produced by computer-assisted cartography for use on screens. One of the reasons temporary maps have been chosen is that the development of geographical information systems confronts the map user more and more with computers and maps on screens.

Returning to the scheme in Figure 2-1 the maps tested in this study are the temporary and virtual suggestive one- and two-image representations (the patterned areas). The three-dimensional presentation techniques used for the more-image representations are, as will be seen in chapter 4.4 not yet suitable for regular use in cartography.

2.6 The map examples used in the research

In the previous section the character of the three-dimensional maps used were indicated. They can be called Spatial Map Images. **A Spatial Map Image can be described as a three-dimensional non-orthogonal representation of spatial phenomena.** This description should be seen in the context of the general definition of three-dimensional maps given at the end of section 2.3. Their contents can have a topographic as well as a thematic nature.

	topographic	thematic
large scale	* 3D URBAN MAP [2.6.4]	* 3D URBAN MAP
small scale	* DTM [2.6.1]	* 3D POINT SYMBOL MAP [2.6.3] * PRISM MAP [2.6.2]

Figure 2-13. Test map characteristics.

This definition comes close to the general definition of three-dimensional maps formulated by Jenks and Brown [1966,p.857]: 'a perspective representation of obliquely (= non-orthogonal) viewed statistical or topographic surfaces'. This would more or less suffice for the Spatial Map Images, but it is too limited for the other three-dimensional maps given in Figure 2-1.

The four map types chosen for this study are located in Figure 2-13. The scheme in this figure classifies these maps according to their scale and functional characteristics. They are the digital terrain model, the prism map, the three-dimensional point symbol map and the three-dimensional urban map. The next four sub-sections will describe them in more detail. For each map a definition and some characteristics are followed by applications and an illustration. This illustration is a wire frame model of the total map data set.

2.6.1 Digital terrain model

A digital terrain model is a numerical representation of terrain characteristics. In chapter 1 it was explained that the term digital terrain model in this thesis refers to a graphical representation of the model. This description has to be refined, since the graphical representations can also include contour maps and slope maps [Sijmons & Stevanovic, 1984] and these do not fit the description of a Spatial Map Image. The term digital terrain model, then, will refer to its graphical non-orthogonal representation. Figure 2-14 shows an example.

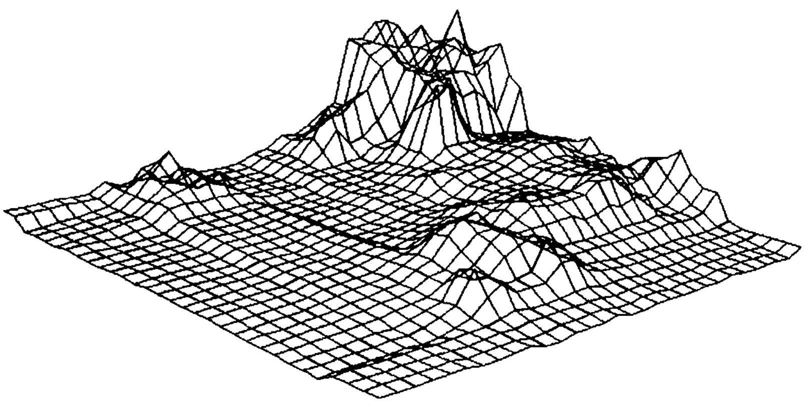


Figure 2-14. The digital terrain model; a wireframe-representation of San Francisco.

Digital terrain models have found a wide range of applications. They are used in civil engineering for the determination of earthwork cut and fill volumes, landscaping, and to create a visual impression of the environmental impact of civil engineering projects. In topographic mapping they are used to visualize the terrain forms. In geological and geophysical mapping they visualize surface and underground structures. They are also in use in navigation simulation, for instance to train pilots. And last but certainly not least, the military applications have to be mentioned. Here digital terrain models provide information on visibility from a specific point while its slope information is used to plan the most suitable route, and some missile guidance systems use digital terrain model information for navigation.

A extensive survey of the basic principles of digital terrain models, data gathering and processing techniques, recent software, as well as an extensive bibliography, can be found in Kennie and Petrie [1987]. On the cartographic aspects of digital terrain models Ryerson [1984] presents some interesting information.

2.6.2 Prism map

The prism map is a thematic map in which geographic areas, often administrative areas, are raised above the map base to a level corresponding with the statistical values for the areas. This map type is a graphical representation of the stepped statistical surface. Figure 2-15 presents an example used in this study.

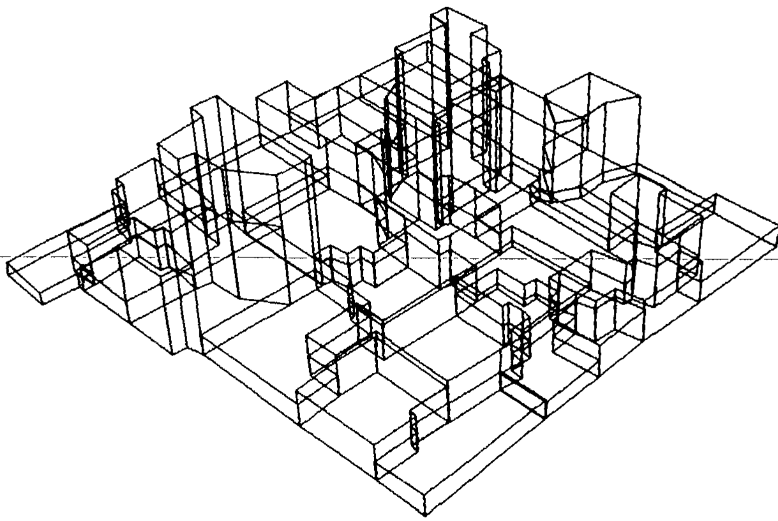


Figure 2-15. The prism map; a wireframe representation of New Mexico (fictive data).

Prism maps present the map user, as do the other three Spatial Map Images used as research examples, with a dramatic view of the mapped phenomena. As mentioned before they are also in use to help classify data for choropleth mapping. A description of the map characteristics is given by Nimmer et al [1982]. Computer-programmes to produce them include SYMVU and PRISM, distributed by Harvard University's Laboratory for Computer Graphics and Spatial Analysis [Franklin, 1979].

2.6.3 Three-dimensional Point symbol map

Three-dimensional point symbol maps are thematic maps with symbols such ascubes, spheres, cylinders and cones. When they display quantitative information they are known as proportional or graduated point symbol maps, and are used to map the spatial distribution of absolute values at point locations. They can also be used to represent non-point values assumed to apply throughout an administrative area.

Three-dimensional symbols make it possible to represent phenomena with a large data range. This because the values represented by the symbols are rendered by volumes, which do have a favuorable scaling factor (n1 / 3), and use less map space. Another advantage is that the use of these symbols creates a visual attractive map [Dent, 1985,p. 259]. The use of these three-dimensional symbols in two-dimensional maps is opposed by many cartographers since the values they represent are often underestimated [Dickinson, 1973, p.110 & Schmid, 1983, p.148]. Chapter 8 will provide more information on the perceptual aspect of these symbols.

Figure 2-16 presents an example of this map, showing the use of the sphere as a symbol. Applications of this map type can be found in census mapping, atlases etc.

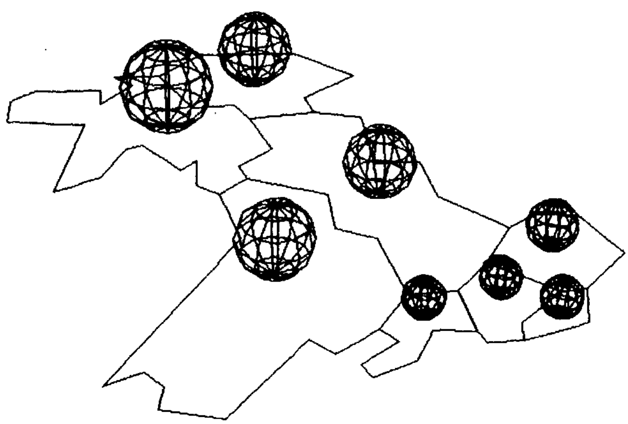


Figure 2-16. The three-dimensional point symbol map; a wireframe representation of Wales (Welsh speaking).

2.6.4 Three-dimensional Urban map

The urban map presents a non-orthogonal, three-dimensional representation of the urban environment. Its contents can have a topographic nature, portraying the morphology of the town [Lo, 1973], or a thematic nature, portraying all kinds of aspects of the town. This map type shown in Figure 2-17 has found many applications in architecture and planning [Makhachouni, 1986 and Peneau, 1987]. It can be used, for instance, to see how a newly designed building will fit into the existing urban environment. This proved to be a practical approach in urban renewal projects [Heimes, 1984].

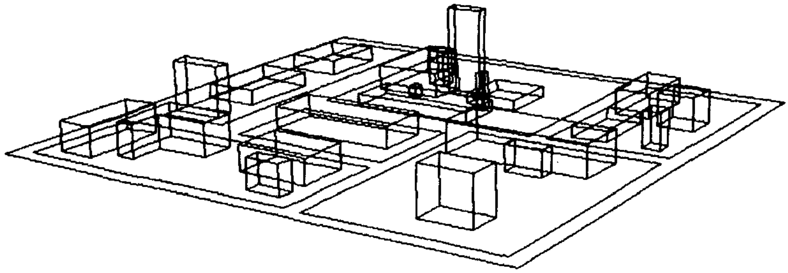


Figure 2-17. A wireframe representation of the urban three-dimensional map.

CHAPTER 3. CARTOGRAPHIC THEORY

3.1 Introduction

This chapter presents an overview of cartographic theory, based on a view which combines cartographic communication and the graphic sign system [Ormeling & Kraak, 1987]. These were introduced separately in section 2.2. Figure 3-1 represents the outline of this approach, called by some [Koeman, 1981, p.27] the 'Utrecht School of Cartography', because it was first presented as such in the cartographic education programme at the University of Utrecht. A description of this approach is necessary for the thesis, since it, together with the three-dimensional perception theory, is the base on which the three-dimensional cartography in chapter 5 is built. In the successive sections of this chapter are emphasized those parts of this approach thought to be essential for three-dimensional cartography.

3.2 The cartographic approach: the Utrecht School of thought

This section concentrates on the scheme in Figure 3-1, and presents a simplified outline of the cartographic approach applied in this study. Three concentric circles can be located in the scheme, each describing several facets of the view.

The inner circle indicates the main cartographic activities: map design, map production and map use. The location of the respective circle sectors is related to the middle circle, which portrays a simplified model of the cartographic communication process [Ratajski, 1973].

The communication process starts with real world information, that is, the data to be transferred. It is gathered by people such as surveyors, photogrammetrists, geographers and statisticians. The cartographer has to study this information before it can be processed into a map. This results in the cartographer's perception of reality. When preparing the map the cartographer should not only consider the map's purpose, but also the people for whom the map is made, since different audiences often require a different design approach. For instance the preparation of maps which have to transfer statistical information will differ from that for maps which are to be used to navigate, such as aeronautical charts. This to ensure the information transfer process runs smoothly.

Based on this knowledge of the information to be transferred, of the requirements of the map audience, and of cartographic theory, the cartographer can design and produce the final map. The information the map user derives from the map results in the map user's perception of reality. This is not necessarily the same view of reality as the cartographer's, and is one of the reason the squares I and I', at the top of the middle circle, are not coincident. In the cartographic communication process, as in any other communication process, information will be lost.

A reason for this loss can be a misinterpretation of the original information by the cartographer, or an incorrect use of mapping techniques to portray it. The map user can also make mistakes, such as using the wrong information from the map in trying to understand the map's message. Another possibility is that the correct information is derived, but that it has been incorrectly interpreted. Mistakes are not the only reason for the difference between I and I'. New information may surface, for instance because the map user links together information derived from the map with his/her own knowledge. Freitag [1971, p.172] suggests that the factor time also plays a significant role.

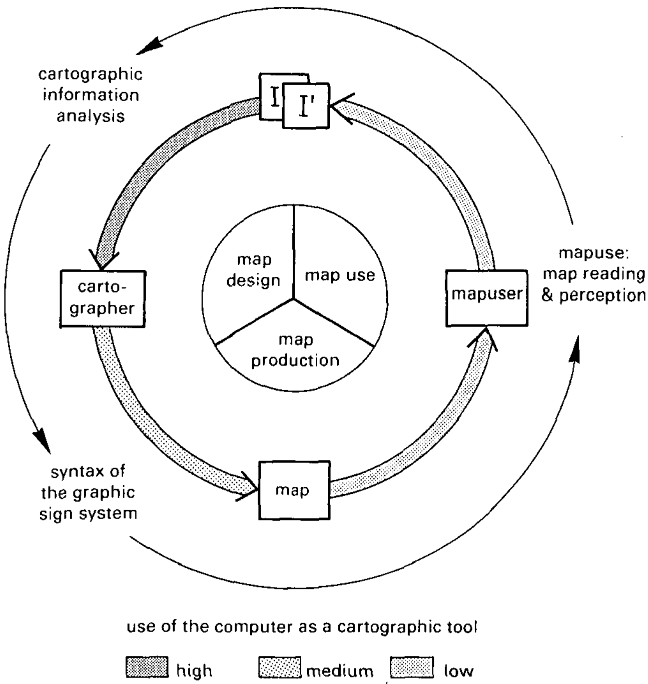


Figure 3-1. Outline of the cartographic approach.

In the figure it can also be seen that the use of the computer as a cartographic tool decreases during the cartographic communication process. When dealing with the right half of the communication model the use of the computer is still limited. This side of the model represents that part of cartography which comes close to the social sciences such as psychology [Blades & Spencer, 1986]. Here the map user's uncontrolled behaviour plays a significant role and influences the communication process.

In the scheme's left half the sign system can be found. The upper left sector presents the process of cartographic information analysis. This is a procedure which lets the cartographer determine the character of the information to be mapped. It also provides links with the sign system's syntax as will be seen in section 3.3.

The lower left sector of the outer circle contains the syntax of the sign system. The sign system or semiology contains rules to organize the signs in a graphic image. The syntax of this system indicates ordered relationships between signs or symbols. Bertin [1967] emphasizes this syntax, which will be treated in section 3.4, but he neglects more or less the semantic aspects of signs. Semantic aspects deal with the relationships between symbols and their meaning: and in producing a correct map the cartographer should be aware of these relations. For instance, for some audiences it might be advisable to use figurative instead of geometric symbols.

The reason that Bertin [1978] did not deal with the semantic aspects of signs is that he saw the sign system as a form of monosemic communication, that is each symbol can have only one meaning. The cartographic communication theory is, according to his views, incompatible with the semiology, since it allows polysemic communication. After all, when symbols have a unequivocal meaning I and I' will always be the same. Practice has proved that this is not true, but Bertin then comments that the maps in question are not properly designed.

The study of the semantics as well as the pragmatics, that is the relationship between the symbol and the map user, can be found in the right half of the scheme. The key-word here is perception, and this will be treated in section 3.5.

Cartographers will try to make I and I' overlap as far as possible. This leads to the necessity of feedback between I' and I in order to be able to judge the effect of the cartographic product. The feedback enables the cartographer to adjust the design of the map whenever necessary.

3.3 Cartographic information analysis

When the cartographer starts the process of designing the map, and when the audience to whom the information is to be transferred is known, the first step is to find out more about characteristics of the information. This is necessary to be able to transcribe the information into elements of the graphic sign system. This procedure is called cartographic information analysis. Figure 3-2 summarizes this procedure and locates it within the cartographic model. The data in Figure 3-3 are used as an example in explaining the procedure. A parallel with informatics can be seen, although the cartographic approach is more narrow. In informatics information analysis includes all activities which lead to the building of the final system (map production in cartography). These activities are to provide a definition of the information and its meaning, a description of the target group as well as defining the information needs [Eilers, 1979, p.351].

Information to be displayed in a map can be divided into variable and non-variable parts. The first consists of a number of components and the second is called the invariant. In Figure 3-3 three components can be distinguished, the 'number of people', the 'sexes', and the 'neighbourhoods'. A component has two important characteristics: its length and its level of organization.

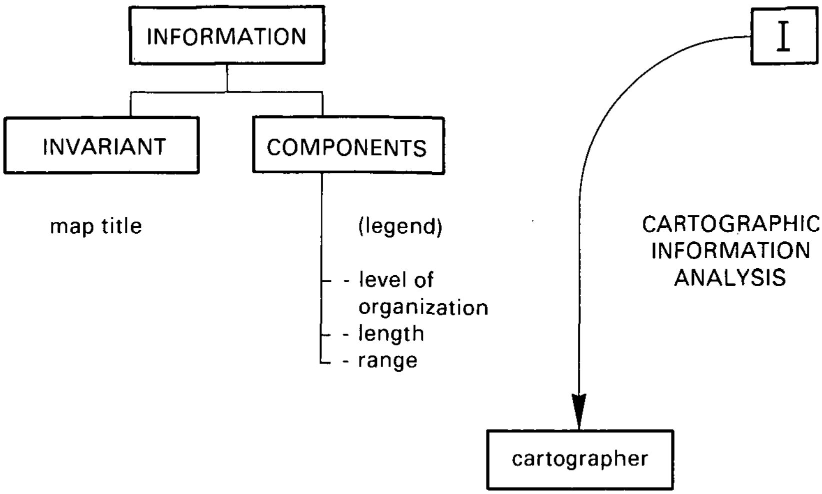


Figure 3-2. Cartographic information analysis.

All the components have a relation with the population of the city of Delft in 1987. This makes 'Delft's population in 1987' the invariant of the information. In a well designed map the map user will always find this invariant included in the map title.

The length of a component describes the number of elements or categories which can be defined. In the example of Figure 3-3 the component 'sexes' has a length of two, male and female. The component 'number of people' has, in principle an infinite length. This length should not be mixed up with the data range, that is the highest minus the lowest data values (18,153-9,329 in the example). The component 'neighbourhoods' has a length of seven: the number of neighbourhoods in the city of Delft.

A component's level of organization is determined by the type of relation which exists between the constituent elements of the component. Three levels of organization are distinguished. If the component includes concepts of a simple differentiation it has a qualitative or nominal level of organization. In the example this is true for the component 'sexes': male and female. If it is possible to rank the component's elements, it is said to have an ordered or ordinal level of organization. When the component's elements have numerical values the level of organization is quantitative (the interval/ratio level). In the example this is true for the component 'number of people'.

The component 'neighbourhoods' has a special character. It is a geographical component and its level of organization is difficult to determine. This will be explained in more detail in the next section. The map user should be able to recognize the components in the map's legend.

a)

Delft's population in 1987

neighbourhood	male	female	total
0	5,793	4,833	10,626
1	6,760	6,760	13,520
2	4,556	4,773	9,329
3	5,321	4,547	9,868
4	9,470	8,683	18,153
5	7,099	7,171	14,270
6	6,225	5,761	11,986
total	45,224	42,528	87,752

b)

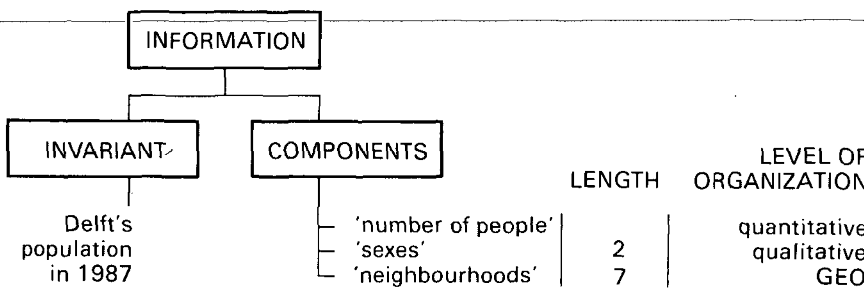


Figure 3-3. An example of cartographic information analysis a) original data; b) result of cartographic information analysis.

When, after the information has been analyzed, there appear to be more then two components, the cartographer has to organize them in a hierarchical array, that is in levels of relative importance. By doing so the cartographer can emphasize certain information catagories of the map, or specific relations between them.

3.4 The graphic sign system

After the phase of analysis the cartographer can transcribe the information into elements of the graphic sign system. Before this can be done the properties of the sign system and its syntax should be known. Figure 3-4 describes the syntax and relates it to the cartographic communication process. In the description of the graphic sign system Bertin's work [1967, 1973] is used, but only its cartographic aspects are highlighted.

In his original work, Sémiologie Graphique, Bertin [1967, p.42] describes the limitations of the sign system. The basis of his approach is a sheet of white paper seen under normal conditions (distance, lighting etc) to portray the permanent map. Temporary maps were not included. Permanent maps such as relief models, as well as all virtual maps were excluded. However, since the introduction of the temporary map Bertin's theories have been applied to maps on screens. In the Preface to the English edition of his work [Bertin, 1983, p.xi] he mentions the transition from the classic graphics (his earlier work) to modern graphics. Part of this transition has been described by Rabiller [1982]. Moving and blinking symbols, one of the typical characteristics of the temporary map, are still excluded because of their dominating perceptual effects.

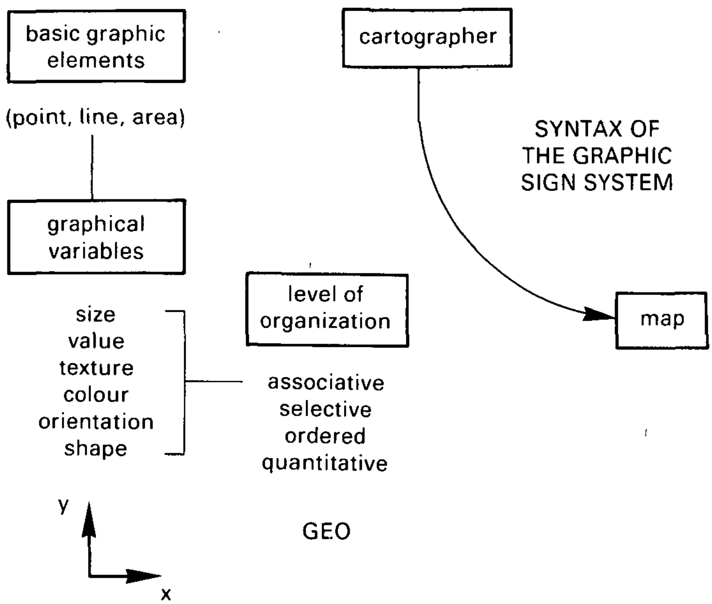


Figure 3-4. Syntax of the graphic sign system.

One of the basic concepts of the graphic sign system is that the plane, the two dimensional medium (originally on paper) on which maps and other graphics are presented, is considered to be continuous, homogeneous and having two dimensions. The implantation, that is representation with either point, line or area symbols (the basic graphic elements), or their combination determines the graphic image on the plane. Each map consists of a combination of these graphical elements.

In cartography it is the geographical component (GEO) which uses the two dimensions of the plane. This component is continuous and uses the x and y directions of the plane to express its level of organization. In the example of Figure 3-3 it is the component of 'neighbourhoods' that occupies the two dimensions of the plane.

To represent the other components in the map retinal or graphical variables, have to be used. These are the basic categories to which all possible variations in the appearance of the point, line and area symbols can be reduced. They are Size, Value, Texture, Colour, Orientation and Shape. Others, such as Morrison [1974, p.124] and Muehrcke [1978. p.46] distinguish more categories, while Robinson et al [1984, p.142] also distinguish six categories, but ascribe them slighty different characteristics. Bertin describes them as visual variables 'above' the plane. Not every graphical variable is suitable to map each component. The graphical variables possess certain perceptual properties. These can be described as the variable's level of organization. Associative, selective, ordered and quantitative levels of organization are distinguished. Each of them has a length, that is the number of elements or categories that can be defined, and has the same characteristics as the length of the components. Only the length of the selective level is limited. The others have theoretically an unlimited length, but are from a perceptual point of view limited. The graphical variables and their levels of organization are expressed in Figure 3-5. Some have a different view on this scheme [Metz, 1971]. And the different approach of the graphical variables by authors such as Morrison [1974], Muehrcke [1978] and Robinson et al [1984], who call them primary graphic elements also influence the behaviour (the level of organization) of the variables. A short discussion of each graphical variable is given below.

GRAPHICAL VARIABLES	LEVEL OF ORGANIZATION (perceptual properties) low ← – – – – – – – – → high			
	associative	selective	ordered	quantitative
size		□	□	□
value		□	□	
texture	□	□		
colour	□	□		
orientation	□	□		
shape	□			

Figure 3-5 Graphical variables and their level of organization.

Size (Figure 3-6a)
Increase or decrease in size is expressed by variations in the dimensions of symbols. Point symbols such as circles and squares can vary in size and line symbols vary in thickness. Area symbols do not vary in size, since this would affect geographic reality, but the interior symbolization may vary in size. Size has selective, ordered and quantitative levels of organization.
Value (Figure 3-6b)
Variation in value is due to the change in the ratio between the total amounts of black and white perceived on a given (coloured) surface. In Figure 3-5 it can be seen that value has selective and ordered levels of organization.
Texture (Figure 3-6c)
Variations in texture imply variations in the symbol patterning. Looking at the graphical elements texture functions best using area symbols. Its application in point and line symbols is limited. The levels of organization are associative and selective.

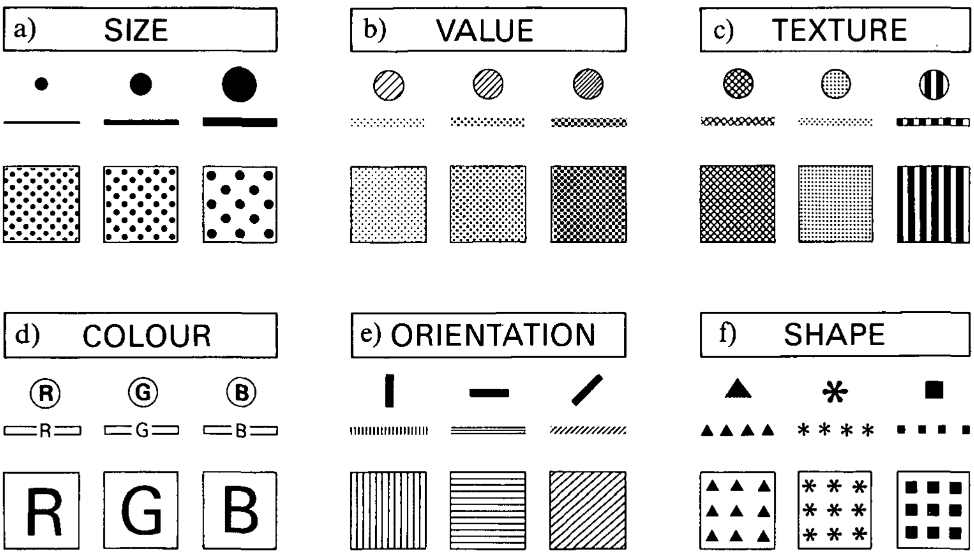


Figure 3-6. Graphical variables and their appearance: a) Size; b) Value; c) Texture; d) Colour; e) Orientation; and f) Shape.

Colour (Figure 3-6d)
The visual effect of colour (hue) is determined by the variations in spectral qualities of light. Variation in colour depends on variation in the wavelengths of light. Colour has selective and associative levels of organization. Specially the first functions excellent. The second is often used on the map user's perception of associations, for instance blue for 'watei' or 'cold' and green for 'vegetation'.

Orientation (Figure 3-6e)
Variation in orientation refers to differences in directional arrangement of the symbols. It can be used for point and line symbols, and the interior of area symbols. Orientation has associative and selective levels of organization.
Shape (Figure 3-6f)
The variation in the shape of elements is in 'unlimited'. For area symbols the variation of shape is reflected to its interior. Shape has only an associative level of organization.

Combinations of the graphical variables are possible, and retain the properties of the variable with the highest level of organization, as determined by the graphical variables location in the scheme in Figure 3-5, were Size has the highest, and Shape the lowest level of organization. They can positively influence the map's legibility, especially when the selective level of organization is involved.

Most of Bertin's work is based on deductive reasoning and on experience with graphical images, but he provides limited experimental material to support his ideas. Muller [1981, p.1] argues that, although Bertin's work appeals to common sense, the lack of experimental material is the reason why his work is so little accepted and used in North America.

3.5 Combining cartographic information analysis and the graphic sign system

As soon as results of the cartographic information analysis are linked with the perceptual properties of the graphic variables, translation of the information by symbols is possible. Direct linking takes place between the levels of organization of the component and the graphical variable. Figure 3-7 presents this link schematically [Wieland, 1980, p.24], and in Figure 3-8 the results of this linking is given for the data of Figure 3-3.

The geographical component 'neighbourhoods' is represented by the two dimensions of the plane and refers to geographic locations. The component 'number of people' has a quantitative level of organization and the use of a graphical variable with the same qualification is advisable. The only graphical variable with the same perceptual quality is 'Size'. The result can be seen in Figure 3-8, where the component is represented by circles varying in size. The component 'sexes' has a qualitative level of organization. When it is the map's purpose to clearly distinguish between the male and female elements the use of a graphical variable with an associative level of organization is necessary. There are four graphical variables with these perceptual qualities: Texture, Colour, Orientation and Shape. This component's graphical representation can be combined with the circles depicting the component 'number of people', and as such directly show the relation between the two components. Since the final map is black and white, Colour is eliminated. Orientation is chosen to display this component as can be seen in the map in Figure 3-8.

This above combination of the results of analysis and the perceptual properties of the graphic sign system leads to a readable map, but there are some factors which can still enhance the result. This is necessary because for a map to be useful it must be efficient. There are some extra rules of design that govern graphic efficiency, and they stem from properties of visual perception. This efficiency concept is measured by the time taken to answer a given question. The most important factors in defining the rules of design are clarity, complexity, visual contrast, visual balance and figure-ground relations, as well as a correct representation of bibliographic data. References to these rules can be found in an appropriate cartographic textbook, such as Keates [1973], Campbell [1984], Robinson et al [1984], ICA [1984] and Dent [1985].

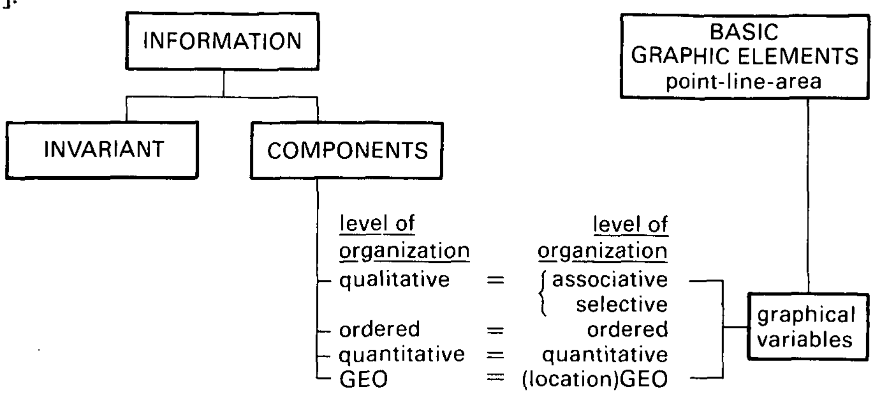


Figure 3-7. Cartographic information analysis and the graphic sign system combined.

Clarity
This refers to the general graphic quality of the map product.
Complexity
This refers to the graphical density of the map. The cartographer must reach an optimum in complexity rather than the least possible complexity [MacEachren, 1982].
Visual contrast
To apply visual contrast it is necessary to be able to distinguish a symbol from the background and adjacent symbols
Visual balance
This reflects the total map layout. The various map elements such as the title, map and legend should be well balanced. Its organization depends on the relative position and visual importance of these map elements.
Figure-ground (visual hierarchy)
The figure-ground relationship deals with the aspect of human visual perception which tries to organize the images in two basically contrasting perceptual impressions [Dent, 1972]: the figure, that which is seen clearly against the

background, and the ground, the amorphous area around the figure. Applying this to a map helps to organize the information. It lets the map user notice first what the cartographer thinks is most important.

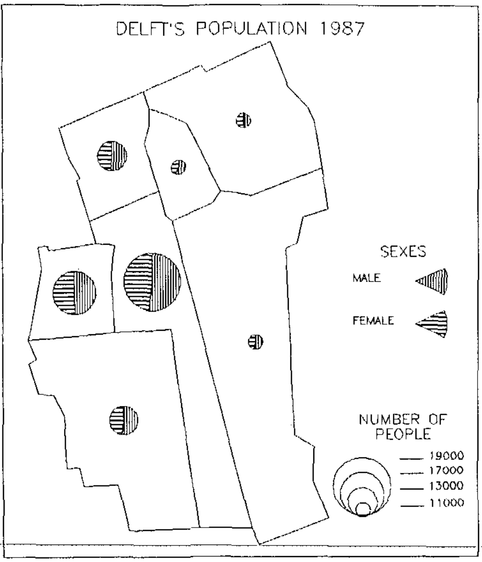


Figure 3-8. Delft map after analysis only.

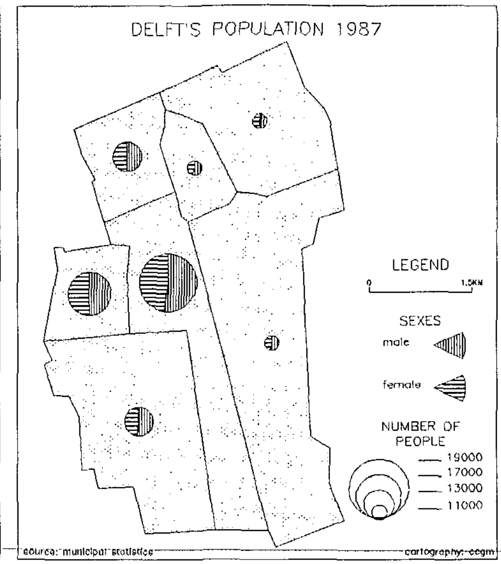


Figure 3-9. Delft map after analysis and application of rules of design.

Figure 3-9 presents Figure 3-8 map after some of these rules have been applied.

3.6 The map - map user relation as object of cartographic study

At the end of section 3.2 it was mentioned that the cartographer would like to design maps in such a fashion that the I and I' in Figure 3-1 overlap as far as possible. To find out how this can be effectuated eventually, it is necessary to understand more of the map user's behaviour. Findings concerning this behaviour might lead to the adaptation or extension of the rules followed by the cartographer to design the map. In this section the map reading process is described together with some research approaches proposed to find out more about this process.

As soon as the map user starts to view the map the process of map reading commences. Map reading can be described as a form of visual information processing. The map user will first try to identify the area and theme which is mapped. In other words the user must identify the map's invariant. This step is called external identification. Second, the map user will check how the information's components are represented graphically, which is the process of recognizing with what visual variables each of the components is mapped. This can be done with an understanding of the map legend. This second step is called internal identification.

Actual map reading can only begin after these two identification processes have taken place. Now the map user is able to recognize the symbols in the map and will link their meaning to geographical locations and reality. The efficiency of the map reading process is directly related to the appearance of the map symbols. Here the semantic aspects play a significant role. After reading the map the map user's next activity can be the analysis and interpretation of the map contents [Muehrcke, 1978] (see also Figure 3-10).

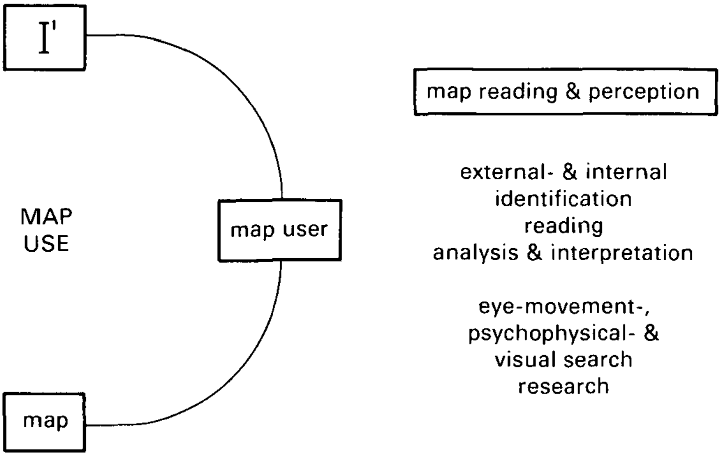


Figure 3-10. The map and the map user.

To enhance the map design and thus increase the efficiency of the map, cartographers should understand as much as possible of how this process of map reading physically takes place. The map user will first scan the map by series of visual fixations. Attention is focused upon several points in the image, and moves between them. Within a second these visual impressions result in a total image of the map, no matter how complex its figuration.

From experiments by psychologists [Haber & Hershenson, 1973] it is known that these points of visual fixation can be found on those spots which appear to hold the most information. In general people tend to look at edges, curves, inflections and contours in the image. Cartographers have been actively involved in eye-movement studies throughout the seventies [DeLucia, 1976, Castner & Lywood, 1978 and Dobson, 1979]. Initially they thought these studies would provide information to document the map reading process, which eventually might lead to the solution of some cartographic problems. The process proved to be more complex, and Castner & Eastman [1984 & 1985] pointed to the importance of task specific viewing in these studies. The overall problem of eye-movement studies is discussed by Steinke [1987].

Another approach to the map user's visual behaviour is the experiment in visual search. Many of these experiments have been done to retrieve information on the speed and accuracy of with which the subject performs specific map reading tasks. These experiments have produced guidelines and recommendations for some aspects of map design. But the overall benefit of these experiments may be the fact that they differentiate those aspects of cartographic communication over which cartographers have some influence from those over which they have no influence [Castner, 1983].

While trying to process map information the user is limited by the psychophysical capacities of human perception, added to which are the differences between individual map user's capacities [Griffin, 1985]. The map user will try to organize the information which is sensed, and doing so he will draw upon his experience. The map user will also strive for invariance (the use of constants) and contrast (information reduction), and is sensitive to the Gestalt laws [Wood, 1972]. Those are indicators which suggest certain shapes to the map user, the map image.

There has also been psychophysical research to see how the map user perceives symbols on the map. The purpose of this research was to find out more about the relation between the map user and the symbols used in the map [Flannery, 1976 & Chang, 1980]. A drawback of the experiments related to this research approach was that it concerned single symbols isolated from the total map context. This approach was criticized and opposed by several cartographers [Olson, 1976 & Gilmartin, 1981]

In any event, these research experiments on the map reading process did not, in general, result in the derivation of a new set of rules for a better map design, but rather to a new set of tools which might, depending on the situation, be used in the map design and map evaluation processes. According to Dobson [1985, p.37] the best way to continue is to make sure that the aim of map user related research is to improve the accuracy and speed of map reading performance. This is presenting spatial data in a form suitable to the task being performed through the exploitation of the human visual and information processing capabilities.

CHAPTER 4. THREE-DIMENSIONAL PERCEPTION

4.1 Introduction

In designing maps the theory of the graphic sign system and the rules of legibility only provide information for the construction of two-dimensional maps. What has to be added to the map to let the map user perceive it as three-dimensional? In chapter 2 the map was described as a model of reality. Is it possible to obtain additional ingredients for a three-dimensional map from this reality?

This chapter will examine how humans see and perceive the three-dimensional world around them. This will be done by describing how the visual system functions by taking a closer look at the process of vision. This results in knowledge of depth perception. Expedients which can be used to enhance the appearance of three-dimensional maps are also discussed.

4.2 Outline of the human visual system

The human visual system comprises a receptor system, the eyes, and a processing system, the brain. The system is schematically displayed in Figure 4-1. The description of the functioning of the human visual system presented here is a generalized one. A more extended explanation can be found in Marr [1982] and Bruce & Green [1985].

Light passes through the lens of the eye to the retina, a thin sheet of neural tissue at the back of the eye. This tissue comprises two kinds of photoreceptor cells, rods and cones, which convert the light into an electrical signal. The rods respond to small changes in light intensity, but they are not sensitive to differences in wavelengths, i.e. colour. The cones need more light to respond than the rods, but they are sensitive to differences in wavelength. The cones can be divided into three types which contain different pigments, that is light absorbing molecules. Each of the three is sensitive to a different part of the visible spectrum. One is sensitive to the shorter wavelengths of blue light, one to the middle wavelengths of green light and one to the longer wavelengths of red light.

The electric signal received from the cones and rods is passed on to the ganglion cells, an inner layer of the retina. This layer contains two intermixed cell types which differ in size and in the way they process the information received from the cones. The larger of these cells lack colour selectivity, while the smaller ganglion cells distinguish between the three cone types. By subtracting the information received from the different cones they can send on information about different colours.

The ganglion cells transmit their signals via the optic nerve to the lateral geniculate bodies. They also consist of two cell types (neurons), which differ in size and in the kind of information they send. The smaller cells (parvo cellular) receive input from the small ganglion cells and the larger (magno cellular) receive input from the large ganglion cells. The parvo and magno systems not only differ in colour selectivity, but also in contrast selectivity, temporal resolution and acuity. The magno system is more sensitive to brightness contrast, and has a faster response time and a lower acuity than the parvo system.

From the lateral geniculate bodies the signals pass to the first cortical visual area (visual area one), situated at the very back of the brain. Signals from the magno system are channeled into the top half and those of the parvo system into the bottom half of this visual area. From visual area one the magno signals are send to visual area two where they are analysed and provide information about motion and depth. The parvo signals are also channeled through to area two, and after analysis do provide information about shape. In the visual area one the inputs from the parvo and magno systems are also combined and processed for colour and luminance information, and then passed on to area two. The final result is the integration of

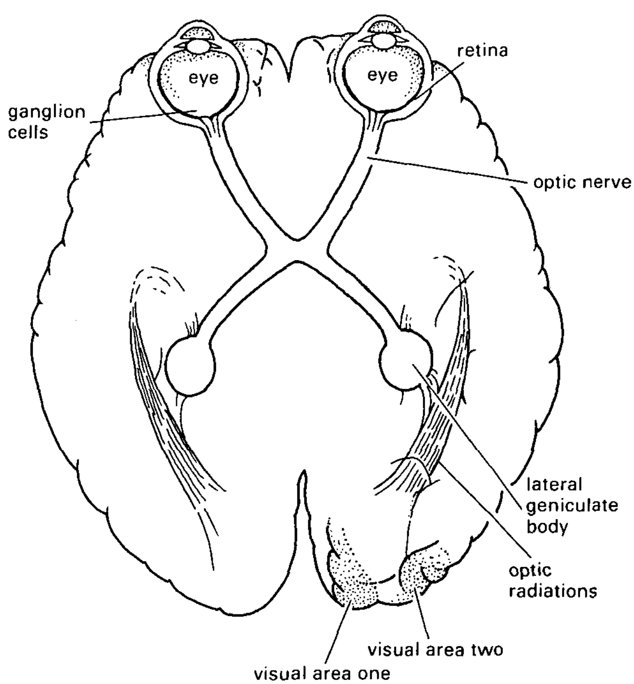


Figure 4-1. A schematic layout of the human visual system.

information from these three pathways, and makes one see a unified three-dimensional world.

The above describes what happens in the human visual system, and its constituent cells which appear to control specific mechanisms. It does not explain how the visual system operates, or how the brain converts these data into some meaningful information.

4.3 Vision

Marr [1982] describes vision as an information processing task. Vision provides information on shapes and spaces as well as on spatial relations. The purpose of vision is to make a description of the shape and position of things from images; that is to obtain a representation of images.

In literature two rival approaches to vision can be found [Gibson, 1979 & Marr, 1982]. The main point of discussion concentrates on the problem of how the physically measurable energy (for instance light) is converted into meaningful information, a percept (for instance, to see a three-dimensional object). The approaches can be distinguished as a 'direct' and an 'indirect' approach [Overbeeke & Stratmann, 1988, p.4].

The 'indirect' approach can be seen as the classical theory and is described by Marr [1982]. In this approach it is assumed that the light which is projected on the retina is ambiguous, and can be interpreted in more than one way. A process of reconstructing the two-dimensional retinal images is necessary to come to a three-dimensional impression of the environment. This can be done using the cues available in the retinal image.

The 'direct' theory described by Gibson [1979] assumes that the light which falls on the retina is structured and unambiguous. This structured light, called the optical array, contains all essential information about the environment. According to these views the image on the retina does not need to go through a reconstruction process to obtain a three-dimensional impression of the environment, because of the non-ambiguous characteristics of the light. This is also the reason why this approach is called 'direct'.

Independent of which theory is supported, both acknowledge the existence of depth information. This depth information can be seen as a set of keys to allow a correct impression of depth. In this thesis it will be shown how some of these depth cues can be applied in a map in order to let the map user perceive it as three-dimensional. It can also be seen in literature [Oatley, 1978 & Rock, 1984] that efforts in perception research are not all centered upon testing which of the two theories is correct, but that researchers tend to look at the nature of the depth cues.

4.4 Depth perception

The depth cues can be divided into those related to physiological characteristics of the visual system, also called the physiological depth cues, and those related to the objects' structure and the way they result in images, also called psychological or pictorial depth cues. The second type of depth cues, such as shading, texture and perspective, can be used as stimuli in the map image to enhance the three-dimensional impression. The first category of depth cues can be used by applying expedients such as a stereoscope. An extensive explication of these depth cues can be found in Held [1972], Okoshi [1976], Hochberg [1978], Gibson [1979], Hodges et al. [1985] and Smets [1986].

4.4.1 Psychological depth cues

Obstruction/overlap or interposition. An object will be perceived as further away, but still complete, from the observer when it is partly hidden by another object. From this situation relative distances can be derived. In cartography overlap/obstruction is often used to visualize the relative importance of the map contents (see also sections 3.3 and 3.5). It is also applied to improve the visual appearance of the map when many symbols are concentrated in one location [Appel et al, 1979 and Rase, 1986], see also Figure 4-2.

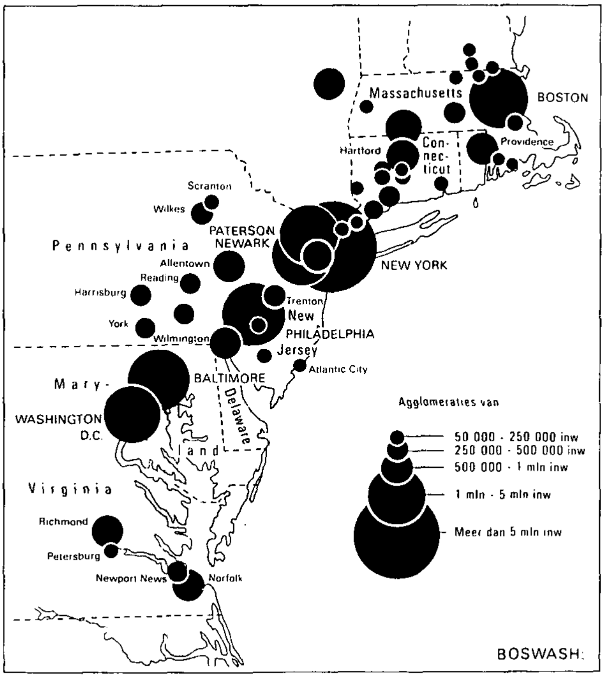
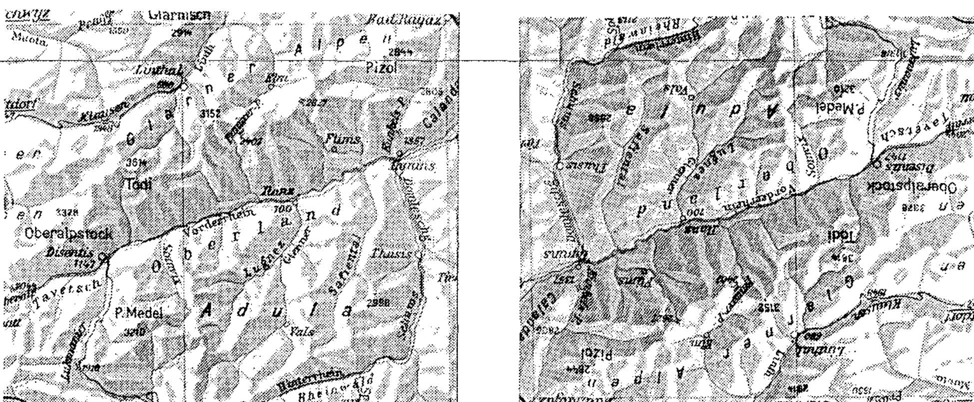


Figure 4-2. Overlap/obstruction.

Shading In combination with a known location of a light source shadow and shading provide information on the position (volume and distance) of objects. Humans are used to the fact the light source is located 'above' objects seen. In cartography shading is applied in relief mapping (see also section 2.4). To function as a useful stimulus to obtain a three-dimensional impression of the map, a light source is assumed to the north-west of the map. Failure to do so will result in relief inversion (compare Figures 4-3a and b). Comments on these perceptual effects of shading in maps can be found in DeLucia [1972], Castner & Wheate [1979] and Elsis [1987].

Perspective Perspective is probably the best known pictorial depth cue. In cartography it is applied in Spatial Map Images (see also section 2.6). When looking at a Spatial Map Image its visual characteristics are influenced by its geometric relationships. Next to the actual perspective construction rules, the elevation angle (the angle formed by the horizon and an imaginary line of sight) and the slope (the angular relationship between the topography or the statistical surface and the horizon) play important roles in its three-dimensional perception [Crawford & Marks, 1973, p.223]. Several more specific depth cues can be derived from perspective:



a) b)

Figure 4-3. Shading: a) correct relief impression; b) relief inversion [Schweizer Weltatlas, 1981, p.15].

line perspective is created by the use of one or more vanishing points in the image. Lines which are parallel in reality seem to converge to one point (see Figure 4-4);
retinal image size or size perspective implies that a larger distance to an object results in a smaller object in the image, and conversely (see Figure 4-5);
texture gradient as a depth cue means that the texture of objects appears coarse in the foreground and grows finer as the objects recedes in the background (Figure 4-6);

aerial perspective is created by the fact that objects at a great distance tend to become hazy and bluish because of atmospheric scattering of the shorter wavelengths;
detail perspective implies that details become less visible at a greater distance, because of the limitations of the human visual system.

Colour is also one of the depth cues. Here it is important to know that the lens of the eye is not corrected for differences in wavelengths. This makes the eye accommodate constantly when looking at a multi-coloured image. The need to accommodate becomes strongest when looking at colours from both ends of the spectrum, such as red and blue (see Figure 4-7). When red and blue are viewed from the same physical distance, they are not perceived as such, since red seems closer then blue. This effect is called chromostereopsis [Murch, 1984 & 1985, and Cowan & Ware, 1985]. This principle was already known at the end of the nineteenth century when the Austrian cartographer K. Peucker [1911] introduced the principle of the hypsometric layer tints.

This principle, where the relief zones are represented by the colours green (low), yellow, orange, red brown (high), can still be found in many atlases, but is not correct when the rules of the graphic sign system are applied. Relief, with and ordered level of organization can not be represented by Colour alone, a graphical variable with qualitative characteristics (see also section 3.4).

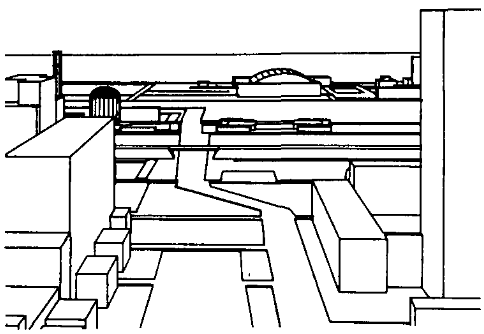


Figure 4-4. Line perspective.

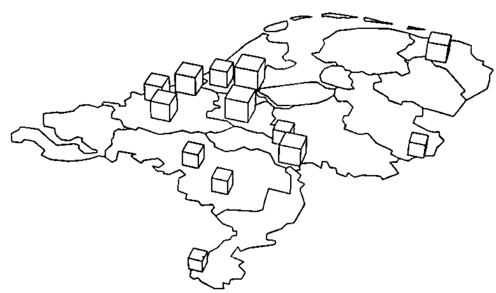


Figure 4-5. Retinal image size.

In many three-dimensional images the psychological depth cues are used in combination with each other. These combinations do not necessarily result in a better three-dimensional impression, and can result in an optical illusion. In chapters on three-dimensional graphics in general textbooks on computer graphics [Newman & Sproull, 1981, Ballard & Brown, 1982 and Foley & Van Dam, 1984] techniques are given to apply these depth cues. To effectuate visual realism in the image perspective projection, intensity depth cueing, clipping, hidden line and hidden surface removal, as well as shading, can be used. In the next chapter the psychological depth cues will be compared with the graphical variables (Size, Value, Texture, Colour, Orientation and Shape) used in cartography.

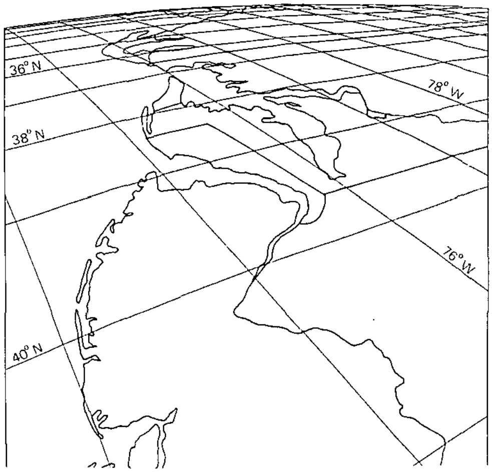


Figure 4-6. Texture gradient.

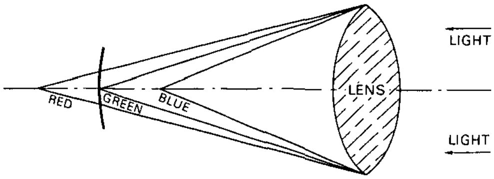


Figure 4-7. Chromostereopsis.

4.4.2 Physiological depth cues

The physiological depth cues are accommodation, convergence, retinal disparity and movement parallax.

Accommodation is a change in thickness of the eye's crystalline lens caused by increasing or decreasing tension on the lens by the ciliary muscle in order to focus on an object.
Convergence is a depth cue which originates from the angle both eye's viewing axes make with each other when both eyes are focused on one point. For an object close to the viewer this results in a wide angle (see Figure 4-8). This angle of convergence is a cue to determine distance.

It has been found [Okoshi, 1976, p.50] that there exists an interaction between accommodation and convergence. Experiments indicate that convergence becomes ineffective beyond 10 metres. Many workers [Rock, 1984 and Overbeeke & Stratmann, 1988] question the value of both accommodation and convergence as depth cues.

Retinal disparity is created by observing one specific scene with both eyes which results in two different images, one on the retina of each eye. This is due to the fact that both eyes observe the scene from a slightly different position; as human eyes are about 6.5 cm apart on average. The perception of depth which originates from observing two unequal images with two eyes is called stereopsis (see also Figure 4-9).

Monocular movement parallax provides depth information by movement of the observer linked to displacement in the image.

In three-dimensional images the physiological and psychological depth cues can be combined. The result of these combinations can weaken or strengthen the depth impression, depending on the type of combination. It can be that the use of a depth cue, such as overlap/obstruction nullifies the effects of retinal disparity [Rock, p.73].

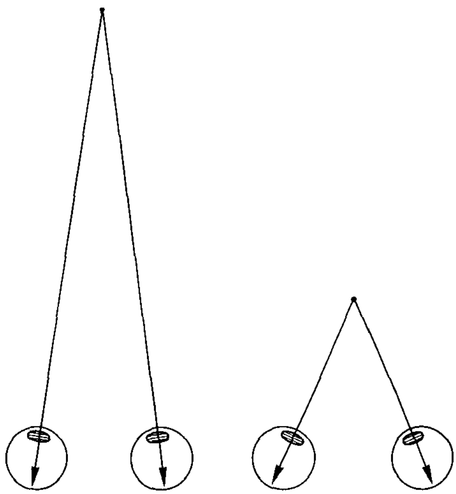


Figure 4-8. Convergence.

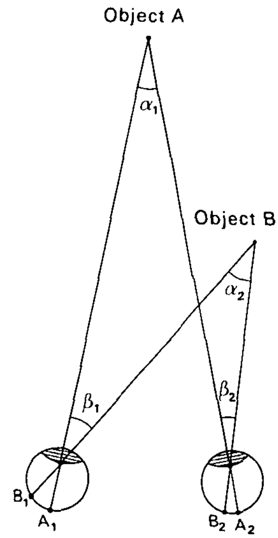


Figure 4-9. Retinal disparity.

4.5 Visual expedients

This section will give an overview of possible expedients which can be used to enhance the three-dimensional perception of an image. The overview is related to the three-dimensional presentation techniques discussed in the scheme in Figure 2-1, and is not intended to be complete. Contemporary literature provides an extensive overview of these techniques and all its derived products [Okoshi, 1976, Lane, 1983, Hodgess et al, 1985 and Overbeeke & Stratmann, 1988]. Expedients which are related to two-image representations are emphasized here. In related disciplines such as photogrammetry the experience of working with such expedients is extensive, and can be transferred easily to cartography.

The next three sections present the principles of optical stereo, anaglyphs and polarization. These techniques have been applied in cartography before, and all need two different images of the same scene, one for each eye. These two images should match as closely as possible the views that would be observed when looking at a similar real scene. Using special glasses to observe the scene, the viewer will perceive a three-dimensional scene which is based mainly on the depth cue of retinal disparity. The two original images can contain some of the psychological depth cues to strengthen the three-dimensional effect. Section 4.5.4 discusses other three-dimensional presentation techniques which, mostly for pragmatic reasons (economics and laborious techniques) have not been used to present three-dimensional maps. These techniques look promising enough to be applied in the cartography to be described.

4.5.1 Optical stereoscope

To be able to see a three-dimensional image using this technique two images need to be viewed through a stereocope. The images, one for each eye, are created from slightly different viewpoints, and by using a stereoscope both images are brought to a distance of 6.5 cm apart (the eye-base) and are merged by the brain into a virtual three-dimensional image. This image is created when the viewer stares through the stereoscope into infinity, which results in a parallel positioning of the axis of both eyes and a merging of the two images. Both left and right images should be presented to the viewer in such a fashion that both image-bases are in line with each other, parallel to the eye-base. Both viewer's eye-axis should, when viewing corresponding parts of the images, be more or less parallel to each other, and perpendicular to the plane of the stereo images.

The British physicist C. Wheatstone was the first to use this technique in 1838. His stereoscope, a mirror stereoscope, has been available for more than hundred years, and the principles have been changed only a little since it can handle stereoscopic images of any size. Figure 4-10a demonstrates its principles. Another advocator of the stereoscope has been D. Brewster who created the prism stereoscope (Figure 4-10b). Today the stereoscope is often a combination of the Wheatstone and Brewster principles. A modified stereoscope has also been used in the map user research in this study, and its use will be explained in more detail in chapter 7. In contemporary photogrammetry the principles of the stereoscope are incorporated into complex devices, and it is in use to retrieve data from stereoscopic photos for geodetic purposes [Ligterink, 1983].

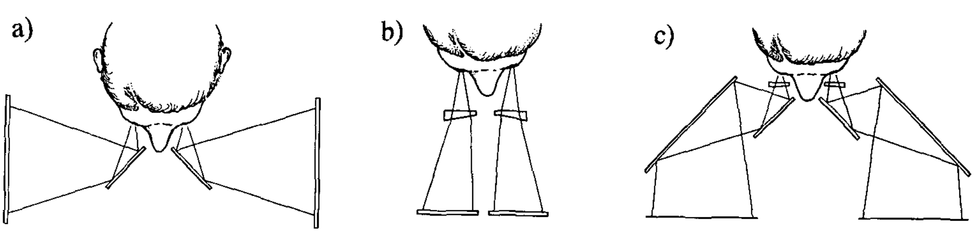


Figure 4-10. Principles of stereoscopes: a) Wheatstone; b) Brewster; c) Table stereoscope.

The advantage of the optical stereoscope to create a three-dimensional impression is that it is relatively easy to realize. When extending it to cartography the need for two images is no real disadvantage. When one has decided to display the map the first image of a stereo pair must be created in any event, and the computer can generate the second image with almost no extra effort, as will be seen in chapter 6. To view both maps on a screen a simple stereoscope will suffice.

A disadvantage of the use of a stereoscope is that it demands the images to be viewed under special conditions (i.e. the distance and position of both images relative to each other and to the stereoscope). This limits the use of same the virtual three-dimensional image to one observer. Another disadvantage is that a small percentage of people (about 10%, according to Julesz in Overbeeke & Stratmann, [1988, p.115]) is unable to see stereoscopically. Experiments with optical stereoscopes in cartography have been conducted by Jensen [1978 & 1980], Freyer [1983], Kraus & Vozikis [1983], Kraak [1984] and Weber [1985].

4.5.2 Anaglyphs

A virtual three-dimensional image is created by printing the two slightly different images on paper or by projecting them on to a screen through filters, both in complementary colours (red and green). These combined images should be viewed through a filter (often red-green glasses) to obtain the three-dimensional impression. Figure 4-11 explains these principles. Again the computer can create both images.

The technique was first developed by the German physicist W. Rollmann in 1853 [Lorenz, 1987]. The three-dimensional image can be seen by more viewers simultaneously, depending on the presentation method, but the use of colour is limited. When a raster screen is used, even within the blue-red range the application of area symbols is not possible since the separate pixels of the screen can have only one colour, that of the colour last 'sent' to the screen. This can be seen as an important disadvantage in computer cartography. The fact that a about 7% of the males and 1% of the females are colour blind for red-green [Carterette, 1975], and that viewing through different coloured filters can be displeasing and can create a retinal rivalry, are also drawbacks of the technique. In cartography this technique has been applied on several occasions [Cholley, 1956 and Egels, 1987].

4.5.3 Polarization

The technique of polarization is based on the separation of light (a circular composed vibration) into two components, a horizontal and a vertical. The two images can be projected using a filter that produces polarized light. The viewer will look through glasses with a horizontal and a vertical polarized glass, which makes the observation of a three-dimensional virtual image possible. See Figure 4-12 for the principles.

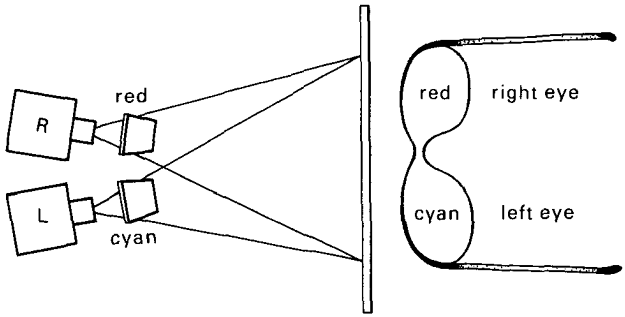


Figure 4-11. Principles of anaglyphs.

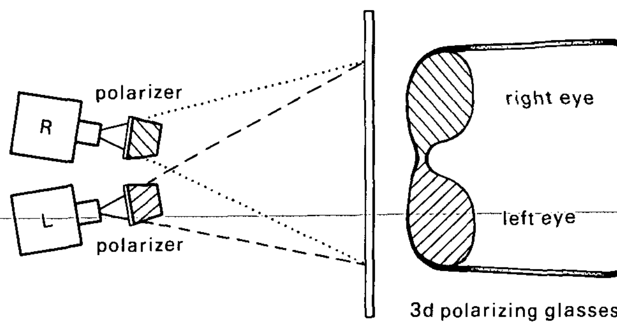


Figure 4-12. Polarization.

Several principles of the presentation of polarized images on screens are known. The first, called the split screen method, uses a half screen for each horizontal and vertical polarized image. Only half of the screen's resolution can be used. The second method, called dual screen, combines two screens positioned at an angle of 90 degrees with a half silvered mirror in between. A third method uses again one screen, but both images are displayed as alternating pairs. The glasses the viewer looks through are adapted and have an electro optical shutter device using lead lanthanum zirconate titanat (PLZT) ceramic wafers [Lipton, 1984a & 1984b]. The PLZT-shutter is being replaced by liquid crystal shutters. The firm Tektronix has recently issued a display with these qualities [DeHogg, 1987]. However, it is still expensive, but its three-dimensional effect is impressive using full colour and shading capabilities. When such equipment becomes available more general, for instance for television, the practical application of three-dimensional cartography can be realized easily. This study tries to prepare the cartographer for such developments, by including an expedient, such as the stereoscope into the three-dimensional map user research.

4.5.4 Other expedients

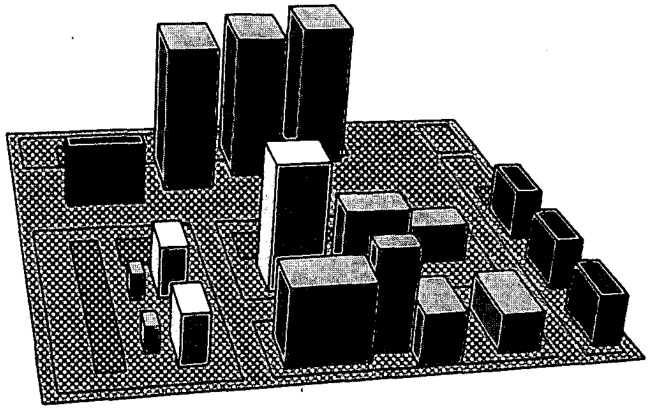
The expedients discussed in this section are holography, vari-focal mirrors, and systems based on movement parallax.

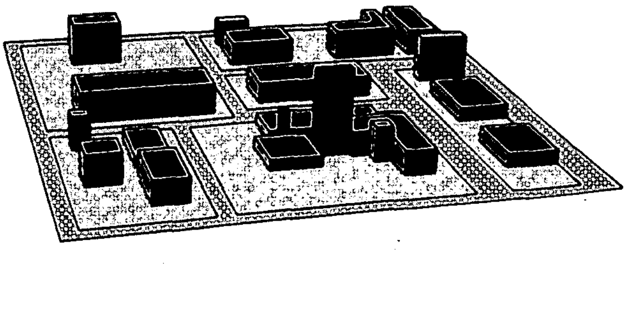
Holography is a photographic recording technique developed in 1948 by Garbor which, using a laser, collects data derived from a three-dimensional object on aphotographic print called stereogram. A significant difference from ordinary photography is that in addition to phase information, amplitude information is also collected which makes it possible to reconstruct the beam of light, and thus the three-dimensional object. The principles of this technique are explained in Gabor [1972] and Frankena [1979]. The stereograms can be generated optically or by computer. This last option is interesting for cartography when holograms can be created from databases, but it requires complex mathematical algorithms and further research is required before the technique can be applied outside laboratories. But there are some significant promises for the future [Benton, 1982 and Prikryl, 1982].

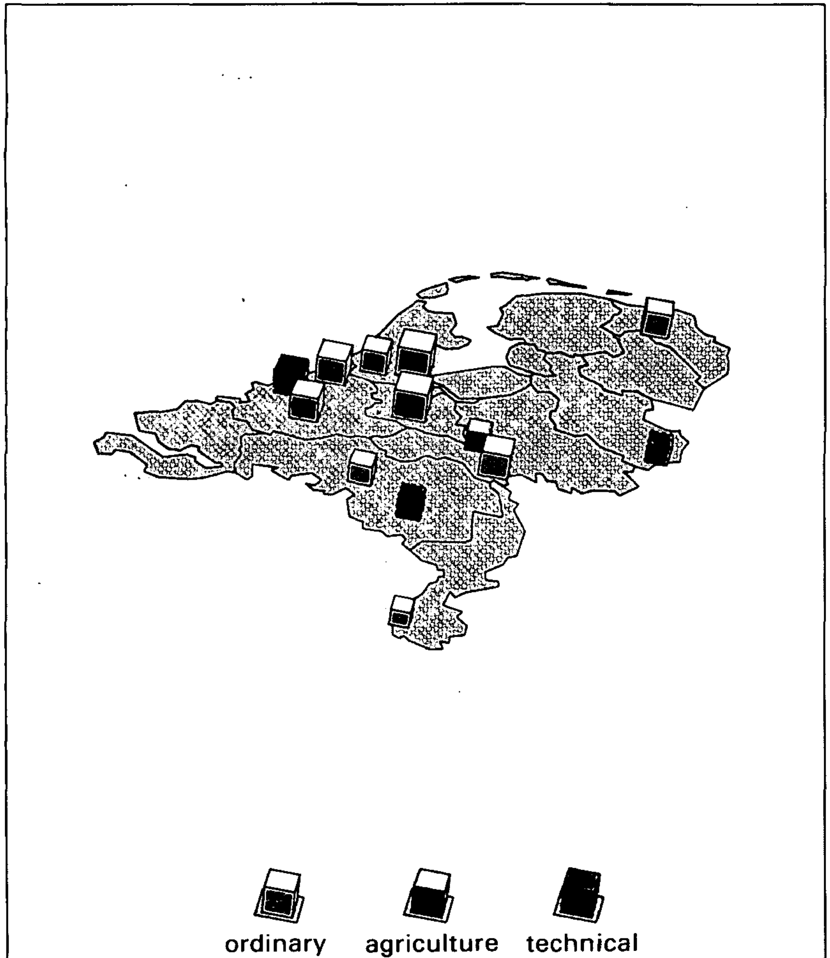
Vari-focal mirrors create the illusion of a three-dimensional image by projecting, in rapid succession a series of two-dimensional images on a vibrating mirror. Each two dimensional image is a cross section, a spatial slice of a three-dimensional object. The display of these cross sections is synchronized with the vibrating mirror so that, when viewed by reflection, each cross section appears at its appropriate location. A characteristic of these three-dimensional images is that they are 'see-through', which in most cartographic applications is a disadvantage.

Other techniques using more than two images to create a three-dimensional image are **fresnel displays** [Lane, 1982], **lenticular displays** [Okoshi, 1976] and **parallax barrier displays** [Kaplan, 1952]. The advantage of all techniques mentioned so far in this section is that they are autostereoscopic, that is the use of a special device, such as glasses, is not necessary to perceive the three-dimensional image. An important disadvantage is that the facilities needed to make use of the techniques are too difficult and laborious in nature to apply them in todays computer-assisted cartographic environment.

Techniques using **movement parallax** to create a three-dimensional illusion use only one image. The literature [Overbeeke & Stratmann, 1988] distinguishes two types of movement parallax: passive and active. Applying the first technique the depth information is obtained from movement only in the observed scene. Examples are certain computer animations and the visidep system [Jones, 1984]. Of the second technique the so called Cambridge and Delft systems are known. The first of is based on perspective deformation [Diamond et al in Overbeeke & Stratmann, 1988], while the Delft system [Smets, Stratmann & Overbeeke 1985] is based on movement in a scene created by movement of the observer round a fixation point.



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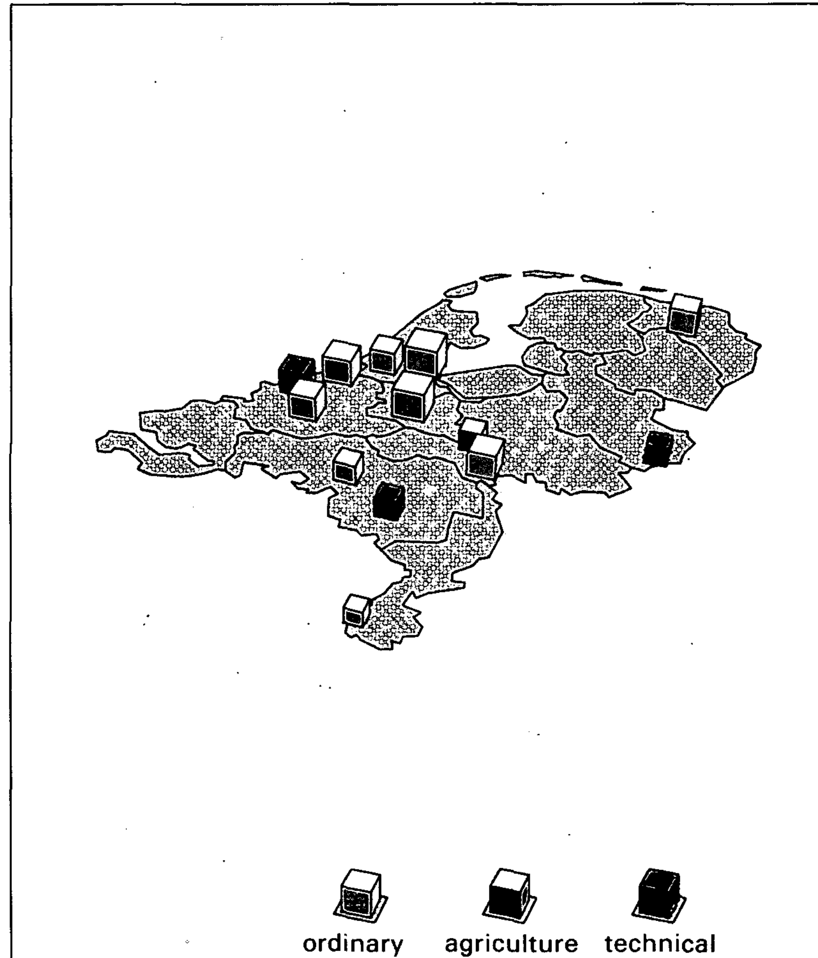
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This fixation point is seen as the most important component in the Delft system's movement parallax.

4.6 The expedient chosen: the stereoscope

In the Spatial Map Images used in the map user test, described in chapter 7, some of the psychological depth cues are used, and during part of the test in combination are with an expedient, a stereoscope. To explain why the stereoscope has been favoured above the other expedients one must return to section 2.4.1, where three factors are mentioned which influence the choice of a three-dimensional presentation technique: human skills, the purpose of the three-dimensional map, and the technical opportunities. The choice has been mainly pragmatic and the last of the three factors has been decisive.

Within the faculty where the research was carried out, the Faculty of Geodesy of the Delft University of Technology, the photogrammetric unit has available the knowledge and equipment needed to use a stereoscope in combination with graphic screens. In the above section advantages and disadvantages of most of the other three-dimensional display techniques have been mentioned. The use of one of these techniques may seem appropriate, but the effort and costs required, would divert to far from the thesis' scope.

Developing mapping software to create the two maps needed for use in combination with a stereoscope is relatively easy, and will be described in chapter 6. Apart from the advantages and disadvantages mentioned in section 4.5.1 the size of the maps to be used is limited by the type of stereoscope (horizontal direction) and the screen characteristics such as size and resolution (horizontal and vertical direction). Both left and right maps are displayed side by side, and only half of the screen can be used. Only a few can fuse the images without the use of an expedient. Most use the stereoscope to see the three-dimensional virtual map.

The virtual map seen through a stereoscope has some specific characteristics which should be known before using it. The most prominent feature is that the vertical scale of the virtual map is exaggerated when compared with the image's horizontal scale. With stereoscopic images in general the exaggeration depends on the geometry of the images (base-height ratio). This vertical exaggeration is not the same for each observer, it is influenced by factors such as the observer's eye-base and subjective quantities [Ligterink, 1964]. The exaggeration can be quantified using ground control points as is done in photogrammetry, where the virtual image of aerial photographs is used to derive height information.

For most cartographic applications these characteristics are not troublesome. However, it should be kept in mind that the Spatial Map Image presented to the map user has probably been manipulated (rotated) in order to fit to its communicative task. This means that the vertical exaggeration in the virtual map does not always occur along the z-axis.

To these 'natural' characteristics of the virtual map the cartographer often adds some 'artificial' characteristics. When Spatial Map Images of the topography (for instance digital terrain models and urban three-dimensional maps) the vertical scale (the area's height) is almost always exaggerated, because the earth's horizontal dimensions are so great compared to its variations in elevation [Crawford & Marks, 1973]. In the thematic Spatial Map Images this method is also applied. Here some care should be taken when dealing with symbols presenting absolute values. A programme producing Spatial Map Images should therefore have the capability for interactive scaling the z-axis.

CHAPTER 5. ASPECTS OF THREE-DIMENSIONAL CARTOGRAPHIC THEORY

5.1 Introduction

This chapter is the synthesis of the previous three chapters. Here knowledge of three-dimensional images and cartography (Chapter 2), cartographic theory (Chapter 3) and three-dimensional perception (Chapter 4) is combined. This synthesis results in questions and assumptions that need testing, and should provide elements for a three-dimensional cartographic theory.

In chapters 2 and 4 three-dimensional aspects have been introduced. This is not the case with the chapter dealing with cartographic theory. In introducing the third dimension to this theory the structure of Chapter 3 will be followed, especially Figure 3-1. The general approach to cartography (the Utrecht School of Cartography) will not be affected. Looking at Figure 3-1 again, the two inner circles, the main cartographic activities and the outline of cartographic communication theory, will not change significantly. However, it can be that the last process runs more or less smoothly when a three-dimensional map is involved. It will be the tools, and their use in the figure's outer circle (cartographic information analysis and the graphic sign system), that need most attention. The map user aspects will be discussed in Chapter 8.

In describing three-dimensional cartography all comments are related to the Spatial Map Images.

5.2 3D-information analysis

The general approach to cartographic information analysis for three-dimensional maps is not different from the two-dimensional case. Knowing the purpose of the map, and having defined the information and user requirements, the cartographer has to analyse the information which is to be mapped. Here the information can also be divided into an invariant and components. In the case of the invariant there is no difference.

Neither will the treatment of most components deviate from the approach in section 3.3. However, it is interesting to see how the geographical component (GEO) in a three-dimensional map differs from its two-dimensional counterpart. In a two-dimensional map the geographical component (further called GEO2) is seen as a single component using the plane's two dimensions (see Figure 5-1a). When there are more components to map, graphical variables are introduced (Figure 5-1b).

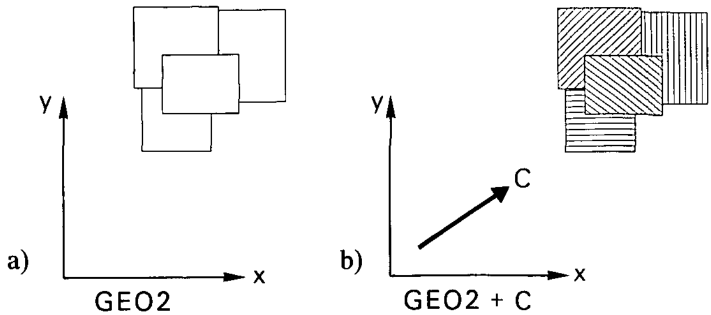


Figure 5-1. The geographical component in a two-dimensional map: a) the geographical component using the two-dimensions of the plane (GEO2 = X+Y); b) the geographical component and one other component (GEO2 + C).

How can a geographical component in a three-dimensional map (GEO3) be described? In addition to the two dimensions of the plane, x- and y-, a z-coordinate is introduced (Figure 5-2a). In GEO3 the z-coordinate can represent a statistical value (examples are the prism map and the three-dimensional point symbol map), or it can derived from 'tangible' data from reality (examples are the digital terrain model and the three-dimensional urban map). It is also possible to introduce more than one component into the three-dimensional map: this will introduce graphical variables (Figure 5-2b).

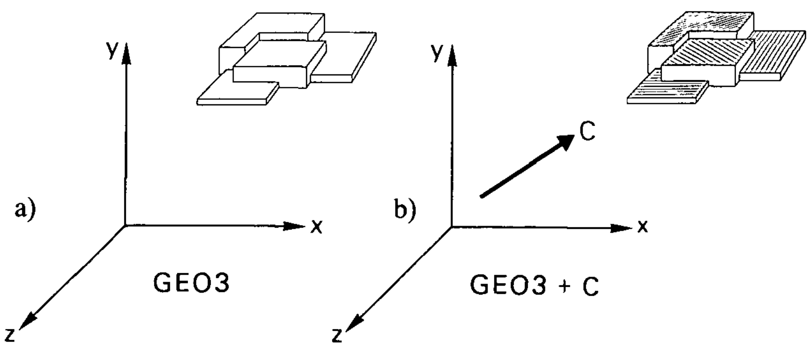


Figure 5-2. The geographical component in a three-dimensional map: a) the geographical component and the two-dimensional plane (GEO3= GEO2+Z); b) the geographical component and one other component (GEO3 + C).

The scheme in Figure 5-3 summarizes the above observations.

GEO2	= X + Y	Figure 5-1a [1]
GEO2 + C	= X + Y + Component	Figure 5-1b [2]
GEO3	= X + Y + Z	Figure 5-2a [3]
GEO3 + C	= X + Y + Z + Component	Figure 5-2b [4]

Figure 5-3. The geographical component in two- [1] & [2] and three-dimensional maps [3] & [4].

What are the characteristics of Z in statement [3] in Figure 5-3? If Z equals a component the three-dimensional geographical component is equal to the two-dimensional geographical component plus one other component ([3]=[2]). Or does it imply the use of a psychological or pictorial depth cue, and can it be said that the three-dimensional geographical component equals the two-dimensional geographical component ([3]=[1]). This would also equal statements [2] and [4] in Figure 5-3.

What is the relevance of these questions? If the first assumption ([3]=[2]) in the previous paragraph is true, the information contents, in terms of results of the cartographic information analysis, of a three-dimensional map equals that of a two-dimensional map. However, no verdict is being made if one of the presentations is to be preferred. If the second assumption ([3]=[1]) is true the information contents of a three-dimensional map is larger.

To understand this last remark, and to see which of the two assumptions is true the Map-To-See has to be introduced, and its relation to the temporary map, as well as to the Spatial Map Image has to be presented.

The concept of a Map-To-See or Image was first introduced by Bertin [1967, p.142], and is a clear graphic representation which can be comprehended in a short moment. Such an efficient graphic construction should provide the map user with answers to all possible questions related to the map, whatever their type or complexity, in a single moment of perception.

A Map-To-See is constructed using the homogeneous plane (GEO2) and one visually ordered graphical variable (Size, or Value: statement [2] in figure 5-3; see also Figure 3-5); Figure 5-4a presents an example. In the cartographic communication process the Maps-To-See are the most efficient means to communicate a message. If indeed GEO3 equals GEO2, i.e. the second assumption is true GEO3, having a larger information contents than GEO2 can also be considered a Map-To-See.

In the map user test described in Chapter 7 Spatial Map Images including GEO3 and GEO3+C are presented to the user. Also maps with GEO2+C characteristics are presented to find out whether the Spatial Map Images can be considered as Maps-To-See. During testing, the nature of the original Z-element in GEO3, i.e. does it refer to topography or to statistics is included, as well as the effect of the use of the stereoscope. The effect of the stereoscope has to be judged, to find out whether GEO3 itself has different characteristics when used in a virtual three-dimensional map or a temporary three-dimensional map.

The importance of knowing the characteristics of GEO3, and it functions in the Map-To-See concept, will be understood when the strong relation between three-dimensional maps and computer-assisted cartography, more specifically the temporary map, is considered as was explained in chapters 1 and 2. Especially the use of the Maps-To-See, as temporary maps, will increase in this information age [Bertin and Muller in Taylor, 1985, p.13]. The characteristics of most screens which can display the temporary map do not allow for complex maps. These complex maps are called Maps-To-Read. The difference between Maps-To-See and Maps-To-Read is graphically displayed in Figure 5-4.

New information systems presented to the map user include TELIDON, VIDEOTEX [Taylor, 1983], but also several navigation systems. They all use relatively small screens, often with a low to medium resolution. Since the maps presented by these systems are computer generated, there is an opportunity to use three-dimensional maps. However, the actual use of this type of map should depend on the application.

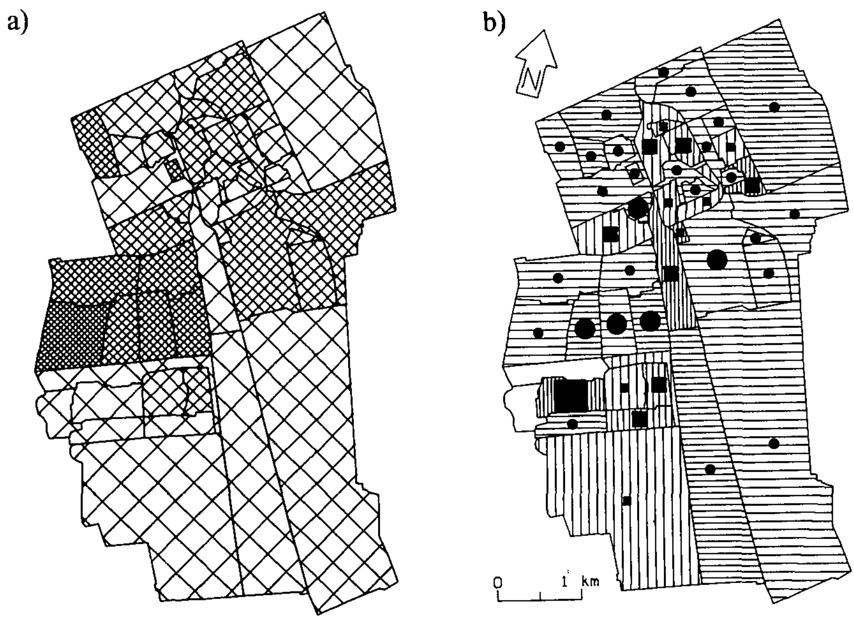


Figure 5-4. a) A Map-To-See (MTS = GEO2 + Co); b) a Map-To-Read (MTR = GEO2 + Cn).

In the definition of a Map-To-See it was stated that their graphic construction allows questions of any complexity to be asked, and that it should be possible to answer them in a single moment of perception. To find out if a Spatial Map Image fits the definition of a Map-To-See, questions of different complexity should be asked during the test. These questions can be organized in levels of complexity, or reading levels. There are three levels distinguished: the elementary, the intermediate and the overall level [Bertin, 1967, p.151; terminology from its english translation, 1983].

To explain the concept of reading levels a map displaying the population density of the city of Delft (see Figure 5-4) is used.

A question of the **elementary level** is introduced by a single element of the component, and will result in a single correspondence (Figure 5-5a). Example: to which density class belongs the most north eastern neighbourhood?
Questions of the **intermediate level** are introduced by a group of elements or catagories, and result in a group of correspondences (Figure 5-5b). Example: in which neighbourhoods is the population density between XX and YY ?
A question of the **overall level** is introduced by the whole component (Figure 5 -5c). Example: where is the highest population density to be found?

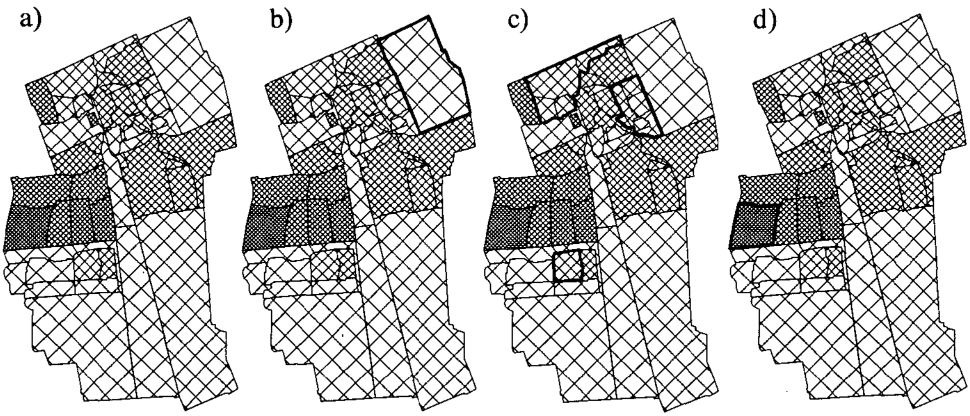


Figure 5-5. Reading levels, example of Delft's population density: a) the map; b) elementary level; c) intermediate level; d) overall level (for examples see paragraph above this figure).

Spatial Map Images have been produced in which the situations described by the statements in Figure 5-3 are expressed. Map users have to answer questions on all levels while looking at those maps. The questions of the single reading levels correspond to the map reading tasks during the test. Figure 7-6 summarizes the character of all questions, and illustrations of the Spatial Map Images together with the question asked can be found in Appendix II and III.

5.3 The graphic sign system and the third dimension

The impact of the third dimension on cartographic theory is most significant with the application of rules of the sign system in three-dimensional maps. Most concepts explained in section 3.4 have, according to Bertin [1967, p.42], only a meaning in two-dimensional graphics. This does not imply that the rules are invalid, but research has not been undertaken on the application of the concepts to three-dimensional graphics.

In section 3.4, the basic concept of the sign system was said to be the two-dimensional plane. This is changed to a three-dimensional space in view of this research approach. There is no doubt of this change when virtual maps are involved. However, for temporary maps, most often presented on flat screens, this change is not a necessity. For these maps it is important to understand the qualities of the geographical component GEO3. It is this geographical component which determines the magnitude of the change. The change to the three-dimensional space is unquestionable when not only the map design, but also the database from which the maps are retrieved, is involved.

Working in three-dimensional space, a fourth basic graphical element has to be added to those in use in two-dimensional graphics. In addition to the point, line and area symbols the volume symbol is introduced, as is explained by Hsu [1979] and Dent [1985].

GRAPHICAL VARIABLES to display spatial distributions	DEPTH CUES to display the third dimension
Size	Retinal image size
Value	Shading
Texture	Texture
Colour	Colour
Orientation	Line perspective
Shape	Perspective
-----	Area perspective
-----	Detail perspective
Visual hierarchy	Overlapping / Obstruction

Figure 5-6. The possible relation between the graphical variables and psychological depth cues.

A question to be answered is whether the perceptual qualities of the two-dimensional graphical variables are still valid in three-dimensional maps, since there is a strong link between them and the psychological or pictorial depth cues discussed in section 4.4.1, and as can be seen in Figure 5-6. Referring to the scheme in Figure 5-6 it can be seen what possible relation between each graphical variable and a similar psychological depth cue exists. Both are used because of their perceptual properties, the first to display spatial distributions and the second to create a three-dimensional impression.

How does this combination function in a three-dimensional map? Here a graphical variable such as value can be used because of its ordered level of organization, while its characteristics are also used to create depth in the image by means of shading. Given this is possible, do they strengthen or neutralize each other?

Each of the above combinations is illustrated and explained in the following subsections. These combinations are approached from a cartographic point of view, using the graphical variables as a base. Test maps have been produced for the map user in which each of the graphical variables, in combination with the psychological depth cues, appear. The answers to the accompanying questions (the users' map reading tasks) should lead to conclusions on the advisability of using them together in a three-dimensional map, and to a possible extension of Figure 3-5.

When the cartographer designs a three-dimensional map the procedure of combining the results of information analysis and the elements of the graphic sign system equals that of procedure for two-dimensional maps. However, the application of the design rules discussed in section 3.5 needs some care, since the visual effect of some of these rules might be influenced when the graphical variables are used in combination with the depth cues.

The relation between the three-dimensional map and the map user is discussed in chapters 7 and 8. Figure 7-6 in chapter 7 presents the character of the questions and the Spatial Map Images which test the relation between the graphical variables and the psychological depth cues.

5.3.1 Relation between size and retinal image size

The perceptual properties of the graphical variable size are commonly used to present information with a quantitative level of organization. The graduated or proportional point symbol maps are the best known cartographic examples of the application of this graphical variable. Figure 5-7a presents an example of such a map.

Variation in the sizes of objects can be used to give the observer the impression of depth in the image: this is the application of the depth cue known as retinal image size. Objects closest to the observer, which in reality have the same size as objects further away from the observer, are displayed larger in size then those in the background of the image (see Figure 5-7b).

Questions which arise are: 'How will the graphical variable of size behave, when used in a three-dimensional map where the depth cue of retinal image size is used to provide the map user with a three-dimensional impression'; 'Is the map user still able to derive the proper quantitative information from the map?'; 'What is the effect of the use of the stereoscope (upon the virtual map) ?'. Figure 5-7c presents a map where the perceptual properties of size in its quality of graphical variable and depth cue are combined. For the map user test several Spatial Map Images are produced to find an answer to the above questions, while other test maps are designed provide information on the combination of the graphical variable size with other psychological depth cues.

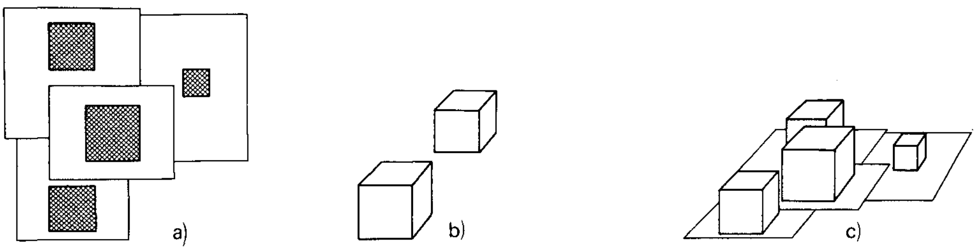


Figure 5-7. The perceptual properties of size: a) size as a graphical variable; b) size as a depth cue; c) size used as graphical variable as well as depth cue.

5.3.2 Relation between value and shading

In cartography the perceptual properties of value are used to express information with an ordered or selective level of organization (see Figure 3-5). The best known application of value in cartography is the choropleth map. In this map differences in the intensities of a phenomena are displayed by differences in value. Figure 5-8a presents an example.

Variations in value are also used in three-dimensional images to create an impression of depth. However the terminology is different. Value is called shading, since its effect is obtained by the use of a light source which lights the object and results in shadow and shading. Its use in cartography is discussed in section 4.4.1, and Figure 5-8b demonstrates its application.

Questions similar to those which arose when discussing the graphical variable size surface here: 'What is the effect of the combined use of the graphical variable value and the depth cue shading?'; 'How does the use of the stereoscope influence the map reading task?'; 'Is the map user distracted from the 'choropleth data' by the shading of the Spatial Map Image?' Figure 5-8c shows a map where the perceptual properties of value as graphical variable and as depth cue are combined. Several Spatial Map Images are produced to find answers to the above questions. The graphical variable value is also combined with other psychological depth cues to see how value behaves in these situations.

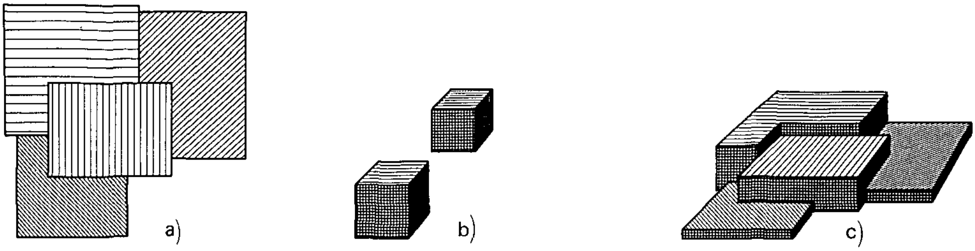


Figure 5-8. The perceptual properties of value: a) value as a graphical variable; b) shading as a depth cue; c) value as a graphical variable, and shading as a depth cue, combined.

5.3.3 Texture and texture gradient

In cartography the perceptual properties of texture are applied to display information with a qualitative (associative and selective) level of organization. The use of texture is seen here through its quality of differences in pattern. The best known map type in which texture is applied is the chorochromatic map, of which Figure 5-9a displays an example.

The use of the texture gradient as a depth cue is based on the effect that the texture of objects appears fine in the background and coarser when the object is in the foreground. Figure 5-9b presents an example in which the density of the pattern increases when the object is further from the observer.

When the graphical variable texture is used in the same three-dimensional map where the texture gradient is used as a depth cue, questions arise, e.g. 'How will the map user perceive the combined use'; 'What does the stereoscope add to the map user's understanding of the cartographic image?'. In Figure 5-9c an example is given of the combined use of the graphical variable texture and the depth cue of texture gradient. Again, spatial map images have been produced for the map user test to obtain answers to the above questions.

5.3.4 Colour

Colour is one of the more expressive graphical variables, and since most current temporary maps are displayed on colour-screens it is applied in almost all such maps. The perceptual properties are used to display information with an associative and selective level of organization. Figure 5-10a presents an indicative but uncoloured example of the application of this graphical variable (the colour illustrations between pages 20-21, 52-53, 84-85, and 126-127 present some proper examples).

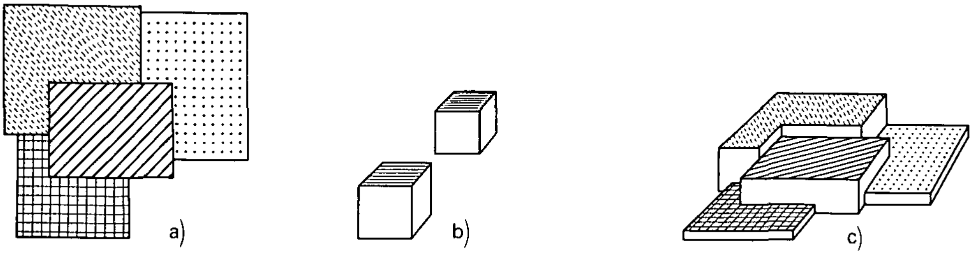


Figure 5-9. The perceptual properties of texture: a) texture as a graphical variable; b) texture as a depth cue; c) texture applied in a map as a graphical variable as well as a depth cue.

When colour is used in temporary maps it is important to realize that the map user will be confronted with emitted light, working with the additive Red-Green-Blue colour-system, instead of reflected light, the subtractive Cyan-Magenta-Yellow system, which might have some perceptual implications [Robinson et al, 1984].

Colour is also in use as one of the psychological depth cues. This is based on the fact that colours of a shorter wavelength, such as red, are perceived to be closer to the observer than colours of a longer wavelength, such as blue, when the colours are physically at the same distance from the observer (see Figure 5-10b).

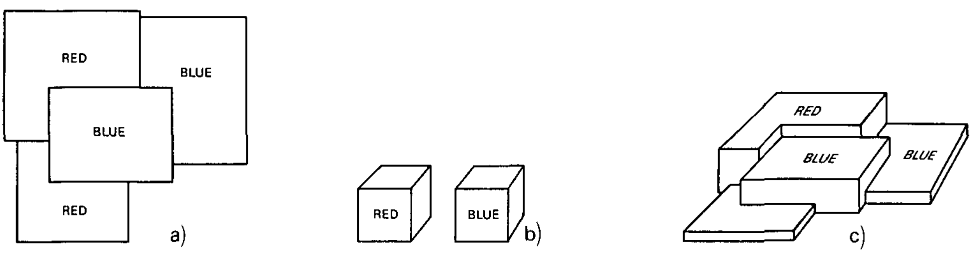


Figure 5-10. The perceptual properties of colour: a) colour as a graphical variable; b) colour as a depth cue; c) colour functioning as graphical variable and depth cue.

When colour is applied to function as a graphical variable as well as a depth cue, questions will have to be answered, e.g. 'If the depth cue characteristics of colours are known, that is red symbols are perceived to be closer then blue symbols, can the same colours still be used to display two different features of equal importance?'; 'Does the result change when a stereoscope is used?'; 'Since colour is used in almost all temporary maps, how does it function in combination with the other depth cues?' Figure 5-10c shows as a monochrome illustration the application of colour as graphical variable and as depth cue in the same map. From both prisms in the back of this map the red-prism will be perceived closer then the blue one.

5.3.5 Relation between orientation and line perspective

The graphical variable orientation has perceptual characteristics which make it possible to display information with an associative and selective level of organization. Figure 5-11a presents an example of its use.

The application of perspective, more specifically line perspectives influences the geometric relationships in the three-dimensional map, but its use results in a strong three-dimensional impression as can be seen in Figure 5-11b.

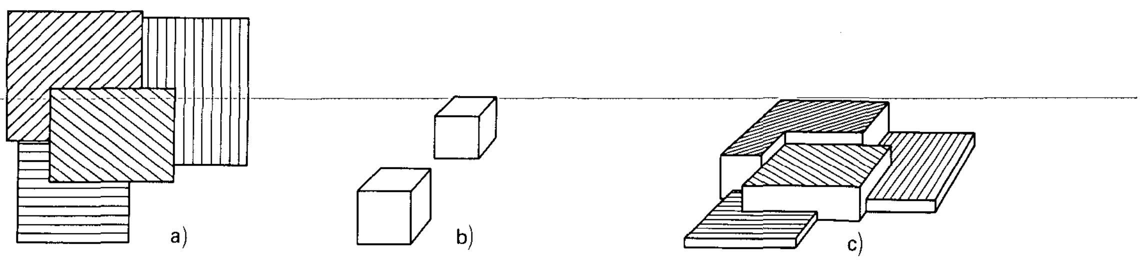


Figure 5-11. The perceptual properties of orientation: a) orientation as a graphical variable; b) line perspective as a depth cue; c) orientation as a graphical variable and line perspective as a depth cue combined.

To be able to judge the value of the combination of the graphical variable shape and the depth cue line perspective, questions will have to be answered. Maps such as that displayed in Figure 5-11c were produced and included in the map user test.

5.3.6 Visual hierarchy and overlap/obstruction

Visual hierarchy, or figure-ground, is not one of the graphical variables, but is one of the more prominent design rules as discussed in section 3.5. It is applied in maps to obtain, graphically, layers of different importance, and is used to organize the map information. The characteristics of the depth cue overlap/obstruction is discussed in 4.4.1, and for two-dimensional cartography is illustrated in Figure 4-2.

Visual hierarchy and overlap/obstruction are applied more or less with the same objective in mind, that is a hierarchical organization of the image, according to relative importance or distance respectively.

5.3.7 The others: shape, area and detail perspective

The graphical variable shape can be used to display information with an associative level of information only. It has no direct relation with any of the depth cues. However, the shape of map symbols, such as cubes, cylinders and pyramids might be affected by the application of depth cue derived from perspective (section 4.4.1).

Area and detail perspective have no direct link with one of the graphical variables. In maps provided to test map users these depth cues have not been used, since it would ask for sophisticated computer graphics software which was not available during this study.

CHAPTER 6. THREE-DIMENSIONAL MAP PRODUCTION

6.1 Introduction

To answer the questions from the previous chapter and to see which of the assumptions in section 5.2 are valid, three-dimensional maps have to be produced and presented to map users. Since there is no standard cartographic software available to produce Spatial Map Images a program had to be developed.

This chapter presents the philosophy of a three-dimensional mapping program (see Figure 6-1). The program includes all components necessary for a correct production of three-dimensional maps. One of the important principles of the program is the possibility for the cartographer to manipulate the Spatial Map Image interactively, and position it according to the purpose of the map.

Before the most essential units of the program are treated, the software options, and several aspects of the computer graphics techniques applied will be explained.

6.2 Software options

Some existing cartographic software packages [Carter, 1987] are able to produce three-dimensional maps, but the procedures followed are not identical to the principles presented in this thesis. One of the principles missing from existing packages is the possibility to manipulate the Spatial Map Image interactively.

The alternative would have been the use of CAD software, a package such as Autocad or CATIA. They have most of the functionality proposed in this thesis, and can be used to produce the Spatial Map Images. The reason they were not used is that they often have a confined data structure, based on simple graphical primitives or mathematical descriptions. However, these packages are in use in cartography in general, as indicated by Shepherd [1986].

A development can be signaled which indicates the growing existence of an interface between cartographic and CAD software [Dangermond, 1986 and Logan & Bruani, 1987]. The CAD software now incorporates facilities for topology, non-graphical attributes and reference systems. However, there are still some significant differences. Cartographic systems have to deal with a much greater data volume, and a wider diversity of data input. CAD systems are vector oriented, while cartographic systems deal with vector data and/or raster data, depending on the application. Examples of vector applications are water and power utilities, whose information is oriented towards pipes and wires. Examples of raster applications are the resources managers and defense, who deal with areal data provided by satellite.

In the near future software available might well be suitable for producing Spatial Maps Images following the philosophy presented here. But at the moment a disadvantage of both the existing cartographic, as well as the CAD, software is that it is almost impossible to manipulate the final images, and to use them in the map user test. Therefore a program was specially developed for this study using a graphical standard, PHIGS, to be able to tailor the program to the needs of this study. The use of a standard has some advantages as is discussed in section 6.4.

6.3 Computer graphics techniques applied

Three stages of three-dimensional graphical modelling in computer graphics can be identified with increasing levels of sophistication [Baer, Eastman & Henrion, 1979, p.253]. First is the image modelling which is focussed upon the reproduction of drawings. Geometric modelling is second, focussing upon the shapes of objects. The modelling of objects is third, in which attributes are added to the geometric model, including density, colour, material, function or whatever is relevant to the application, but excluding the attribute of shape. Their use is common in the fields where Computer Aided Design and Computer Aided Manufacturing techniques are used. A survey of the representation of three-dimensional objects is given by Aggarwal [1981], while Herman [1982] and Tuy & Tuy [1984] concentrate on the representation of the three-dimensional objects on a two-dimensional screen.

The Spatial Map Images can be seen as a product of geometric modelling. Only one attribute is added to the geographic entity, visualized by the colour of the entity, as will be explained in section 6.4. Three types of geometric modelling techniques are distinguished [Bronsvoort, Jansen & Van Wijk, 1984, p.51].
Wireframe modelling: objects are represented by a wireframe, a collection of connected lines (see for instance Figure 2-14);
Surface modelling: objects are represented by surface elements. Surface types such as polygons, analytical surfaces (for instance parts of spheres or cylinders), and patches (curved surfaces) are used to describe the objects.
Solid modelling: objects are represented by volumes. Solid modelling is the only method which guarantees a complete and unambiguous description of objects [Kraak, 1987a].

The second type of geometric modelling, surface modelling is used in the program discussed in this chapter. The main and pragmatic reason is that the data collection for the spatial images, even when it is the collection of x-, y- and z-coordinates, is vector oriented: the manual digitizing of existing maps, surveying and photogrammetry. These vectors are combined into polygons (surfaces) to describe the geographic entities. An additional argument is that PHIGS can only handle surfaces. However, when the Spatial Map Images are used in a spatial information system, and not only in their function of test map as is done in this study, object modelling might be more appropriate in the future. This provides better opportunities for work with the attributes of geographic entity. When the data structure of these systems becomes less restrictive this will result in links with administrative databases [Dangermond, 1986].

6.4 The graphic standard: PHIGS

The program which displays the Spatial Map Images on a screen is written in FORTRAN using graPHIGS, IBM's version of PHIGS (Programmer's Hierarchical Interactive Graphical Standard) [ANSI, 1985]. PHIGS is a detailed description of graphics functions, error conditions, and Fortran, C and ADA language bindings. It is intended to provide a common programming base for graphics hardware and application program developers, and is used for the actual drawing and manipulation of the Spatial Map Images. PHIGS routines function like those of GKS (Graphical Kernel Standard), and have at present the status of an ISO working draft [Singleton, 1986].

It is used to guarantee hardware independent software, and was preferred to GKS since it has special facilities for three-dimensional applications. The graphical primitives used are defined in three-dimensions (i.e. in x- y- and z-coordinates). PHIGS consists of four main parts, the control centre, the data definition system, the data display centre, and the interaction handler [Plaehn, 1987, p.276]. The first maintains the state of the entire system and monitors access to the other subsystems. The second controls the construction, manipulation, editing, archiving, and retrieval of graphical objects called structures (known as segments in GKS). The third controls the access to graphic display devices such as screens and plotters. The fourth, the interaction handler, manages the interactive input processes and takes care of feedback to the data definition and display system.

The use of a graphic standard has some important advantages [Klok & Peters, 1987. p.64]. The program will be less hardware dependent, have a prolonged life span, and the application programmers can work more efficiently since they have to know only one standardized set of graphic concepts. Other positive features are the development of a set of concepts, the possibility to evaluate software that contains the standard, simplifying the writing of device drivers, and the possible exchange of meta-files. Meta-files contain information on the graphic image only, and can be used to draw the image directly.

A disadvantage of the use of graphical standards can be that facilities such as shading and hidden surface calculations have to be produced by the programmer himself, while commercial packages have these functions often as standard options. The fact that the programmer/user has to write the whole program himself is by some seen as another disadvantage. These standards should therefore be considered as guidelines, and not as the definitive answer to all graphics software development and exchange problems, since there will always be applications which are too specific for the use of the standard.

6.5 The procedure of Spatial Map Images production

The procedure for producing Spatial Map Images as proposed in this thesis is shown schematically in Figure 6-1. For each of the Spatial Map Images, of which the characteristics were discussed in section 2.6, five steps have to be followed. They are roughly the same for all map types. These steps include 1. data collection; 2. data processing; 3. pre-display of the Spatial Map Image; 4. manipulation of the map; 5. the final visualization. Steps 3, 4 and 5 are thought to be most essential for the production of Spatial Map Images. Steps 1 and 2 are necessary for any map, but the method and techniques used for their execution can be adapted depending on developments in methods and techniques available to the cartographer. An extensive description of the program can be found in Kraak [1987b], and Appendix I provides the structure of the program. The following subsections will deal with each step in more detail.

6.5.1 Data-collection

Under the heading Data-collection in Figure 6-1 several techniques for gathering the necessary coordinates for the maps are given. The choice of one of these techniques depends on the nature and scale of the Spatial Map Image to be produced. This is also the reason for making a distinction between the collection of the x- and y-coordinates and the z-coordinate.

The digital terrain model and the three-dimensional urban map have a more topographic nature, and here photogrammetric techniques are very suitable for collecting the z-coordinates from aerial photographs, but this technique can also be used to collect the x- and y- coordinates. Promising for the collection of the coordinates for the three-dimensional urban map is development of the terrestrial-photogrammetric technique of the CASSPAR system, a computer aided surveying technique using scanned panoramic registrations [Poelstra, 1988].

The z-coordinates in prism maps and three-dimensional point symbol maps are based on statistics. The x- and y-coordinates of these maps are most often collected by manual digitizing.

6.5.2 Data-processing

The collected data are structured into two sequential data files, one in which the x- and y-coordinates are structured into polygons, and one for the z-coordinates. This second file not only contains information on the map's third dimension, but also attribute information, i.e. thematic information which determines the colours of the geographic entities (polygons). The resulting files have the same structure for each of the Spatial Map Images to be produced. The program merges these file in preparation for step 3.

1. Data-collection for Spatial Map Images	
X- and Y-coordinates * digitizing, surveying, photogrammetry & databases Z-coordinate * surveying, photogrammetry, databases & statistics	digital terrain models prism maps 3D point symbol maps 3D urban maps

2. Data-processing
data structuring into simple sequential files: * file 1: X- and Y-data; file 2: Z-data * result is similar for *all* Spatial Map Images

3. Pre-display of the Spatial Map Image
display wireframe of the Spatial Map Image on screen * including axis system and legend

4. Manipulation of the map
positioning the Spatial Map Image according to the purpose of the map (its message and target group) * rotate around x-, y- *and* z-axes * scale along z-axis * zoom-in and zoom-out

5. Final visualization
presenting the Spatial Map Image * wireframe display * hidden line operations * hidden surface and shading operations

Figure 6-1. The structure of the program to produce Spatial Map Images.

6.5.3 Pre-display of the map

The steps discussed in this subsection, and the next two, are seen as being explicitly necessary for the production of Spatial Map Images. In the pre-display phase the wireframe model of the Spatial Map Image is displayed on a screen. This display includes an axis system for orientation and the map legend. During this step the cartographer has an option to choose the projection type i.e. parallel or perspective. When this last option is chosen it is possible to display the map in stereo on the screen. This results in two images side by side on the screen seen from slightly different viewing points. The stereoscope to view these maps is shown in Figure 7-1. In Appendix II and III examples of stereo and non-stereo displays of maps are given. This step prepares the Spatial Map Image for the manipulation phase.

6.5.4 Manipulation of the map

The manipulation of the map takes place using a wireframe model of the map. Using a mini-computer, as was done during this research, a real time manipulation of the map is only possible when in wireframe mode. The manipulation is necessary since in a three-dimensional image presented on a flat screen there will always be dead ground, that is elements which disappear behind other elements. This means loss of information. This may sound contradictory since the three-dimensional appearance of the image is used to add information. To keep this loss to a minimum an ideal image position has to be found, keeping the purpose of the 3D-map in mind.

To find this ideal position it is possible to rotate the map around each of the x-, y- and z-axes separately. In addition, it is possible to zoom-in or zoom-out. An important feature is the possibility to scale the map along the z-axis to find the proper exaggeration, as discussed in section 4.6. Another feature of the program is that each separate legend symbol will follow the movements of the map when this is rotated, scaled or zoomed. This in order to have an identical orientation of the legend symbols relative to the map symbols (see colour illustration between pages 20-21, 52-53, 84-85, and 126-127.

A wireframe model of the map will offer most future map users a confused image when he or she wants to start his/her map reading task, and this makes the last step in the production process of the Spatial Map Images necessary.

6.5.5 Final visualization of the Spatial Map Image

A more sophisticated visualization method has to be found for presenting a Spatial Map Image that can be understood by the user. Hidden-lines or hidden-surface and shading algorithms can be used for this. The last method will produce especially attractive 3D-maps as can be seen in the colour illustration between pages 20-21, 52-53, 84-85, and 126-127.

CHAPTER 7. MAP USER RESEARCH

7.1 Introduction

This chapter describes the computer-assisted map user test conducted within the framework of this study, in which map users were confronted with Spatial Map Images. These maps were produced using the program discussed in Chapter 6. The purposes of the tests were threefold: first, to see how the geographical component functions in a Spatial Map Image; second, to see how the perceptual aspects of the graphical variables interact with the psychological depth cues in a three-dimensional map; and third, to measure the effects of the use of stereoscopic images. The interpretation and discussion of the results take place in the next chapters.

The following sub-sections concentrate on the general aspects of computer-assisted map user tests (7.2), the subjects (7.3), the test environment (7.4), the test map characteristics (7.5), the questions asked (7.6), and the test procedure itself (7.7).

7.2 Computer-assisted map user research

Developments in cartography and the creation of Geographical Information Systems confront the map user more and more with the computer [Burrough, 1987, p.6]. Not only are the maps in which the user is interested displayed on screens (i.e. temporary maps), but very often it is the user who is now also responsible for the design and display or production of the map. Some believe that because only one person is involved in the complete cartographic communication process, this might be the opportunity for I and I' in the communication-model (Figure 3-1) to overlap almost fully. Apart from factors mentioned in section 3.2, this seems less likely since most users working with Geographical Information Systems tend to be experts in their own fields, and not in cartography. However the introduction of cartographic expert systems as an integral part of Geographical Information Systems [Muller, Johnson & Vanzella, 1986] may change the extent of the overlap.

Cartographers are not yet using the full potential of the computer to test and respond to the behaviour of the map user. The computer can be used to assist the cartographer with map user research to improve the cartographic product. This is necessary since the map user plays an important role in the process of cartographic communication. The increase in the use of temporary maps, and the suitability of this type of display for presenting the Spatial Map Image (see section 2.4.1), the map user test, thought to be necessary to find out more about the Spatial Map Images, is done with assistance of the computer.

Map user research is done to evaluate the cartographic product using the reactions and responses of users, and when necessary, the original map may be enhanced or changed. The researcher must try to isolate the variable that is being studied, while keeping all other map elements constant. This proves to be difficult since maps present both relational and contextual information. Moreover symbols should not be isolated from real situations, i.e. the map as a whole. Eastman [1981, p.15] has shown that even the simplest, more or less realistic, test map has the potential for providing conflicting cues to the test subjects.

In practice this means that the map user is presented with a specific map reading task in order to retrieve information on certain map properties. Olson [1976, p.152] distinguishes three hierarchical levels of map reading tasks: the first involves comparisons of the characteristics of individual symbols, level two is that of recognizing properties of symbol groups within the map as a whole, while on level three the map is used as a decision making device through integration of symbols with other information. Independent from the map reading task, it is important that the tests are performed in the same environment as that in which the final map is likely to function, e.g. maps produced for use on a display should be tested on a display.

When the computer is used the maps and questions should be placed in a real-time environment, and the necessary stimuli needed for the test should be produced by computer [Dobson, 1985, p.41]. While the maps and questions are shown on a display, the subjects can respond using the keyboard or other devices connected to the computer. During the test, subjects may be frightened by the computerized approach and react accordingly. Extra attention must therefore be given to the test procedure since, for example, it should not be possible for a wrong keystroke to disrupt the test procedure and influence the results. The software which runs the test should have an excellent user interface to ensure the test runs without interruption, the subject is informed properly on the next action or task, and the responses are registered. The type, and quality of the hardware used also plays a significant role. The size and resolution of the screen, and its colour capacity can influence the subjects' comprehension of the maps displayed, while the type of device used to interact with the program, such as the keyboard, a cursor, or a mouse can ease the subjects responses. Figure 7-1 demonstrates the equipment used in the computer-assisted map user test discussed in this chapter.

There are many other factors influencing map user tests. These include the kind of instructions given to the subjects before and during the test [Shortridge & Wells, 1980]; the way the questions are posed; the character of the test maps (the type and complexity); and the subjects involved (the level of education, familiarization with maps, experience with computers, and their expectations). Since it is not possible to control all these factors to the level that would be desired, they must be remembered when analysing the test results.

7.3 The test subjects

It is not easy to find subjects who can be regarded as true representatives of the potential users of Spatial Map Images. The probable users are planners, managers, and researchers working with spatial information. It will be likely that these are mainly people with a post-secondary education. Together with the environment where the test had to be executed (a university laboratory), this led to the obvious, and pragmatic choice of students.

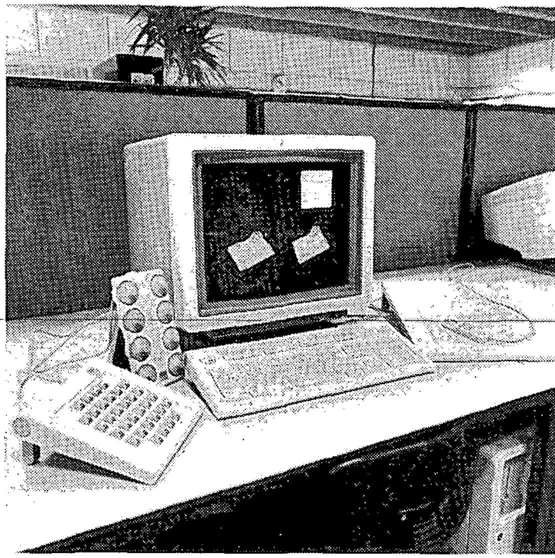


Figure 7-1. Hardware used in the computer-assisted map user test.

The group of fifty students was a mixture of geodesy and cartography students who all had a basic background in cartography, and who had the same level of knowledge of the types of maps to be tested. The group of subjects can therefore be regarded as being homogeneous, and because their education as future users of the maps to be tested. In an academic environment the use of a uniform group of subjects in a map user test is no problem, but this will be different for government and commercial cartographic agencies whose work has a much wider use [Petchenik, 1983, p.48]. The effects of individual differences within a group of subjects, and their experience, is discussed by Griffin [1985] and Eastman & Castner [1983]. Here, important factors to consider are the subjects' specific map reading skills, and more general their intelligence and exposure to visual material.

7.4 The test environment

Part of a terminal room was used as the test site. The site was isolated from the rest of the room by temporary walls to allow the subjects to work as quietly as possible. Figure 7-2a presents a plan of the site. Behind the temporary walls the graphic screen was placed on a platform to make it possible for the subjects to observe the Spatial Map Images comfortably at eye level, especially necessary when viewing them by stereoscope. The tablet with the locator was situated at the right side of the screen, and was used to move the cross-hair over the screen to answer the questions. The stereoscope was located at the left side of the screen. It was to be moved in front of the screen when test instructions indicated to do so. Figure 7-2b shows the use of the equipment.

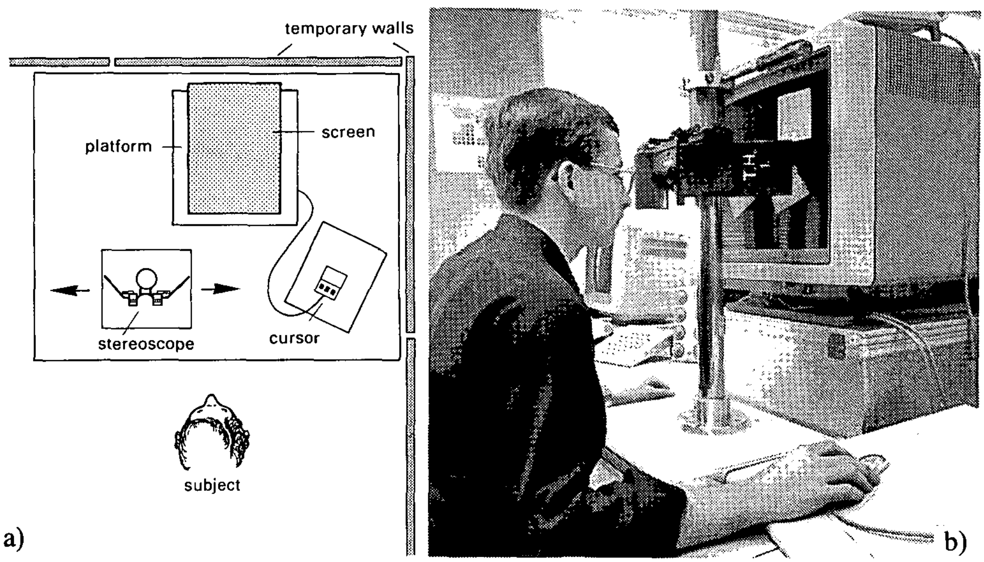


Figure 7-2. The test site: a) plan of the test site and b) the use of the test equipment.

The software necessary to run the test program was written in FORTRAN using graPHIGS. The descriptive data for the Spatial Map Images were retrieved from files produced by the program discussed in the previous chapter. The corresponding questions were read from a separate file. The test program registered the answers and the response times. They are presented in Appendix IV.

7.5 The test map characteristics

To achieve the best possible test results the design of the test maps needs considerable attention. This is important since performance will vary within a selected group of subjects; and even the same person will react differently to the same type of question during a test session.

The symbols under investigation in the test are always perceived as a part of the total map image, and therefore the test is performed on the map as a whole. The map contents was kept to a level of information density and complexity relative to the expected answers, and therefore it can be said that the contents of the map was in agreement with the subjects' map reading tasks. Olson [1976] defined map reading tasks as of a low level when they involved only the comparison of symbols. A task is classified as of a high level when relationships between symbols have to be found. The map reading tasks in this test were at low, medium and high level.

For most Spatial Map Images used in the test, real world data are used as map bases. Maps of geographic areas such as the Netherlands, Britain, Australia, New Mexico, and San Francisco can be found in Appendix II and III. Fictional areas were used only for the urban three-dimensional map. For the thematic content of the maps the share of fictional data used is significantly larger. In the legend of the Spatial Map Images three symbols were shown. When a quantitative theme was displayed the minimum, mean, and maximum values were shown. When a qualitative theme was mapped the legend explained the meaning of the symbols used. On the screen the size of the Spatial Map Image in mono is almost twice that of one of the stereo pairs, as can be seen in Figures 7-3 and 7-4.

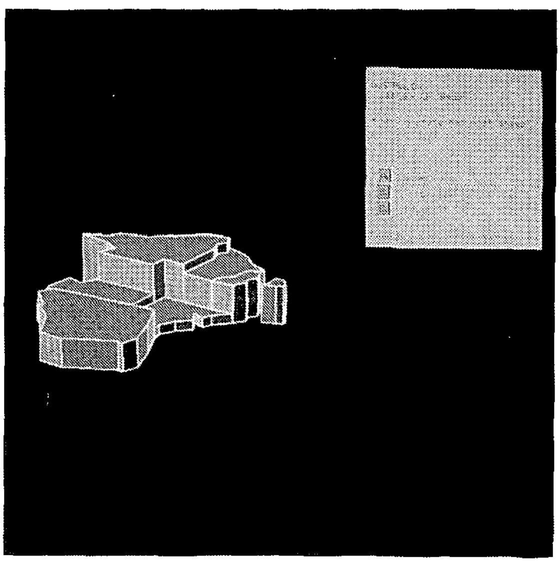


Figure 7-3. An example of a mono Spatial Map Image of Australia, portraying the number of sheep in each state, and also displaying a sample question.

The character of the test maps partly determines the type of possible questions to be asked. The absolute or relative x-, y-, and z-coordinates can be considered as quantitative information. Only in the prism map and the three-dimensional point symbol map can the z-coordinate be used to display quantitative information, but then a graphical variable such as colour of texture has to be used to depict the different qualities. In all types of Spatial Map Images studied here qualitative or ordered information can include the geographical elements' attributes, such as colour. This has been done frequently in the test maps. Appendix III presents all Spatial Map Images used, and the questions asked in the test. The illustrations between pages 20-21, 52-53, 84-85, and 126-127 present some examples in colour. Figures 7-5 and 7-6 summarize and combine the character of maps and questions.

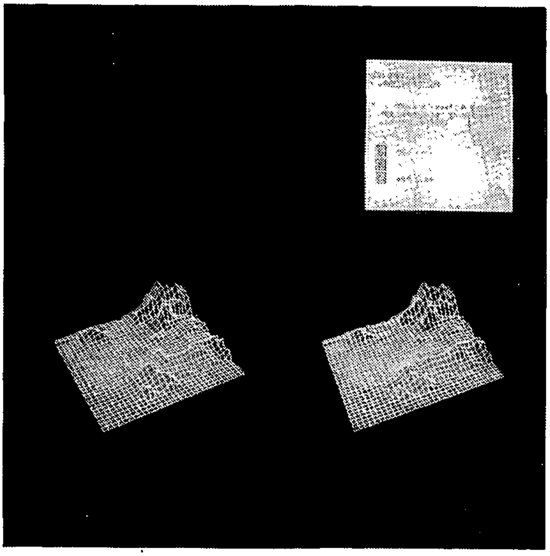


Figure 7-4. An example of a stereo Spatial Map Image of San Francisco, displaying the precipitation in the city.

7.6 The questions

The level and structure of the questions asked is related to the types of issues to be examined. Questions concerned with the geographical component are of a different nature from those which are related to the graphical variables. No special questions are necessary to test the effects of the stereoscope. Rather there are two situations, one in which a mono Spatial Map Image appears, and the other a stereo image. Figure 7-3 and Figure 7-4 depict these situations respectively.

SUMMARY OF QUESTIONS ASKED

Geographical component
questions corresponding with the level of reading: elementary, intermediate, and overall (see section 5.2).
example, referring to Figure 7-3: * which state has most sheep ? * how much less sheep does the island have compared with the state with most sheep ? * where can the states with the fewest sheep be found ?

Graphical variables in relation to the depth cues used
questions of the overall level of reading:
example, referring to Figure 7-4: * is there a relation between the precipitation pattern and the relief ?

Mono - stereo
Similar questions for the mono and stereo situations, using the Spatial Map Images related to the geographical component and the graphical variables:
example, refer to Figur 7-3 and 7-4, as well as to the questions above. * 'no special questions asked - see text'

Figure 7-5. The nature and examples of the questions asked.

However, the content of the questions depends on the type of Spatial Map Image, e.g. the digital terrain model, the three-dimensional urban map, the prism map, and the three-dimensional point symbol map. The character of these Spatial Map Images determines the potential of the map, as discussed in section 7.5, and therefore the possible questions.

The scheme in Figure 7-5 summarizes the type of questions asked during the test. These questions can be regarded as representative of all questions asked. All questions can be found in Appendix III, together with the Spatial Map Images to which the questions belong. However, these illustrations are in black and white due to constraints upon colour reproduction. Because of the importance of colour in a computer-assisted cartographic environment, and to obtain a correct impression of the type of Spatial Map Images used in the test, a sample set of the colour maps can be found throughout this work, between pages 20-21, 52-53, 84-85, and 126-127.

Figure 7-6 presents the relationships between the Spatial Map Images and the nature of the questions asked. Each row represents a single question, and the numbers in the first column are the question numbers which correspond to the numbers in Appendices II, III and IV. The other columns refer to the image (IMAGE: M=mono; S=stereo); the type of Spatial Map Image (MAPTYPE: 1=digital terrain model; 2=prism map; 3=three-dimensional point symbol map; 4=three-dimensional urban map); the geographical component of the theme mapped (GEO: G=GEO3; C=GEO3+C); part of the map contents to which the question refers (CONTS: G=GEO3; C=GEO3+C; B=GEO3 & GEO3+C); the graphical variable used to represent the map contents (GRAVAR: S=Size; V=Value; T=Texture; C=Colour; O=Orientation); and the reading level of the question asked (LEVEL: 1=elementary; 2=intermediate; 3=overall).

The first block in Figure 7-6 refers to the introduction test, which is discussed in the next section. The results are discussed in section 8.2. The next four blocks in the figure represent questions which deal with the geographical component, as discussed in section 5.2. The answers to these questions can be found in Appendix IV, and they are discussed in section 8.3. The questions in the last five blocks in Figure 7-6 are used to describe the relationships between the use of the graphical variables and the psychological depth cues, as discussed in section 5.3. The results can be found in Appendix IV and are discussed in section 8.4. Questions selected from all blocks were used to describe the relationships between mono and stereo Spatial Map Images. The results are described in section 8.5.

In all situations the questions were displayed in the upper right corner of the screen, as can be seen in Figure 7-3. The questions asked were of the multiple-choice type. However, the use of open-ended questions would give the subjects the opportunity to answer more spontaneously, but they are ruled out because of format constraints and the fact that a comparison of open-ended, individual answers is very difficult. The subject had to use the cursor and tablet to move the cross-hair on the screen to the correct box (A, B, C or D) according to the subject's opinion. This method of answering avoids errors such as typing characters wrongly, or pressing the Enter key before the subject has actually answered the question. A disadvantage of this method is that it restricts the choice to a maximum of four possible answers.

For most Spatial Map Images there was more than one question to be answered, as was explained in the instructions at the beginning of the test. After the subject chose an answer box the latter would change colour from orange to red to indicate which answer was actually chosen. The subject was unable to change the first choice. This was due to the method of registering the answers.

In addition to the answer chosen (A, B, C or D), the time taken to answer the question was registered. This registration of response time was the reason the subject was not allowed to correct the answer. It would influence the registration, and make it almost uncontrollable.

7.7 The test procedure

The test discussed here is split into two sections. The first is an introductory test and the second is the main test. Since computerized map user testing is new, especially to most subjects to whom the test was given, an introductory test was thought to be necessary to let the subjects accustom themselves to the test environment. The purpose of this introduction was also to test the presence stereoscopic acuity of the subject and to provide a link between the Spatial Map Images and two-dimensional maps.

The only oral instructions given to the subjects before the actual test started were related to their first actions, i.e. how to use the locator to move to the first screen with instructions, how to use the stereoscope, and modify its set-up to view a proper stereo image.

	IMAGE		MAPTYPE				GEO		CONTS			GRAVAR					LEVEL		
QN	M	S	1	2	3	4	G	C	G	C	B	S	V	T	C	O	1	2	3
Aa	*														*				
Ab	*														*				
Ba	*												*						
Bb	*												*						
Ca	*														*				
Cb	*														*				
D	*											*	*						
E		*																	
F		*																	
G		*																	

QN: Question number (this number refers to the questions, illustrations and answers in the Appendices II, III & IV)
IMAGE: M=mono; S=stereo
MAPTYPE: 1=dtm; 2=prism; 3=point; 4=urban
GEO: G=GEO3; C=GEO3+C
CONTS: Question refers to G=GEO3; C=GEO3+C; B=GEO3 & GEO3+C
GRAVAR: Graphical Variable S=Size; V=Value; T=Texture; C=Colour; O=Orientation
LEVEL: Reading level 1=elementary; 2=intermediate; 3=overall

Figure 7-6a. The nature of the questions: the introductory test.

	IMAGE		MAPTYPE				GEO		CONTS			GRAVAR					LEVEL		
QN	M	S	1	2	3	4	G	C	G	C	B	S	V	T	C	O	1	2	3
prism maps																			
1a	*			*			*		*								*		
1b	*			*			*		*									*	
1c	*			*			*		*										*
2a	*			*				*		*			*				*		
2b	*			*				*		*			*					*	
2c	*			*				*		*			*						*
3a		*		*			*		*								*		
3b		*		*			*		*									*	
3c		*		*			*		*										*
4a		*		*				*		*			*				*		
4b		*		*				*		*			*					*	
4c		*		*				*		*			*						*
digital terrain models																			
5a	*		*				*		*								*		
5b	*		*				*		*									*	
5c	*		*				*		*										*
6a	*		*					*		*					*		*		
6b	*		*					*		*					*			*	
6c	*		*					*		*					*				*
7a		*	*					*			*				*		*		
7b		*	*					*		*					*			*	
7c		*	*					*		*					*				*
8a		*	*					*			*		*				*		
8b		*	*					*			*		*					*	
8c		*	*					*			*		*						*
9a		*	*				*			*							*		
9b		*	*				*			*								*	
9c		*	*				*			*									*
three-dimensional point symbol maps																			
10a	*				*			*		*		*			*		*		
10b	*				*			*		*		*			*			*	
10c	*				*			*		*		*			*				*
11a	*				*		*		*								*		
11b	*				*		*		*									*	
11c	*				*		*		*										*
12a		*			*			*		*					*		*		
12b		*			*			*		*					*			*	
12c		*			*			*		*					*				*
13a		*			*		*		*								*		
13b		*			*		*		*									*	
13c		*			*		*		*										*
three-dimensional urban maps																			
14a	*					*		*	*								*		
14b	*					*		*		*					*			*	
14c	*					*		*		*					*				*
15a	*					*	*		*								*		
15b	*					*	*		*									*	
15c	*					*	*		*										*
16a		*				*	*		*								*		
16b		*				*	*		*									*	
16c		*				*	*		*										*
17a		*				*		*		*					*		*		
17b		*				*		*		*					*			*	
17c		*				*		*		*					*				*

Figure 7-6b. The nature of the questions: the geographical component and the Spatial Map Images.

	IMAGE		MAPTYPE				GEO		CONTS			GRAVAR					LEVEL			DC
QN	M	S	1	2	3	4	G	C	G	C	B	S	V	T	C	O	1	2	3	
Size																				
18	*				*		*		*			*					*			+R
19	*				*		*		*			*					*			+R
20	*				*		*		*			*					*			-S
21	*				*		*		*			*							*	-T
22	*				*		*		*			*							*	+C
23	*				*		*		*			*							*	-C
24	*				*		*		*			*					*			-R
25		*			*		*		*			*					*			+R
26		*			*		*		*			*					*			+R
Value																				
27	*			*				*		*			*						*	-S
28	*			*				*			*		*						*	-T
29	*			*				*			*		*						*	+S
30	*			*				*			*		*						*	-P
31		*		*				*			*		*						*	+S
32		*		*				*			*		*						*	-S
Texture																				
33	*			*				*			*			*					*	-C
34	*			*				*			*			*					*	+C
35	*			*				*		*				*					*	-R
36	*			*				*		*				*					*	+T
37		*		*				*		*				*					*	+T
Colour																				
38	*				*			*		*					*				*	+R
39	*				*			*		*					*				*	+R
40	*				*			*		*					*				*	-R
41	*					*		*		*					*				*	-T
42	*					*		*		*					*				*	-S
43		*			*			*		*					*				*	+C
Orientation																				
44	*			*				*			*					*			*	-R
45	*			*				*			*					*			*	+S
46		*	*					*		*						*			*	+R

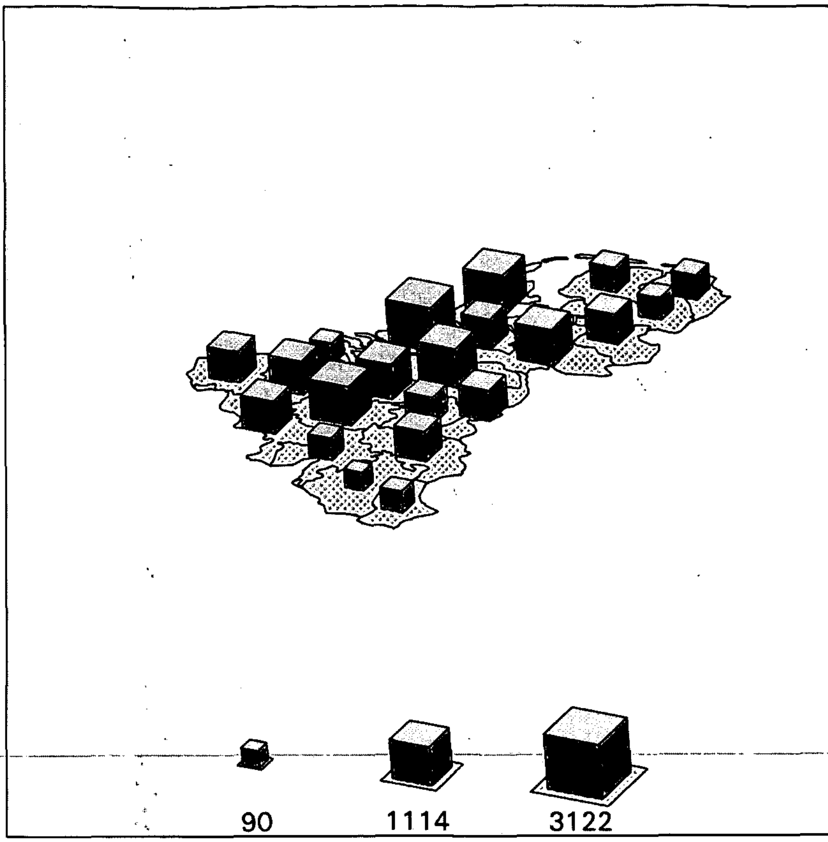
QN: Question number (this number refers to questions, illustrations and answers in the Appendices II, III & IV)
IMAGE: M=mono; S=stereo
MAPTYPE: 1=dtm; 2=prism; 3=point; 4=urban
GEO: G=GEO3; C=GEO3+C
CONTS: Question refers to G=GEO3; C=GEO3+C; B=GEO3 & GEO3+C
GRAVAR: Graphical Variable S=Size; V=Value; T=Texture; C=Colour; O=Orientation
LEVEL: Reading level 1=elementary; 2=intermediate; 3=overall
DC: Depth cue [+ = applied / - = omitted] R= retinal image size; S= shading; T= texture; P= perspective; C= colour

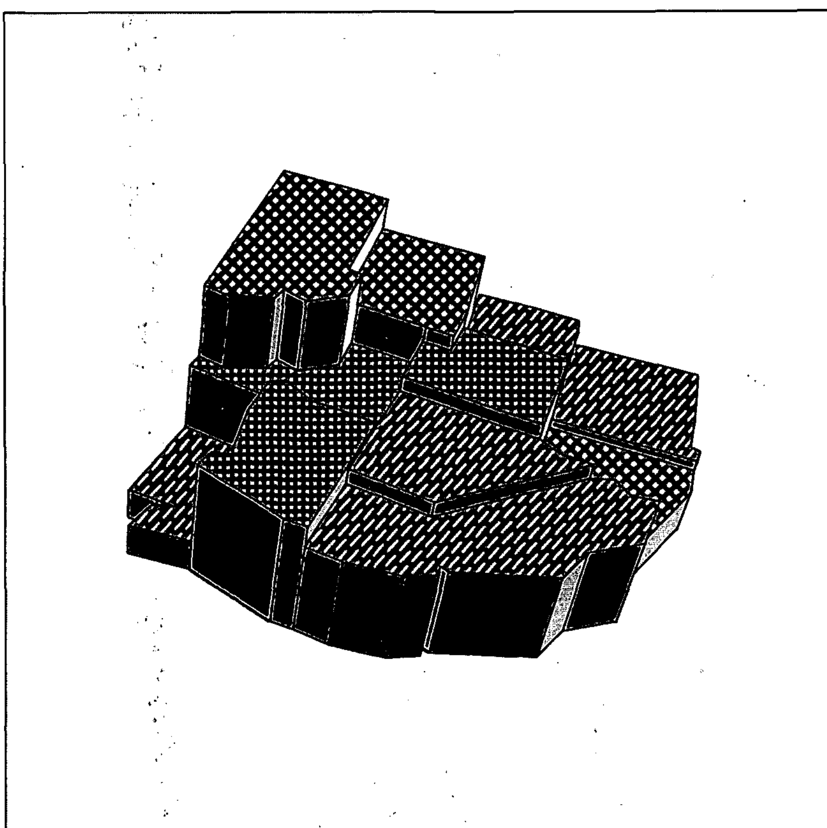
Figure 7-6c. The nature of the questions: the graphical variables.

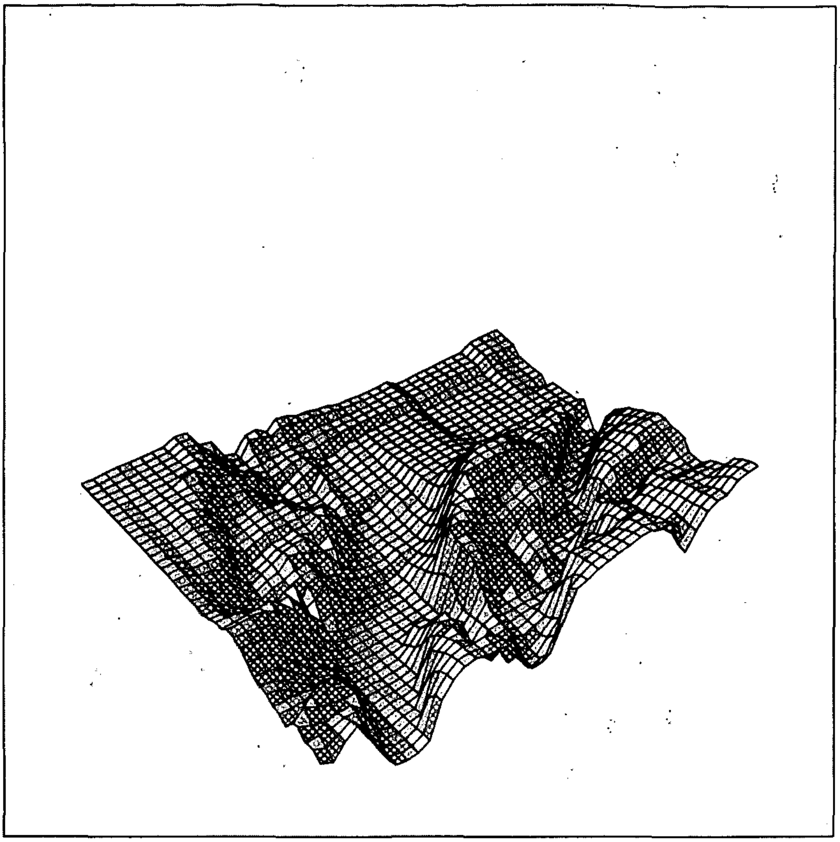
The first four screens provide information on what the subjects could expect, their tasks, and how they were expected to respond to questions asked. The full introductory test can be found in Appendix II. After these instructions a first map appeared. A simple question accompanied the map. The purpose was to demonstrate how maps and questions were presented, and how these had to be answered using the locator. After the question was answered, a new question belonging to the same map appeared to demonstrate the possibility of having more questions with one map. The answers to these two questions were registered and processed, but not used in the interpretation phase since they had only a procedural function.

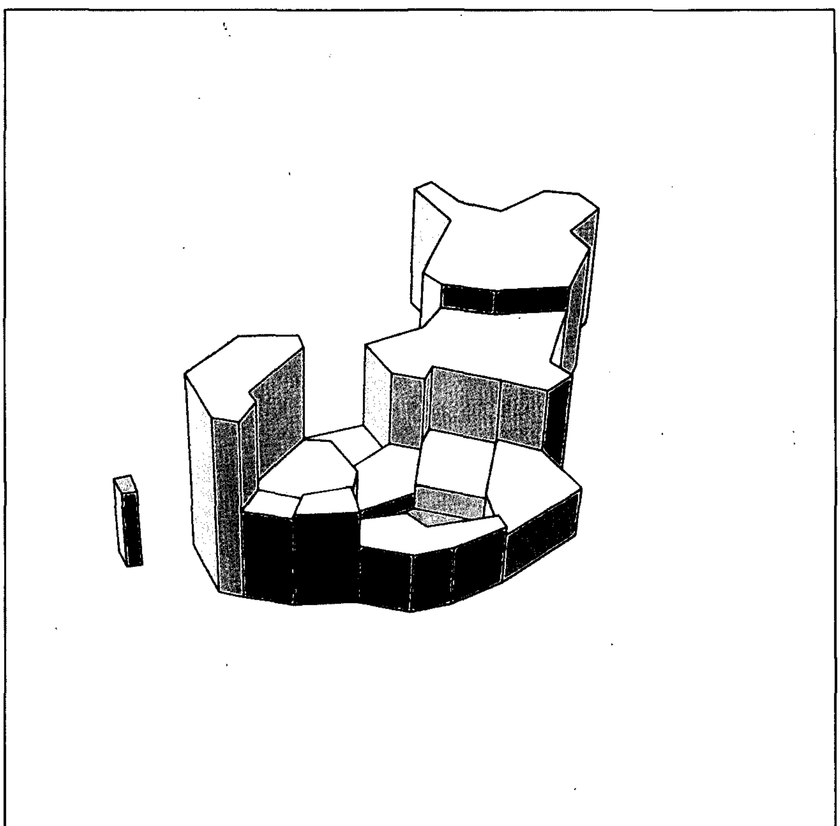
The following three maps were two-dimensional maps, and their purpose was to provide information on Maps-To-See and Maps-To-Read as well as to provide information for a link between two-dimensional maps and the Spatial Map Images. The last three questions in the introduction were used to test the presence of stereoscopic acuity of the subjects. Before the questions appeared instructions were given to install the stereoscope. Simple geometric figures such as a cube and squares were used for the stereo test (see Appendix II). The subjects were allowed to make one mistake without being failed. If they failed by making more then one mistake they were not allowed to continue because of their lack of stereoscopic vision. This actually occurred with three subjects.

However, for most subjects a screen appeared with a notice that the main test was to begin, implying that they successfully completed the stereo vision test. The main test consisted of two parts, of which the maps and questions can be found in Appendix III. Part one contains questions on mono maps, and part two on stereo maps. This division in two sets was made to avoid a continuous positioning of the stereoscope in front of the screen. At the end of the mono set an instruction appeared with a message to install the stereoscope. The first stereo question was used as a practice question to let the subject accommodate to the stereoscopic environment. At the end of the second map set the subjects were thanked for their cooperation.


90
1114
3122







CHAPTER 8. DISCUSSION OF THE TEST RESULTS

8.1 Introduction

This chapter presents the test results of the computer-assisted map user test discussed in the previous chapter. The results, as registered by the test program, and after a first statistical processing phase, are given in Appendix IV. Section 8.2 provides an overview of the results of the introductory test. The next three sections deal with the results of the main test. These sections present answers to assumptions made, and questions raised in Chapter 5. Section 8.3 deals with the geographical component, section 8.4 discusses the relation between the graphical variables and the psychological depth cues, and section 8.5 looks at the effects of the use of the stereoscope.

Each of these sections starts with descriptive statistics, centred around a diagram that presents the test results. This is followed by some analytical statistics. Tests of significance have been made for particular groups of questions, referring to the same problem, to be able to judge the value of the test results [Williams,1984 and Clark & Hosking, 1986]. These tests of significance do not include all questions from the test. The conclusions can be found in the next chapter.

To compare the mean response times of, for example the questions related to the mono and stereo Spatial Map Images, the two-sample, two-tailed, t-test is being applied. For this test of significance the samples are considered to be drawn from normal or near normal populations. The null-hypothesis is that there is essentially no difference between the two samples. The null-hypothesis will be rejected if the statistic t does not fit the 95% confidence interval (see 't-table' in Figure IV-2 in Appendix IV - the location of t in the table depends on the number of degrees of freedom). If the null-hypothesis is rejected, the two samples differ in mean more than can be reasonably attributed to chance. If the null-hypothesis is not rejected, it is regarded as possible, but not necessarily correct. In the tables in figures 8-4, 8-6 and 8-8 the mean and standard deviation of both samples of the test, as well as the degrees of freedom, the statistic t and the result can be found.

The Mann-Whitney two-tailed U test is used to compare the quality of the answers given. For this test the samples under investigation do not need to be drawn from a normal population. It is a very general test in that it considers differences in mean, variance and shape of distributions. It results in a statistic U. U is used to calculate the statistic Z when both samples contain more then 20 items, as is the case in this study. The null-hypothesis, as with the t-test, is that there is no difference between the two samples. The null-hypothesis will be rejected if the statistic Z does not fit the

95% confidence interval (see 'Z-table' in Figure IV-3 in Appendix IV - from the table it can be derived that the interval lies between + or - 1.96). If the null-hypothesis is rejected there is a significant difference between the two samples. If the null-hypothesis is not rejected, it is regarded as possible, but not necessarily correct. In the tables in the Figures 8-4, 8-6 and 8-8 the number of correct answers to both samples, the statistics U and Z, as well as the result can be found.

8.2 The introductory test

The purpose of the introductory test was, in addition to letting the subjects accustom themselves to the test environment, to link Spatial Map Images in the main test to two-dimensional maps, and to test the present stereoscopic acuity of the subjects. The questions and illustrations of this test can be found in Appendix II, and the character of the questions asked is shown in Figure 7-6a.

Figure 8-1 describes the results in two diagrams. The upper diagram presents the quality of the answers, and the lower diagram shows the response times and standard deviations of the questions.

Question A was used to demonstrate the method of questioning. The relatively high response time to question Ba is probably due to the structure of the question. In this question the location indicators relative to the position on the screen, such as upper right, centre, and left, were used for the first time.

The map to question Bb is constructed as a Map-To-See (see section 5.2), and question Bb is of the overall reading level which makes the response time to this question of importance in comparing the character of the geographical components in the next section (for instance GEO2 versus GEO3). The questions Cb and D are also of the overall reading level, but the maps are, according to the definition, not Maps-To-See. However, the response time is only slightly larger than that of question Bb, although the standard deviation is higher. A Map-To-See should be understood, independent of the type of questions asked, in a single moment of perception, which is difficult to define. The response times in this test include also the reading and understanding of the map reading task, and the response action itself. These parts of the response time are certainly not included in a 'moment of perception'. This makes it difficult to quantify the 'moment of perception', especially since the reading and understanding of the map reading task, which varies in complexity was not separated from the actual answering during response registration. The last three questions in both diagrams (E, F & G) refer to the stereo test. Question E has an extreme high response time (81 seconds) because the subjects had to install the stereoscope to their personal needs, especially the eye-base, to be able to answer the question. Three of 48 subjects failed the stereo test.

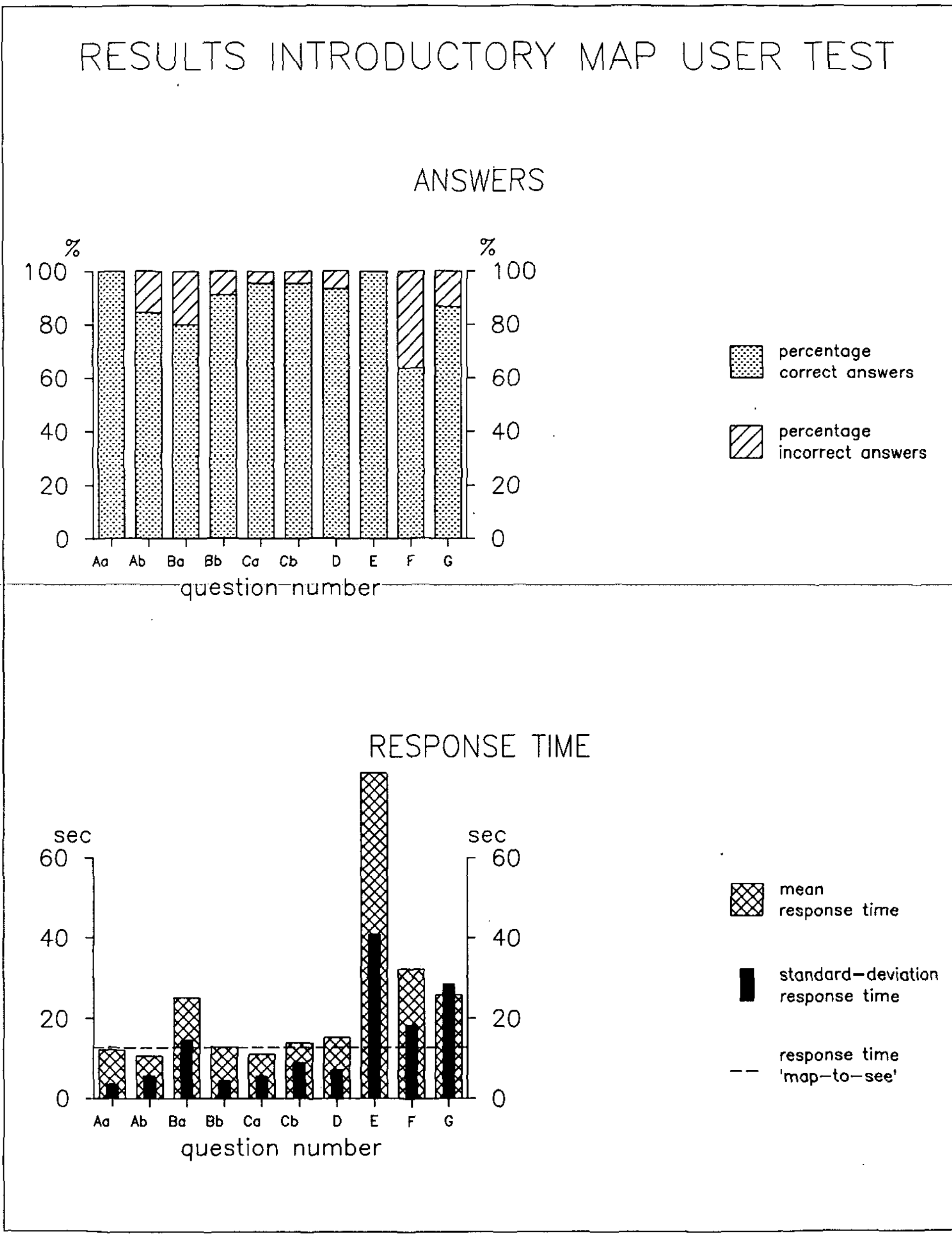


Figure 8-1. The results of the introductory test. The numbers on the x-axis of the diagrams refer to the questions and illustrations in Appendix II. For the numerical information on this test see Appendix IV, Figure IV-1a.

8.3 Spatial Map Images and the geographical component

Part of the computer-assisted map user test was used to characterize the geographical component in a Spatial Map Image. The purpose of this characterization is to see in which occurrence (GEO3 or GEO3+C) the Spatial Map Image equals a Map-To-See. The importance of this last map type for the temporary cartographic mediums was explained in section 5.2.

One of the reasons the registration of response time was done during the test, was to be able to compare the different approaches to the geographical component (GEO2, GEO2+C, GEO3 and GEO3+C; see Figure 5-3), and to see which of these can be described as a Map-To-See. This Map-To-See was defined in section 5.2 as a graphic construction which should provide answers to any question, regardless of its complexity, in a single moment of perception. However, not only the response time was registered; the quality of the answer was also noted since a Spatial Map Image with short response times to all questions asked, but with wrong answers, is of no value.

The complexity of the map reading task given to the subjects, i.e the questions, is expressed in the reading level of the question (see Figure 5-4). If an answer to the highest reading level can be given in a single moment of perception the map is said to be a Map-To-See. In the previous section it appeared difficult to quantify a 'moment of perception'. Figure 7-6 characterizes the reading level of each single question asked.

In the test the questions 1 to 17 were used to find out more about the geographical component. For each of the four types of Spatial Map Images under investigation a group of questions was formulated. The results are shown in the diagrams in Figure 8-2. The upper diagram shows the quality of the answers i.e. the percentage correct/incorrect, and the lower diagram shows the response times and their standard deviations.

Figure 7-6b describes the character of each question asked, and Figure IV-1b in Appendix IV provides the numerical information on the results. Each question number consists of three questions, one for each reading level (for instance 1a refers to the elementary, 1b to the intermediate and 1c to the overall reading level).

From the diagrams in Figure 8-2 it can be seen that, except for the digital terrain models, the quality of the answers for the four types of Spatial Map Images is about the same. Here question 5 disturbs the general pattern. For the response time a similar pattern can be seen. In each block of questions in Figure 8-2 the first and third question refer to GEO3, and the second and fourth question to GEO3+C. The Spatial Map Images presented with the first and third questions in each block are in mono, and the second and fourth in stereo. The effects of mono and stereo are discussed in section 8.5.

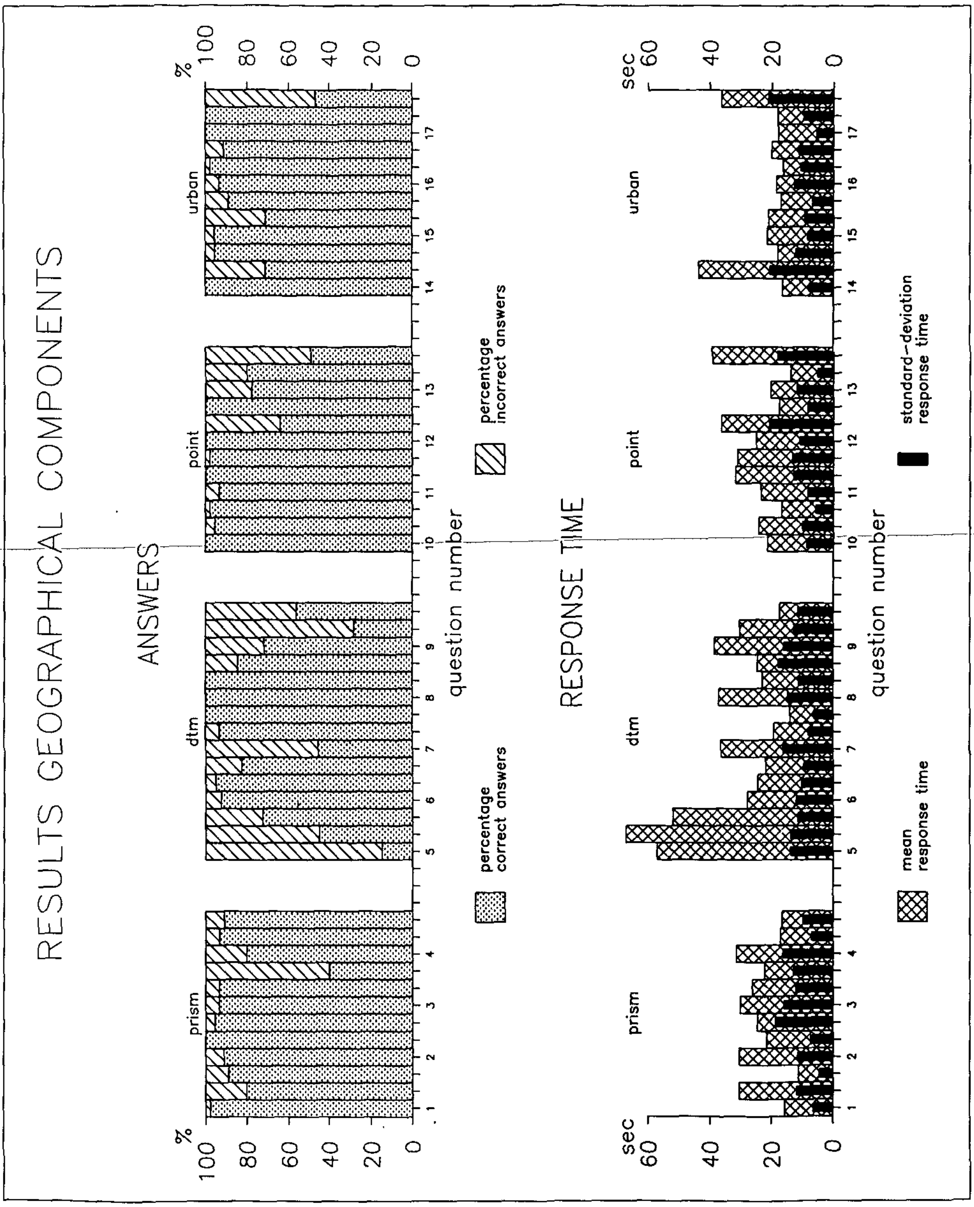


Figure 8-2. Results of the questions related to the geographical component. Refer to Figure 7-6 & Appendices III & IV.

Figure 8-3 provides information on the reading levels, independent of the type of geographical component, or Spatial Map Image. In the diagram it can be seen that the response times decrease when the reading level increases. The quality of the answers decreases with an increase in the reading level.

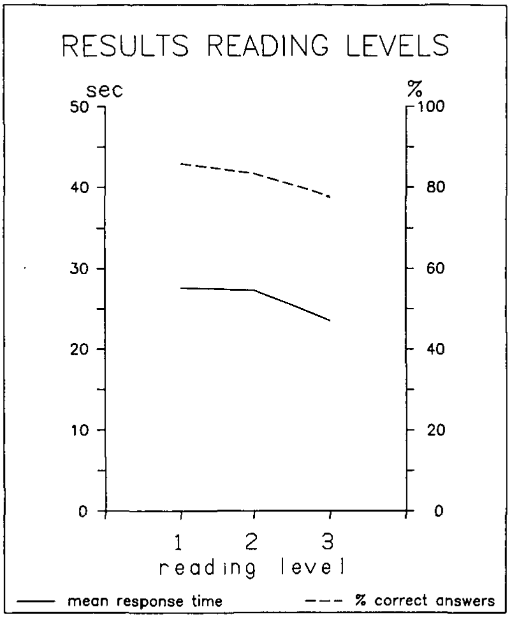


Figure 8-3. Reading levels & response time (the solid line), and reading levels & percentage correct answers (the dashed line).

From the diagrams it is difficult to judge if there are significant differences between GEO3 and GEO3+C. Therefore four tests of significance have been conducted. Figure 8-4 provides the results of these tests in tabular form, and Figure VI-4a provides the numbers of the questions which were used in the tests of significance.

Set 1 tests GEO3 (A) versus GEO3+C (B). Set 2 looks at the differences between GEO3 (A) and GEO3+C (B) for Spatial Map Images with a topographic character, the digital terrain models and the three-dimensional urban maps. Set 3 tests the same differences for Spatial Map Images with a thematic character, the prism maps and the three-dimensional point symbol maps. In Set 4 different type of questions are compared. A question concerning the 'C' from GEO3+C (Set 4A) is tested versus a question concerning the whole map (Set 4B). Set 5 compares a two-dimensional map from the introductory test (Set 5A) with a three dimensional prism map (Set 5B).

From Figure 8-4 it can be seen that for all four sets there is a significant difference in response time between the samples A and B of each set. For Sets 1, 2, and 3 GEO3+C has a shorter response time then GEO3. Here a critical remark is necessary. Although the question dealt with the overall reading level, it was concerned only with 'C' in GEO3+C (e.g. the choropleth information on a prism map as in Figure III-2 of Appendix III). It seems that because of the map reading task, the subjects isolated the choropleth map from the Spatial Map Images and responded to the question. If the question refers to the whole map, as is the case in Set 4, the pattern changes. The response time to 'GEO3+C' (Set 4B) is almost twice that of 'C' (Set 4A) only. The quality of the answers of the samples in Set 4 is not significantly different. From the table in Figure 8-4 it can be seen that for Sets 1 and 2 a shorter response time corresponds with a better quality. Figure 8-4 shows that the response times, as well as the quality of the answers do not differ significantly.

Conclusions on the geographical component in a Spatial Map Image, in combination with the relevant questions from the introductory test can be found in Chapter 9.

			TIME (t-test)					ANSWERS (Mann-Whitney)			
N	NQ	NS	M	S	DF	t	R	A	U	z	R
1A	8	39	26.1	17.6	622	3.80	+	227	307.00	4.53	+
B	8	39	21.1	14.8				275			
2A	4	39	25.7	19.1	310	3.26	+	100	275.50	4.84	+
B	4	39	19.6	13.2				143			
3A	4	45	26.8	15.7	358	2.82	+	147	925.50	0.70	-
B	4	45	22.1	15.4				153			
4A	1	44	14.0	6.1	87	-3.66	+	44	836.00	1.26	-
B	1	45	24.5	17.8				38			
5A	1	45	12.9	4.4	88	1.84	-	41	990.00	0.18	-
B	1	45	11.2	4.3				40			

N: Set number
NQ: Number of questions per set
S: Standard deviation
t: result of t-test
U: result of M-W test
ZR: test result (accept [+] or reject [-] null-hypothesis)
M: Mean time (in seconds)
NS: Number of subjects per question
DF: degrees of freedom
A: number of correct answers
Z: statistic

(Appendix IV gives the numbers of the questions belonging to a particular set)

Figure 8-4. Geographical component; statistical analysis.

8.4 Graphical variables and psychological depth cues in Spatial Map Images

Section 5.3, and especially Figure 5-6, indicates a relationship between the graphical variables and the psychological depth cues in a Spatial Map Image. To find out more about this relationship the subjects were presented with questions 18 to 46. In

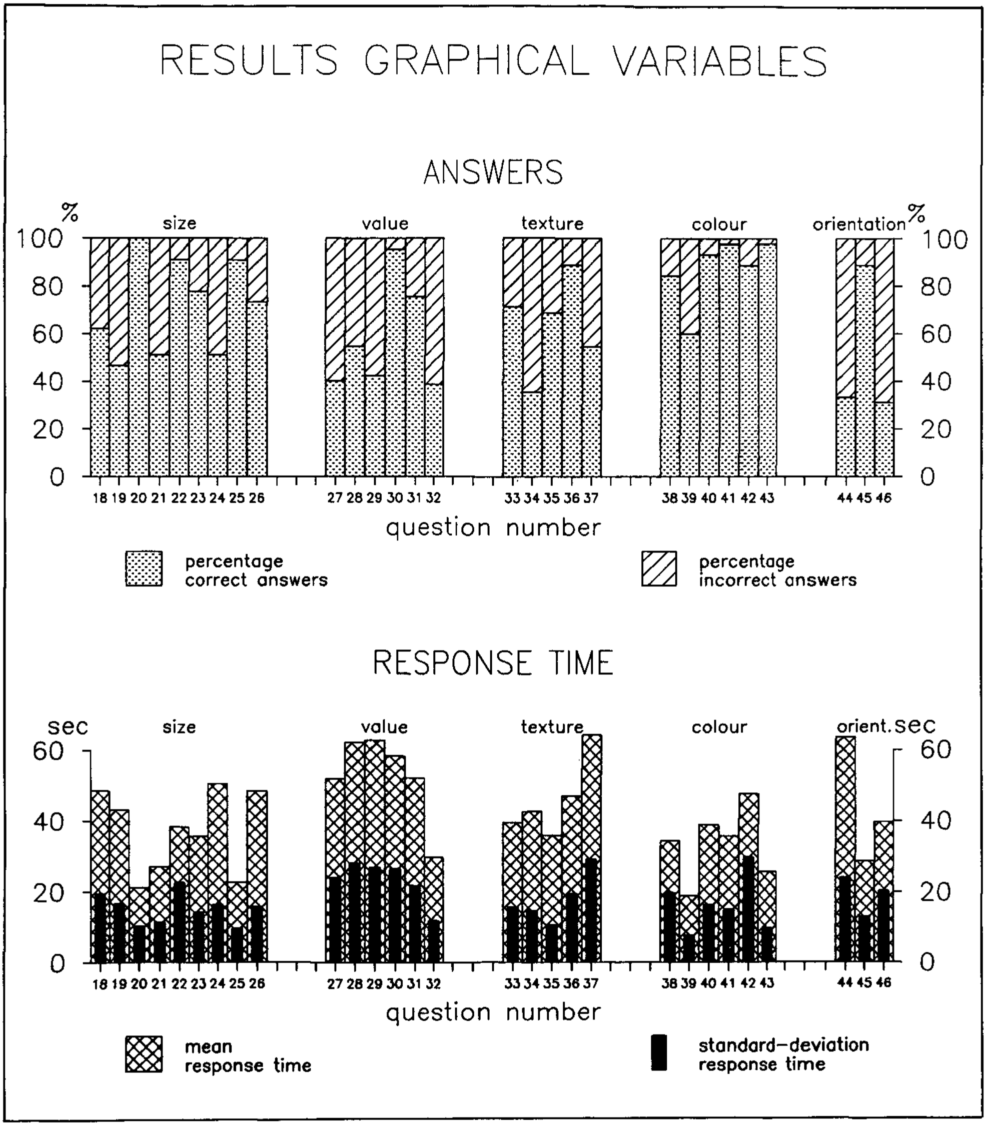


Figure 8-5. Results of the questions related to the graphical variables. Refer to Figure 7-6 and Appendices III & IV.

the Spatial Map Images which belong to these questions (see Appendix III) the graphical variables can be found, with or without the depth cues applied. The test should provide an answer to the question whether and how the graphical variables and the depth cues influence each other.

In Figure 8-5 can be found the results of the questions 18 to 46, and Figure IV-1c in Appendix IV provides the numerical values. The quality of the answers is presented in the upper diagram, and in the lower diagram the response times. For those graphical variables for which a relation was expected to exist in Figure 5-6, a block of answers in both diagrams can be found.

Comparing the response times with those in Figure 8-2 it can be seen that those in Figure 8-5 are longer. It can also be seen that the quality of the answers is lower than those in Figure 8-2. This is mainly due to two reasons: the character of the questions asked, and the construction of the Spatial Map Images. In Figure 7-6c it can be seen that most of the questions in Figure 8-5 concern the whole Spatial Map Image, i.e. 'GEO3+C'. This figure also gives an indication of which depth cues are applied or left out. The application or omission of a depth cue, can influence the readability of the Spatial Map Image.

To be able to judge if differences found in the diagrams are statistically significant, twelve tests have been conducted. Figure 8-6 provides the results of these tests in tabular form, and Figure VI-4b in Appendix IV provides the numbers of the questions which participated in the tests of significance. The first four test sets refer to the graphical variable Size, set 5 to 7 refer to Value, 8 and 9 refer to Texture, and 10 to 12 refer to Colour.

Size

In the tests of significance concerning the graphical variable Size, the base is a Spatial Map Image in which Size is used to depict the map theme. Set 1 tests if there
is a significant difference between Spatial Map Images with (Set 1A) and without (Set B) the application of the depth cue retinal image size. Set 2 tests the influence of the addition or omission of the depth cue shading. Set 3 looks at the effects of the application of chromostereopsis, and set 4 tests the influence of the addition of Texture to the map. All map reading tasks had to do with size estimations.

It can be seen from Figure 8-6 that for set 1 the most important result is the effect on the quality of the answers of not applying the depth cue retinal image size. When it is not applied, and all symbols of equal size in the map are also physically equal, the results are significantly better then when it is applied. When shading is not applied the results are better and the response times are shorter. The application or omission of the depth cue colour did not influence the results when the map reading task was size estimation. The significant difference in response times between Spatial Map Images with and without the depth cue texture applied, suggests a faster 'understanding' of the map when texture is omitted, yet the results are significantly better when it is applied.

Value

To see how the graphical variable Value can be used in combination with the psychological depth cues, all Spatial Map Images in these tests of significance used value. In Set 5 applying and not applying the depth cue shading was tested, while Set 6 tested the Spatial Map Images with and without texture. Set 7 tested the effects of adding retinal image size to the variable of Value, and omitting it.

Figure 8-6 shows that although the response time is significantly shorter when shading is omitted, the quality of the answers is better when it is applied. From the same table it can be seen that the depth cue texture does not influence the results. It

						TIME (t-test)					ANSWERS (Mann-Whitney)			
GRAVAR	DEP-CUE	(A/O)	N	NQ	NS	M	S	DF	t	R	A	U	z	R
Size	R.Size	A	1A	1	45	48.7	19.6	88	-0.53	-	28	562.50	3.63	+
		O	B	1	45	50.7	16.4				23			
	Shading	A	2A	1	45	43.2	16.7	88	7.50	+	21	472.50	4.35	+
		O	B	1	45	21.1	10.2				45			
	Colour	A	3A	1	45	38.4	22.7	88	0.66	-	41	877.50	1.09	-
		O	B	1	45	35.7	14.3				35			
	Texture	A	4A	1	45	38.4	22.7	88	2.96	+	41	607.50	3.26	+
		O	B	1	45	27.0	11.3				23			
Value	Shading	A	5A	2	45	57.5	25.0	176	4.69	+	40	691.00	2.45	+
		O	B	2	44	40.8	22.0				34			
	Texture	A	6A	1	45	62.7	27.1	87	0.10	-	19	868.00	1.00	-
		O	B	1	44	62.1	28.2				24			
	R.Size	A	7A	1	45	62.7	27.1	88	0.76	-	19	472.50	4.35	+
		O	B	1	45	58.4	26.7				43			
Texture	R.Size	A	8A	1	45	47.2	19.5	88	3.34	+	40	810.00	1.63	-
		O	B	1	45	36.0	10.5				31			
	Colour	A	9A	1	45	39.7	15.7	88	-0.95	-	32	652.50	2.90	+
		O	B	1	45	42.8	14.7				16			
Colour	R.Size	A	10A	1	45	34.5	19.8	88	-1.18	-	38	922.50	0.72	-
		O	B	1	45	39.0	16.3				42			
	Colour	A	11A	1	45	34.5	19.8	88	-0.36	-	38	877.50	1.09	-
		O	B	1	45	35.8	15.0				44			
	Shading	A	12A	1	45	34.5	19.8	88	-2.46	+	38	967.50	0.36	-
		O	B	1	45	47.8	29.9				40			

N: Set number
NQ: Number of questions per set
S: Standard deviation
t: result of t-test
U: result of M-W test
M: Mean time (in seconds)
NS: Number of subjects per question
DF: degrees of freedom
A: number of correct answers
Z: statistic
ZR: test result (accept [+] or reject [-] null-hypothesis)
GRAVAR: Graphical Variable
DEP-CUE: Depth cue
(A/O): A= applied / O= omitted

(Appendix IV gives the numbers of the questions belonging to a particular set)

Figure 8-6. Graphical variables; statistical analysis.

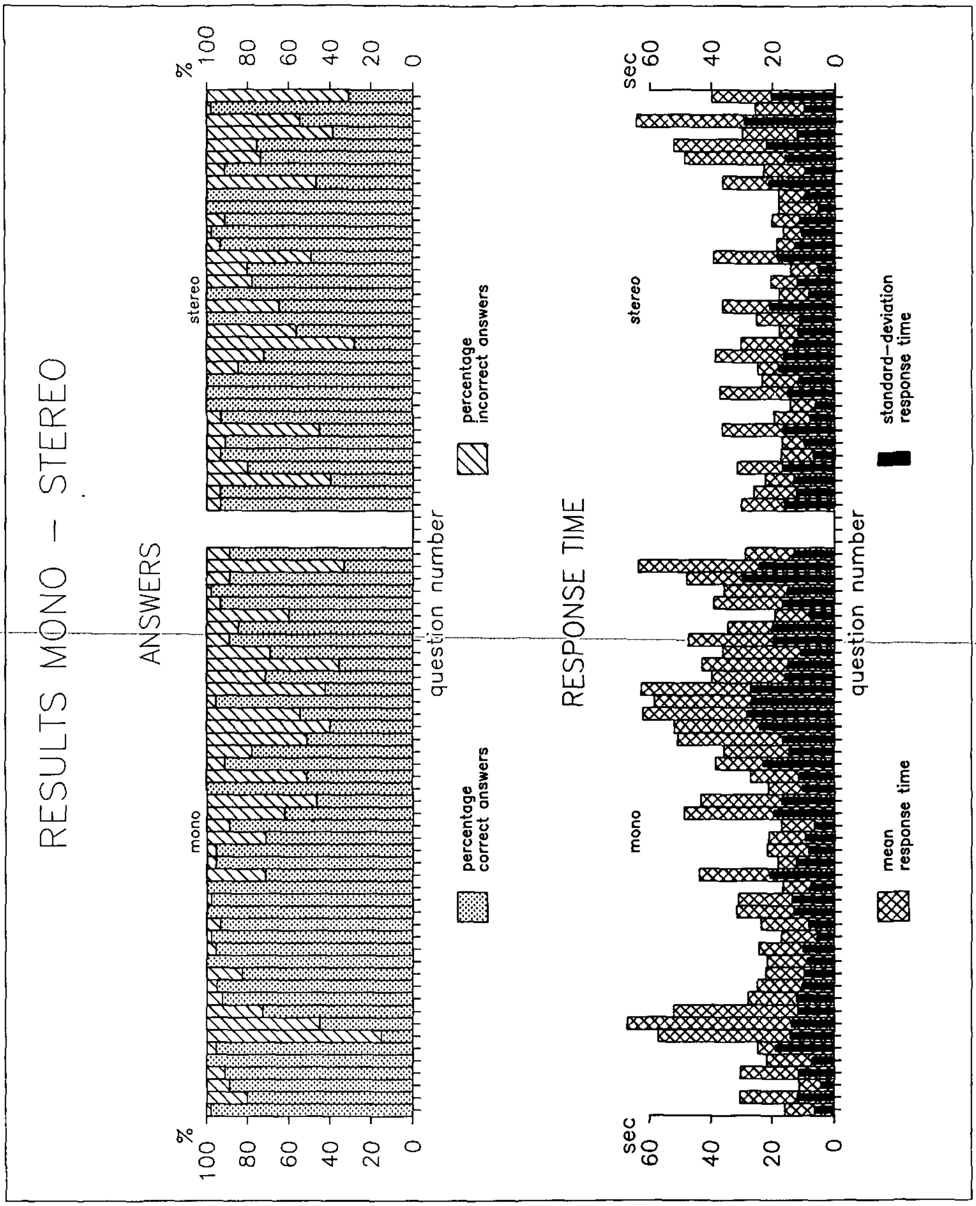


Figure 8-7. The relation between mono and stereo Spatial Map Images. For the numerical information see Appendix IV. No question numbers can be found along the x-axis of both diagrams; the order of the questions is according to Figure 7-6, with the exception that all questions related to mono Spatial Map Images are given first, followed by those in stereo.

is also clear that for the specific map reading task the results are significantly better when the depth cue retinal image size is not applied in the Spatial Map Images.

Texture
To test the graphical variable Texture (differences in patterns) versus the depth cues, the Spatial Map Images were constructed using Texture with and without the application of certain depth cues. In Set 8 the effect of the combination of the graphical variable texture with and without the depth cue retinal image size is tested. Set 9 tests the effects of Texture and the depth cue colour.

It can be seen in Figure 8-6 that the response time to questions related to Texture without retinal image size applied is shorter, but the quality of the answers is lower. Looking at the combination Texture and colour (Set 9), it can be seen that the response times do not differ, but that the quality of the answers is better when colour is applied correctly, i.e. a blue background with red symbols.

Colour
Three tests of significance have been conducted to see how the graphical variable Colour can be used in combination with some of the depth cues. In Set 10 the effects of the use of retinal image size is tested, set 11 looks at the application of the depth cue colour, and Set 12 tests Colour with and without shading applied.

Figure 8-6 shows that both the depth cues retinal image size and texture hardly influence the results for the graphical variable colour. When shading is used the response time is significantly shorter, but it does not influence the quality of the answers.

Conclusions on the effects of the combination of graphical variables with psychological depth cues can be found in Chapter 9.

8.5 Spatial Map Images in mono and stereo

In the computer-assisted map user test 42.5% of the questions concern Spatial Map Images presented to the subjects in stereo. The purpose of this was to see whether the three-dimensional Spatial Map Images would be better understood when they really could be experienced by the subjects in three dimensions (the virtual map). The characteristics and quality of the stereoscope used during the test were explained in sections 4.5 and 4.6.

Figure 8-7 presents the results to all questions in the test distinguishing those referring to the Spatial Map Images in mono from those in stereo. In the upper diagram are given the quality of the answers, and in the lower diagram the response times.

			TIME (t-test)					ANSWERS (Mann-Whitney)			
N	NQ	NS	M	S	DF	t	R	A	U	z	R
1A	24	40	27.8	17.6	1990	4.94	+	827	705.50	1.40	-
B	24	43	24.1	15.2				868			
2A	6	45	22.3	13.1	532	-1.47	-	249	586.50	3.31	+
B	6	44	24.0	14.0				218			
3A	6	40	41.8	21.3	502	9.63	+	161	312.00	5.08	+
B	6	44	25.9	15.5				230			
4A	6	45	24.7	11.3	538	-0.53	-	263	299.50	5.75	+
B	6	45	25.4	16.5				212			
5A	6	45	22.9	15.1	532	1.36	-	235	990.00	0.00	-
B	6	44	21.2	14.4				232			
6A	12	40	31.5	20.0	946	6.01	+	378	490.00	2.84	+
B	12	39	24.5	15.5				337			
7A	12	40	24.0	13.8	994	0.10	-	449	425.50	3.96	+
B	12	43	23.9	15.4				438			
8A	2	45	46.0	18.3	178	3.74	+	24	582.00	3.47	+
B	2	45	35.7	18.4				45			
9A	1	45	62.7	27.1	88	2.01	+	19	675.00	2.72	+
B	1	45	52.2	21.8				34			
10A	1	45	36.0	10.5	87	-6.03	+	31	848.00	1.16	-
B	1	44	64.3	29.3				24			
11A	1	45	34.5	19.8	88	2.65	+	38	877.50	1.09	-
B	1	45	25.7	9.7				44			
12A	1	45	63.7	24.1	88	5.03	+	15	900.00	0.18	-
B	1	45	39.8	20.3				14			

N: Set number
M: Mean time (in seconds)
NQ: Number of questions per set
NS: Number of subjects per question
S: Standard deviation
DF: degrees of freedom
t: result of t-test
A: number of correct answers
U: result of M-W test
Z: statistic
ZR: test result (accept [+] or reject [-] null-hypothesis)

(Appendix IV gives the numbers of the questions belonging to a particular set)

Figure 8-8. The relation between mono and stereo Spatial Map Images; statistical analysis.

To be able to see if there is a significant difference between mono and stereo Spatial Map Images twelve tests of significance have been made. The results of these tests are displayed in Figure 8-8. The first seven tests have been done using questions 1 to 17, and the last five tests used questions 18 to 46. Figure IV-4c in Appendix IV shows which questions were involved in which test.

Set 1 examines the overall differences between mono and stereo. Sets 2 to 5 test mono versus stereo for the separate types of Spatial Map Images; prism maps, digital terrain models, three-dimensional point symbol maps, and three-dimensional urban maps respectively. Set 6 looks at possible differences for GEO3; and Set 7 does the same for GEO3+C.

Sets 8 to 12 test the effects of the use of the stereoscope for the graphical variables. Set 8 looks at Size, Set 9 at Value, Set 10 at Texture, Set 11 at Colour, while Set 12 tests the graphical variable Orientation.

From the table in Figure 8-8 it can be seen that for the combined Spatial Map Images the response time is significantly shorter when they are viewed in stereo, and the quality of the answers to the 'stereo-questions' is higher, though not statistically significant. For the separate Spatial Map Images the result for the digital terrain models (set 3) improved significantly when viewed in stereo. There are however still several errors as can be seen in the upper diagram in Figure 8-2. Another notable result is that there is a significant difference in the quality of the answers for the thematic Spatial Map Images, where the mono questions performed better than those in stereo.

Looking at both Sets 6 and 7 concerning the geographical component, it can also seen that the mono Spatial Map Images have a better score. However, the response times for the stereo GEO3 maps are significantly lower than for the mono maps.

Figure 8-8 indicates that when the graphical variable Size is concerned the stereo maps have a significantly shorter response time, as well as a better quality of the answers. The same result can be seen for shading, a shorter response time and a better quality of the answers for the stereo maps. For the other three graphical variables the response times differ significantly, but the quality of the answers does not. Note the shorter response time for the mono maps where texture is used.

Conclusions on the effects of the stereoscope can be found in Chapter 9.

CHAPTER 9. THREE-DIMENSIONAL CARTOGRAPHY

This chapter summarizes the work of this thesis, and will reflect upon the three main topics of this study:
1. a procedure for the production of Spatial Map Images;
2. a computer-assisted map user test;
3. cartographic theory and the three-dimensional map.

Topics 1. and 2. are discussed first, because they have been tools in order to find out more about topic 3. The methodology used to produce the Spatial Map Images and the computer-assisted map user test have influenced the approach to three-dimensional maps. Before these three topics are treated in more detail, the objective of this study will be reviewed.

In the first chapter it was stated that the objective of this thesis was to see what characterizes three-dimensional maps and to determine whether indeed three-dimensional maps produced by computer-assisted cartography give the map user a better understanding of the mapped phenomena. To accomplish this, a study of (three-dimensional) cartography was made which resulted in assumptions and unanswered questions. A program for three-dimensional map production was designed and developed. Maps produced by this program were used in a computer-assisted map user test to find answers to the questions, and to test the validation of the assumptions. The detailed test results were described in the previous chapter and the general conclusions are given below.

In Chapter 2 it was stated that a map, considered as a graphic representation of the milieu, is said to be three-dimensional when it contains stimuli which make the map user perceive its contents as three-dimensional. These maps can be permanent (for instance on paper), temporary (on screens), or virtual (in the mind). In this thesis a selection of three-dimensional maps have been studied. These are the non-orthogonal three-dimensional maps or Spatial Map Images, in a temporary or virtual status. The Spatial Map Image with a temporary state of display was chosen because developments such as geographical information systems confront the map user more and more with computers and maps on screens. The virtual state of displaying the Spatial Map Image was studied when the maps were observed with a stereoscope.

In this information age with the computer as a cartographic tool, it is specially the Spatial Map Images that provide the cartographer with the opportunity to manipulate and experiment with the full three-dimensional map data set with relative ease. This would be almost impossible to achieve without the computer.

Four types of Spatial Map Images have been used in this research project, two with a topographic nature (the digital terrain model and the three-dimensional urban map), and two with a thematic nature (the prism map and the three-dimensional point symbol map).

1. A procedure for the production of Spatial Map Images

To be able to produce three-dimensional maps, and more specifically the Spatial Map Images, a program was designed and developed. This program is based on the philosophy of a three-dimensional mapping procedure, and includes all components necessary for production of three-dimensional maps. One of the important principles of the program is the possibility for the cartographer to manipulate the Spatial Map Image interactively, and position its elements according to the purpose of the map.

This quality is notably missing from existing cartographic software packages, and as such diminish their usefulness. The alternative would have been the use of CAD software. This software has most of the functionality proposed in this thesis, and can be applied to produce the Spatial Map Images. But because these packages often have a restricted data structure, based on simple graphical primitives or mathematical descriptions, they were not used.

An added disadvantage of both the existing cartographic and CAD software is that it is almost impossible to manipulate the final images. Therefore a program was developed specially for this study using a graphical standard, PHIGS, to be able to tailor the program to the needs of this study. The program includes five major steps which are approximately the same for each of the Spatial Map Images discussed here. These steps include 1. data collection; 2. data processing; 3. pre-display of the Spatial Map Image; 4. manipulation of the map; 5. the final visualization. Steps 3, 4 and 5 are considered to be essential for the production of Spatial Map Images.

In the near future available software might well be suitable for producing Spatial Map Images following the philosophy presented here. Such software, possibly part of a larger system such as a geographical information system, when combined with dedicated hardware might include features for dynamic cartography. This would give the map user the opportunity to move real-time through the map model. For Spatial Map Images such as the three-dimensional urban map this is a particulary promising outlook. However, more sophisticated data structures will be necessary, since these dynamic features will probably involve larger data sets which might cause deterioration in system performance.

2. A computer-assisted map user test

The computer can be used to assist the cartographer with map user research to improve the cartographic product. This is necessary since the map user plays an important role in the process of cartographic communication. Given the increase in the use of temporary maps, and the suitability of this type of display for presenting the Spatial Map Image, the map user test with the assistance of the computer was necessary to find out more about the Spatial Map Images.

The purposes of the test were threefold: first, to see how the geographical component functions in a Spatial Map Image; second, to see how the graphical variables can be used in a three-dimensional map in combination with the psychological depth cues; and third, to measure the effects of the use of a stereoscope.

While the maps and questions are shown on a display, the subjects can respond using the keyboard or other devices connected to the computer. Extra attention must therefore be given to the test procedure since, for example, it should not be possible for a wrong keystroke to disrupt the test procedure and influence the results. The software which runs the test should have an excellent user interface to ensure uninterrupted test runs, that the subject is informed properly about the next action or task, and that the responses are registered. The type and quality of the hardware used also play a significant role. The size, resolution, and colour capacity of the screen can influence the subjects' comprehension of the maps displayed; while the type of device used to interact with the program, such as the keyboard, cursor, or mouse, can ease the subjects' responses.

The test discussed here is split into two sections. The first is an introductory test and the second is the main test. Since computerized map user testing is new, especially to most subjects, an introductory test was thought to be necessary to allow the subjects to accustom themselves to the test environment. The purpose of this introduction was also to test the present stereoscopic acuity of the subject, and to provide a link between the Spatial Map Images and two-dimensional maps. The second section of the test dealt with the Spatial Map Images, and can be considered the actual test. Its results were discussed in Chapter 8, while the conclusions can be found below.

During this study the results of the computer-assisted map user test were only used to increase the insight into specific three-dimensional maps, the Spatial Map Images. In the total design process of maps in general the results of such tests should be used directly to enhance the map design. This gives the cartographer the opportunity to increase the effectiveness of the cartographic product. However, this implies a strong relationship between the target group of the map and the subjects participating in the test. The use of computer-assisted map user tests increases the influence of the computer in the cartographic communication process, and might well lead to a further overlap of I and I' in Figure 3-1.

3. The cartographic theory and the three-dimensional map

Since it would be too ambitious to include the whole cartographic concept which combines cartographic communication theories and the cartographic sign system, as presented in Chapters 3 and 5, the research has been focused on those parts of the approach thought to be essential for three-dimensional cartography. These include elements of the process of cartographic information analysis, i.e. the geographical component, and elements of the syntax of the sign system and perception of the maps, i.e. the relation between the graphical variables and the psychological depth cues. The assumptions and questions resulting from the study of these sub-topics were reflected in the Spatial Map Image concept. In computer-assisted map user test subjects were confronted with these maps, and the test results should reveal the specific characteristics of the three-dimensional map. In addition to information on the geographical component and the graphical variables, the tests should also result in an indication of the effect of using a stereoscopic expedient.

The relevance of knowing the effects of the geographical component in a three-dimensional map, and its functioning in the Map-To-See concept, is related to the environment in which Spatial Map Images are likely to function, and their role in the cartographic communication process. The strong relationship between these temporary maps and computer-assisted cartography was explained in Chapters 1 and 2. The characteristics of most screens which can display the temporary map do not allow for complex maps. It is expected that especially the use of the Maps-To-See as temporary maps will increase in the future. The Spatial Map Image as a Map-To-See is best used to present an overview of a relatively simple spatial phenomenon. The relationships between the 'extreme' objects or values in the map can also be clarified.

This leads to some general remarks on the geographical component in a Spatial Map Image. Its test results are discussed in section 8.3. When the map reading task includes the map as a whole, GEO3 has a significantly shorter response time then GEO3+C. Comparing the response times of the two dimensional Map-To-See from the introductory test (GEO2+C) with a similar three-dimensional map (GEO3), see Set 5 in Figure 8-4, it shows there is no significant difference between the two. From this it follows that the geographical component in a Spatial Map Image (GEO3) is equal to the geographical component plus one component in a two-dimensional map (GEO2+C). Therefore the Z in GEO3 is equal to 'C' in GEO2+C. This leads to the conclusion that when a Spatial Map Image must function as a Map-To-See, only the geographical component should be used.

Section 8.3 also reveals some minor differences between maps depending, for instance, on their complexity, the type of Spatial Map Image, and the map readingtask. One of the more striking features is related to the map reading task. For 'complex' prism maps (GEO3+C), and a map reading task concerning 'C' only, it seems that the viewer isolates the choropleth map element from the map as a whole map and treats it as a two dimensional map.

Figure 5-6, in chapter 5 suggests relations between the graphical variables and the psychological depth cues in a Spatial Map Image. To find out more about these relations, and about the use of graphical variables in three-dimensional maps, the character of these relations was investigated. Both are used because of their perceptual properties, the first to display spatial distributions and the second to create a three-dimensional impression. Results can be found in both highlighted diagonals in the two diagrams in Figure 9-1.

The different Spatial Map Images in the computer-assisted map user tests included each of the graphical variables, with or without the depth cues applied. However, the results of the tests do not reveal a specific pattern for all graphical variables together. Figure 9-1 summarizes the test results of the relations between the graphical variables and the psychological depth cues in two diagrams. The diagram in Figure 9-1a concerns the understanding of the Spatial Map Images (response time) in the given situation, while Figure 9-1b emphasizes the relative quality of the

	DEPTH CUES					
	1	2	3	4	5	6
Size	O (shaded)	–	–	O	▪	▪
Value	O	– (shaded)	O	▪	▪	▪
Texture	–	▪	▪	O	▪	▪
Colour	O	O	▪	O (shaded)	▪	▪
Orientation	▪	▪	▪	▪	▪ (shaded)	▪
Shape	▪	▪	▪	▪	▪	▪

a) Understanding

	DEPTH CUES					
	1	2	3	4	5	6
Size	– (shaded)	–	+	O	▪	▪
Value	–	+ (shaded)	O	▪	▪	▪
Texture	O	▪	▪	+	▪	▪
Colour	O	–	▪	O	▪	▪
Orientation	▪	▪	▪	▪	▪	▪
Shape	▪	▪	▪	▪	▪	▪

b) Quality

1:Retinal image size; 2:Shading; 3:Texture; 4:Colour; 5:Line perspective; 6:(Perspective);
+ = advised; – = not advised; O = no specific advise; [shaded] = positive stereo effect; ▪ = not tested.

Figure 9-1. The relation between the graphical variables and the psychological or pictorial depth cues. Figure 9-1a shows the understanding of the three-dimensional map, and Figure 9-1b the relative quality of the combinations.

relation. Reading both diagrams it should be noted, however, that the map reading tasks were oriented towards the functioning of the graphical variables, e.g. for Size the task was to estimate sizes.Referring to both diagonals in Figure 9-1 it appearsthat Size in its application in combination with the depth cue size influences the quality of the results negatively. For Value the opposite is true, the combination with the depth cue shading leads to better results. For Colour it seems there are no problems with or without the proper use of the depth cue colour. Details can befound in section 8.4. Positive combinations, when the quality of the answers is concerned, are Size with the depth cue texture and the graphical variable Texture with the depth cue colour. Colour and Size in combination with shading should be avoided. When referring to the understanding of the map the combinations Size and Value with the depth cue shading should be avoided, as well as Texture with the depth cue size.

With the results of the computer-assisted map user test, which took most subjects at least one hour to perform, it was not possible to complete the whole diagram since this would have involved at least 142 different situations for the graphical variables alone. Further research might prove to be necessary.

The purpose of part of the computer-assisted map user test was to see whether the three-dimensional Spatial Map Images would be better understood when they really could be viewed by the subjects as three-dimensional (the virtual map). Therefore almost half of the test maps were presented to the subjects in stereo. A simple table stereoscope was modified and placed in front of the screen to view the stereo Spatial Map Images.

From section 8.5 it can be learned that for the combined Spatial Map Images the response time is significantly shorter for the stereo maps compared with the mono maps. However the quality of the answers to the 'stereo-questions' does not differ significantly from the 'mono-questions'. Viewing a Spatial Map Image in stereo means a faster, but not necessarily a better, understanding of the map. See also Figure 9-1.

An improvement of the stereoscopic possibilities, for instance with a device with liquid crystal shutters, might shorten the response times to the 'stereo-questions' even more, and might even influence the quality of the answers given in a positive way, because only a primitive method was used where the subjects first looked through the stereoscope; adjusted their view to their virtual image; looked alongside the stereoscope to read the question; and then through the stereoscope again, to retrieve the virtual map image and process the question. However, tests will have to be done to prove this, but this part of the thesis can be seen as a preparation of the cartographer for future technical improvements in this field. It should also be noted that stereo Spatial Map Images were always seen at the end of the test. This might have some influence on the response time since the subjects will have gained some experience in answering the questions.

In section 8.5 more details can be found on the differences between mono and stereo, depending for instance on the map complexity and the type of Spatial Map Image. An interesting aspect of the results concern the three-dimensional point symbol map, which utilises the graphical variable of Size, and involves a map reading task of estimating the sizes of three-dimensional point symbols, such as cubes and spheres. In this situation the stereo maps lead to significantly shorter response time and improved quality of the answers. This result leads to the conclusion that when such symbols are viewed in stereo they are less underestimated

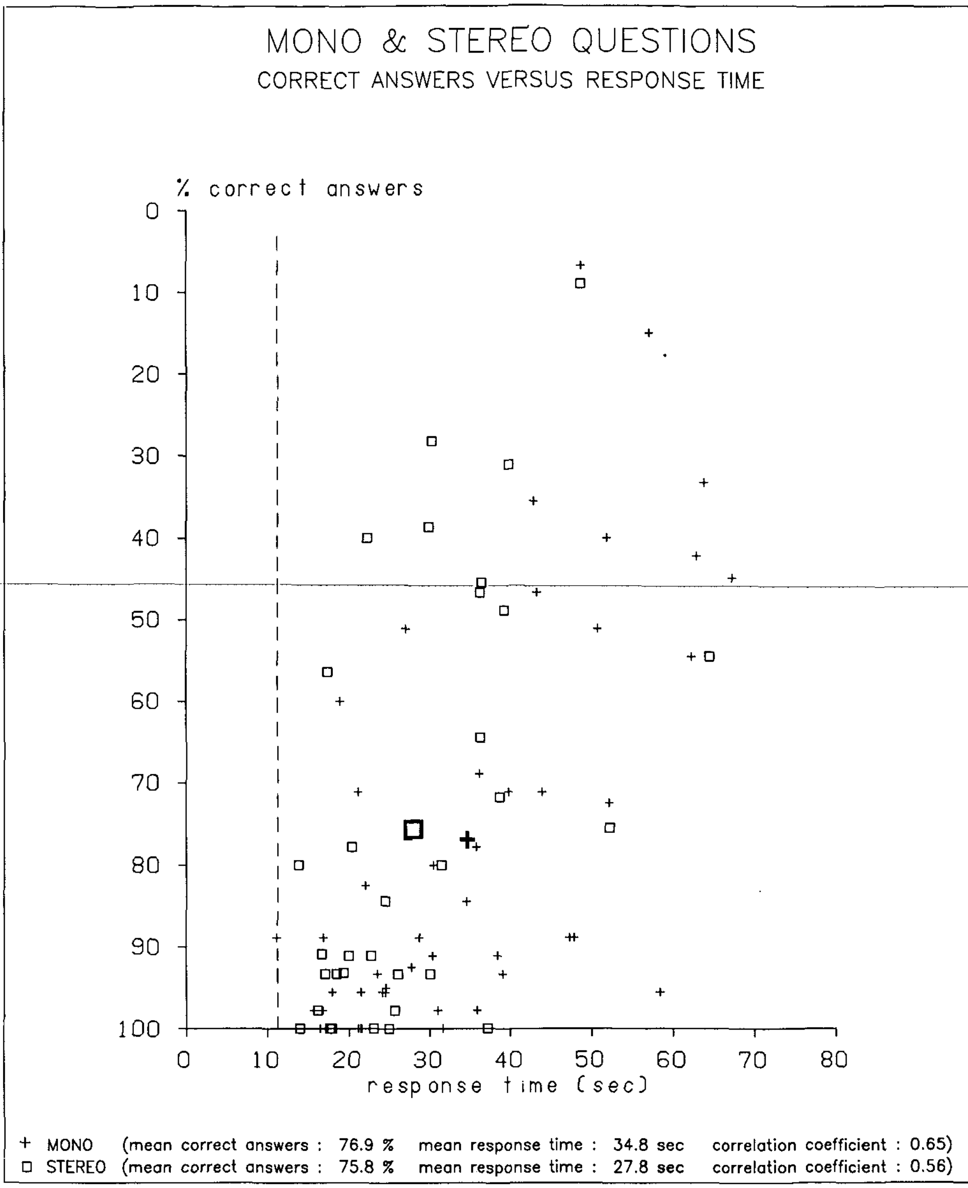


Figure 9-2. The relation between response time and percentage correct answers for mono and stereo Spatial Map Images.

than when looked at in mono. However, the test does not relate these results to two-dimensional maps with two-dimensional symbols such as circles and squares.

Figure 9-2 combines all results of the test in a scatter diagram, distinguished in mono and stereo. It enables one to see whether a relation exists between the percentage of correct answers and the response times. The calculated correlation coefficient (0.6) indicates a possible relation, but not conclusive. From the diagram it seems that when response times (= understanding of the map) is concerned, stereo performs a better than mono, despite the rather primitive stereoscope in use. The quality of the answers is almost equal for both mono and stereo. The difference between response times for mono and stereo becomes more distinct when the zone from 0 to 12 seconds, in the left of the diagram where no observation are found, is left out. This zone corresponds with the time needed to read and understand the map reading task (see Figure 8-1). This zone is indicated by the dotted line in Figure 9-2.

In discussing the three main topics of this thesis the characteristics of the Spatial Map Images have become clear. Referring to cartography as a whole it can be said that the general cartographic theory can be applied, with a few exceptions as discussed above, to three-dimensional maps such as the Spatial Map Images. In the cartographic communication process these maps, provided they are kept relatively simple and are used as Maps-To-See, function at least as well as two-dimensional maps. For more complex maps further comparison between two- and three-dimensional maps will be necessary.

CHAPTER 10. SUMMARY / SAMENVATTING

Computer-assisted cartographical three-dimensional imaging techniques

Cartographers are concerned with the information transfer of spatially distributed data by means of maps. For centuries mainly manual techniques have been used to design and produce the maps. In mapping phenomena related to the earth the three-dimensional real world has to be projected on to the plane surface of paper, for long the most important carrier of cartographic information. In some maps the cartographer attempted to represent the three-dimensional world as closely as possible. This was a difficult and laborious undertaking.

Since the 'Sixties, however, the importance of the computer as a cartographic tool has increased. It has made the practice of cartography change considerably, but the basic principles have remained relatively unchanged. The application of computer graphics techniques has introduced new aspects to cartography.

Developments in this field have led to an increased use of these techniques in many disciplines. The use of the computer makes the graphic presentation of research results more flexible then before. The application of three-dimensional graphics seems to contribute especially to the evolution of disciplines such as molecular biology (a better understanding of the DNA structure), architecture (a better perception of the plan) and engineering (CAD/CAM, interactive design; robotics & kinematics).

Is such a trend also apparent in cartography? Can the application of three-dimensional computer graphics help to solve some of today's cartographic problems? The computer creates opportunities for the cartographer to work on map types which are, without the use of the computer, difficult or laborious to produce. This is certainly valid when the third dimension is involved.

To answer this question closer look at three-dimensional cartography is necessary by combining knowledge of cartographic theory, three-dimensional perception and computer graphics using new technological developments. The following observations indicate an interest in three-dimensional cartography.

1. Computer technological developments
Looking at developments in computer technology, it can be seen that computer systems are becoming smaller while their capacity increases. A similar trend is seen in peripherals. Computerized data handling, input, storage, manipulation and output become easier. These developments make the technology become more

generally available. For cartography it may facilitate possibilities for sophisticated map presentation.

2. Developments in computer graphics
Since many computer graphics applications involve the display of three-dimensional objects and scenes, techniques were developed to display them on two-dimensional screens. These techniques deal with questions such as how depth, the third dimension can be displayed on screen and how the three-dimensional world should be modelled in the computer so that images can be generated.

3. Developments in computer-assisted cartography
The introduction of the computer as a cartographic tool has made cartographers change their approach to the discipline. It has already penetrated many sub fields of cartography. Several trends can be distinguished in current cartography:
- automation of mapping and charting processes;
- the production and use of thematic mapping software;
- interest in the cartographic component of geographical information systems;
- interest in the development of cartographic expert systems;
- an interest in 'new' cartographic products, such as prism maps and digital terrain models, can be seen.

The combination of these observations led to the start of this research project: computer-assisted cartographical three-dimensional imaging techniques. The objectives are to see what characterizes three-dimensional maps, and to determine whether indeed three-dimensional maps produced by computer-assisted cartography give the map user a better understanding of the mapped phenomena.

In this thesis a map, considered as a graphic representation of the milieu, is said to be three-dimensional when it contains stimuli which make the map user perceive its contents as three-dimensional. These maps can be permanent (for instance on paper), temporary (on screens), or virtual (in the mind).

A short description of the theoretical approach to cartography as a framework for this research project is given in Chapter 2. Definitions and descriptions of specific terminology used in this project are given and explained. To illustrate ideas throughout the project four different types of non-orthogonal three-dimensional maps, or Spatial Map Images, are used: the digital terrain model and the three-dimensional urban map, which have a topographic nature, and the prism map and the three-dimensional point symbol map, which depict thematic features.

An overview of cartographic theory is given in Chapter 3. This is necessary since it is the base on which the three-dimensional approach in Chapter 5 is built. Cartographic communication theory, cartographic information analysis, and the principles of the (carto)graphic sign system are combined.

Chapter 4 examines how humans see and perceive the three-dimensional world around them. From this knowledge elements can be obtained to help improve the three-dimensional map too and let the map user truly perceive it as three-dimensional. The chapter also takes a closer look at expedients, especially the stereoscope, which can be used to enhance the appearance of three-dimensional images. The chapters following concentrate on the main topics of this thesis.

- The extension of cartographic theory (Chapter 5)

  This is concentrated on the use of the graphical variables in Spatial Map Images, in relation to the psychological or pictorial depth cues. Here knowledge from cartography and three-dimensional perception is combined. The characteristics of the geographical component in these maps, as well as the effects of the use of a stereoscope, also receive attention.

- A procedure for the production of the Spatial Map Images (Chapter 6)

  The basic principles of the three-dimensional map production system should be data collection and processing, the pre-display of the map, its manipulation and the final step in creating the map. The pre-display and manipulation of the map are an explicitly necessary when producing three-dimensional maps. Because there will always be dead ground in these maps information will be lost. To keep this loss to a minimum an ideal image position will have to be found, keeping the purpose of the map in mind. The final step in the map production process can be a hidden surface operation.

- A computer-assisted map user test

  A computer-assisted map user test was conducted in which map users are confronted with Spatial Map Images to find answers to assumptions made and questions raised when discussing the three-dimensional approach to cartography. Attention is given in Chapter 7 to the characteristics of the test map, the test environment, the subjects, the questions and the test procedure. Chapter 8 discusses the test results.

The final chapter, Chapter 9, summarizes the results of this thesis. The characteristics of the Spatial Map Images are given, and referring to cartography as a whole it is concluded that, with a few exceptions, the general cartographic theory can be applied to three-dimensional maps. In the cartographic communication process the Spatial Map Images function at least as well as two-dimensional maps, provided they are kept relatively simple (used as Maps-To-See). For more complex maps a further comparison between two- and three-dimensional maps will be necessary. Viewing the Spatial Map Images in stereo resulted in a faster, but not necessarily better understanding of the map.

Computer-gesteunde kartografische drie-dimensionale beeldvormings technieken

Kartografen houden zich bezig met de informatieoverdracht van ruimtelijk verspreide gegevens middels kaarten. Eeuwenlang zijn bij het ontwerp en de produktie van kaarten voornamelijk manuele technieken gebruikt. Bij de kartering van allerlei verschijnselen moest de drie-dimensionale werkelijkheid worden geprojecteerd op het twee-dimensionale papier. Papier is lang de meest belangrijke drager van kartografische informatie geweest. In sommige kaarten probeerde de kartograaf de drie-dimensionale wereld zo goed mogelijk te benaderen. Dit bleek een moeilijke en bewerkelijke onderneming.

Sinds de jaren zestig is het belang van de computer als kartografisch gereedschap toegenomen. Dit leidde tot een andere benadering van de kartografie, maar de basis-principes zijn nagenoeg onveranderd gebleven. De toepassing van computer graphics technieken introduceerde nieuwe aspekten in de kartografie.

Ontwikkelingen in dit veld leidde tot een toename van deze technieken in vele disciplines. Het gebruik van de computer maakt de presentatie van onderzoeksresultaten flexibeler dan voorheen. De toepassing van drie-dimensionale graphics lijkt bij te dragen tot met name de ontwikkeling van vakken als moleculaire biologie (een beter inzicht in de DNA-struktuur), architectuur (een beter begrip van de bouwtekening) en diverse constructievakken (CAD/CAM, interactief ontwerp; robotica en kinematiek).

Is een dergelijke trend ook zichtbaar in de kartografie? Kan de toepassing van drie-dimensionale computer graphics bijdragen tot de oplossing van enkele hedendaagse kartografische problemen? De computer creëert voor de kartograaf mogelijkheden om met kaarttypen te werken, die zonder gebruik van de computer een moeilijk en bewerkelijk produktieproces kennen. Dit geldt met name als de kaart de derde dimensie bevat.

Om een antwoord te vinden op bovengenoemde vraag is het noodzakelijk om te kijken naar de drie-dimensionale kartografie in combinatie met kennis van de kartografische theorie, drie-dimensionale perceptie en computer graphics, gebruikmakend van de nieuwste technologische ontwikkelingen. De volgende waarnemingen zijn een indicatie voor interesse in de drie-dimensionale kartografie.

1. Computertechnologische ontwikkelingen
De ontwikkelingen op het gebied van de computertechnologie beschouwend, kan worden opgemerkt dat computersystemen kleiner worden, terwijl de capaciteit toeneemt. Een dergelijke trend is ook zichtbaar wanneer men naar de randapparatuur kijkt. Computer-gesteunde gegevensverwerking, invoer, opslag, manipulatie en uitvoer worden eenvoudiger. Deze ontwikkelingen hebben tot gevolg dat de technologie meer algemeen beschikbaar komt en dit opent perspectieven voor de kartografie.

2. Ontwikkelingen in computer graphics
Daar vele computer graphics toepassingen betrekking hebben op de afbeelding van drie-dimensionale objecten en voorstellingen zijn er allerlei technieken ontwikkeld om deze op twee-dimensionale schermen af te beelden. Deze hebben betrekking op hoe diepte, de derde dimensie, op het scherm afgebeeld kan worden en hoe de drie-dimensionale wereld door de computer gemoduleerd moet worden om de beelden te genereren.

3. Ontwikkelingen in de computer-gesteunde kartografie
De introductie van de computer als kartografisch gereedschap leidde tot een andere benadering door de kartograaf van het vak, waarin het nieuwe gereedschap momenteel al in vele subvelden is doorgedrongen. Kijkend naar de hedendaagse kartografie kunnen er enkele trends onderscheiden worden:
- automatisering van het 'topografisch' karteringsproces;
- productie en gebruik van software voor thematische kaarten;
- interesse in de kartografische component van geografische informatiesystemen;
- de ontwikkeling van kartografische kennissytemen;
- intresse in 'nieuwe' kartografische produkten als de prisma kaart en digitale terreinmodellen.

De combinatie van deze waarnemingen leidde tot dit onderzoeksproject: Computer-gesteunde kartografische drie-dimensionale beeldvormingstechnieken. Het doel was uit te vinden wat de drie-dimensionale kaart karakteriseert en te bepalen of drie-dimensionale kaarten, geproduceerd met behulp van de computer de kaartgebruiker een beter inzicht geven in het gekarteerde verschijnsel.

In deze dissertatie wordt een kaart, een grafische afbeelding van het milieu, beschouwd als drie-dimensionaal wanneer het stimuli bevat die de kaartgebruiker de kaartinhoud als drie-dimensionaal doen ervaren. De kaarten kunnen permanent (bv. op papier), tijdelijk (op een beeldscherm) of virtueel (in gedachte) zijn.

Een korte beschrijving van de theoretische benadering van de kartografie als basis voor dit onderzoeksproject wordt in hoofdstuk 2 gegeven. Definities en omschrijvingen van specifieke terminologie kunnen eveneens in dit hoofdstuk gevonden worden. Vier verschillende niet-orthogonale drie-dimensionale kaarten, of ruimtelijke modellen, zijn gebruikt om ideeën te illustreren. Het betreft het digitale terreinmodel en de drie-dimensionale stadskaart, beide met een topografisch karakter, de prismakaart en de drie-dimensionale puntsymboolkaart met een thematisch karakter.

Een overzicht van de kartografische theorie wordt gegeven in hoofdstuk 3. Dit is noodzakelijk daar dit de basis is waarop de drie-dimensionale theorie in hoofdstuk 5 rust. Kartografische communicatietheorie, kartografische informatieanalyse en de principes van de (karto)grafische tekenleer zijn er gecombineerd.

Hoofdstuk 4 beschouwt hoe de mens de drie-dimensionale wereld rondom zich ziet en ervaart. Van deze kennis kunnen elementen gebruikt worden om de drie-dimensionale kaart te verbeteren en de kaartgebruiker de kaart als echt drie-dimensionaal te laten ervaren. Dit hoofdstuk gaat ook nader in op hulpmiddelen, met name de stereoscoop, die gebruikt kunnen worden om de drie-dimensionale indruk van de kaart te verbeteren.

De volgende hoofdstukken concentreren zich op de hoofdthemas van dit onderzoek.

- Uitbreiding van de kartografische theorie (hoofdstuk 5)

  Dit onderdeel concentreert zich op het gebruik van de grafische variabelen in ruimtelijke modellen, in relatie tot de psychologische diepteaanwijzingen. Hier wordt kennis van kartografie gecombineerd met die van drie-dimensionale perceptie. Ook de karakteristieken van de geografische component in deze kaarten, alsmede het effect van het gebruik van een stereoscoop krijgen aandacht.

- Procedure voor de produktie van ruimtelijke modellen (hoofdstuk 6)

  De basisprincipes van de produktie van ruimtelijke modellen behoren te zijn het verzamelen en bewerken van gegevens, de voor-afbeelding van de kaart, de manipulatie en de uiteindelijk afbeelding. De voor-afbeelding en manipulatie worden gezien als stappen die expliciet noodzakelijk zijn bij de produktie van ruimtelijke modellen. Er zal namelijk altijd informatie verborgen zijn achter andere informatie. Om dit informatieverlies te beperken moet er een ideale positie van het model gevonden worden, uitgaande van het doel van de kaart.

- Een computer-gesteunde kaartgebruikstest

  De kaartgebruikers werden in een computer-gesteunde kaartgebruikstest geconfronteerd met de ruimtelijke modellen om antwoorden te vinden op veronderstellingen en vragen uit eerdere hoofdstukken. Hoofdstuk 7 schenkt aandacht aan de test (kaart, omgeving, personen en procedure). Hoofdstuk 8 bespreekt de testresultaten.

Hoofdstuk 9 vat de resultaten van het onderzoek samen. De karakteristieken van het ruimtelijk model worden gegeven. Er kan worden geconcludeerd dat, enkele uitzonderingen daargelaten, de kartografische theorie op dergelijke kaarten kan worden toegepast. In het kartografisch communicatieproces functioneert het ruimtelijk model minstens zo goed als de twee-dimensionale kaart, zolang deze relatief eenvoudig wordt gehouden (een 'Image'). Voor complexere kaarten is een nader vergelijk tussen twee- en drie-dimensionale kaarten noodzakelijk. Het bekijken van een ruimtelijke model in stereo levert een sneller, maar niet noodzakelijkerwijs beter begrip van de kaart op.

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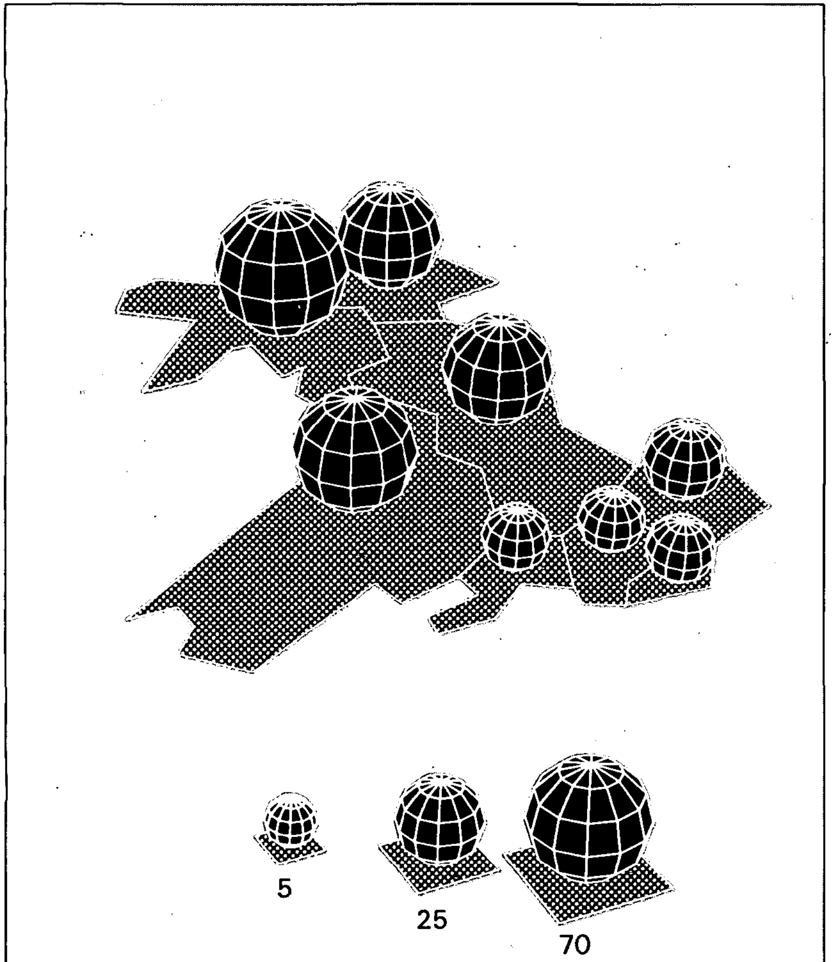
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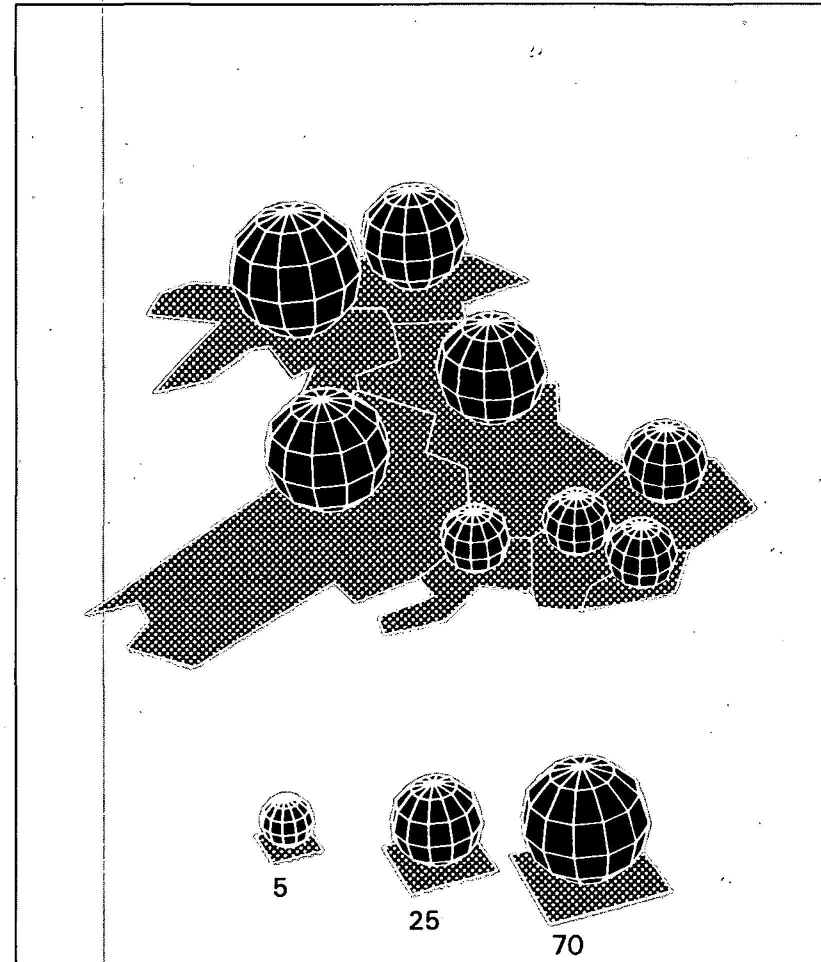
25
70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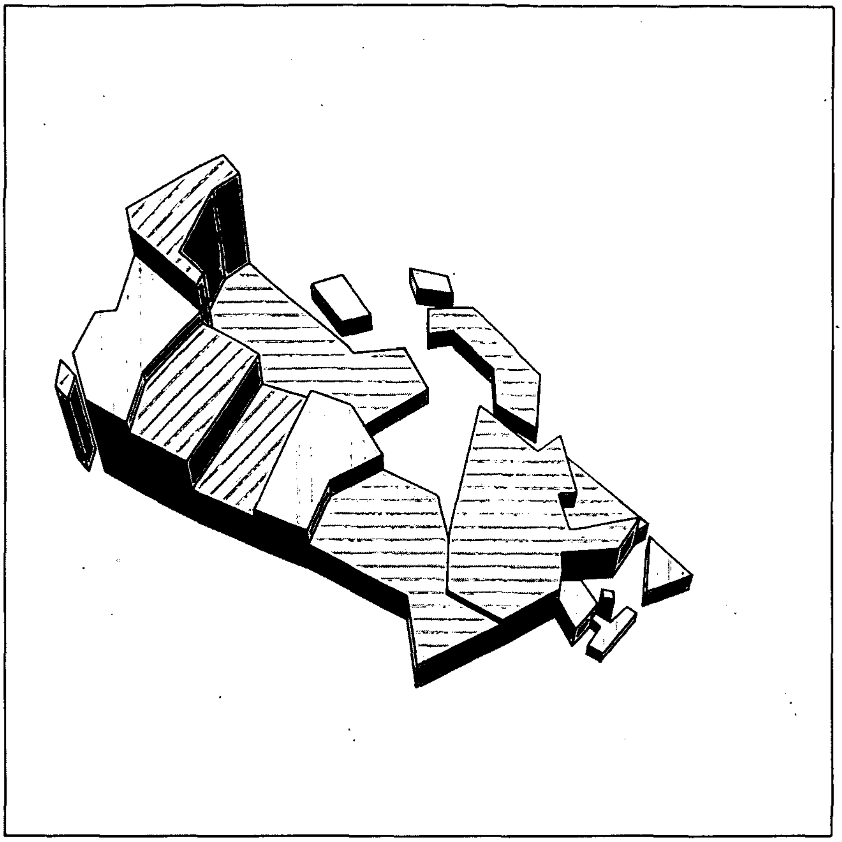

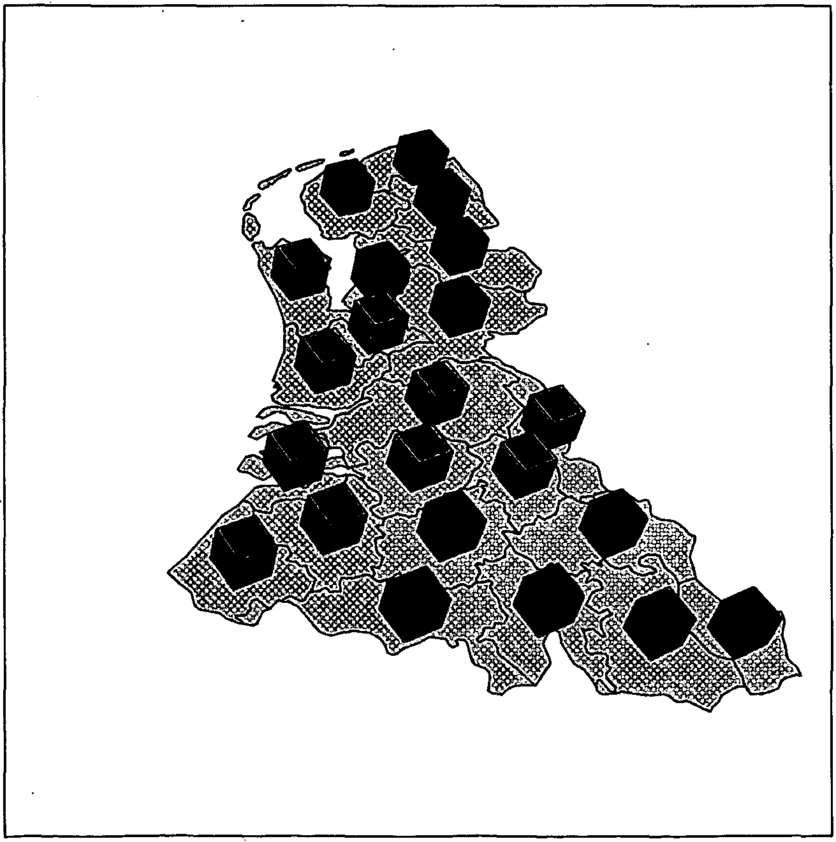

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APPENDIX I. THE PROGRAM STRUCTURE

This appendix presents a description of the program discussed in Chapter 6, where Figure 6-1 explains the program's main principles. It starts with a broad outline of the program (Figure I-1), and an explanation of how the program can be used (Figure I-2). The appendix ends with Figure I-3, the program structure at sub-routine level with an explanation of the purpose of each sub-routine.

As is shown in the scheme below (Figure I-1), five modules make up the program. Module one opens graPHIGS and takes care of the proper installation of the necessary devices and displays the program title. Modules two, three and four are equivalent to the stages 3, 4 and 5 of the three-dimensional-map production process (the pre-display of the map model, the manipulation of the map model, and the final representation of the map respectively - see Figure 6-1) described in section 6-4. Module 5 closes graPHIGS and exits the program. The full program listings are available on request (M.J. Kraak; Faculty of Geodesy, Delft University of Technology; Thijsseweg 11; 2629 JA Delft; Netherlands).

CARTPRO	produce prototype 3d-maps for CARTDIM	
	INTRO	prepare graPHIGS environment
	MAPTYP	choose map and display its wireframe
	MANIPU	manipulate the wireframe
	DISPLA	display final results
	CLOSE	close graPHIGS and exit program

Figure I-1. The programme's five main modules.

The program runs on an IBM 4361 using a 5080 workstation configuration. The colour raster screen used, an IBM 5081, has a resolution of 1024 x 1024 on a screen of 28 by 28 cm. A lower resolution is not advised, since when using a stereoscope the view is enlarged slightly which makes the separate pixels visible.

How does the program work?
After starting the program its title is displayed, followed by a menu. From this menu the user has to choose the Spatial Map Image required. There are four possibilities, providing the proper data sets are connected: 1. the prism map; 2. the digital terrain model; 3. the three-dimensional point symbol map; 4. the three-dimensional urban map.

Once the user has decided on a map type, the projection of the three-dimensional image has to be chosen (parallel or perspective). When the perspective projection is chosen, then there is an option for a mono or stereo image. When the user opts for the stereoscopic image, extra depth can be added to the image providing the user has a stereoscope available. When all choices have been made, the wireframe of the map model appears on the screen, together with an x-, y-, and z-axes for orientation.

Then the user can manipulate the map model, using the valuators (dials), i.e. rotate around the x-, y- and z-axes, scale along the z-axis, and zoom-in and zoom-out. When the map model is manipulated according to the user's wishes (the correct map position), key 1 of the lighted-programmable-function-key (lpfk) board can be used

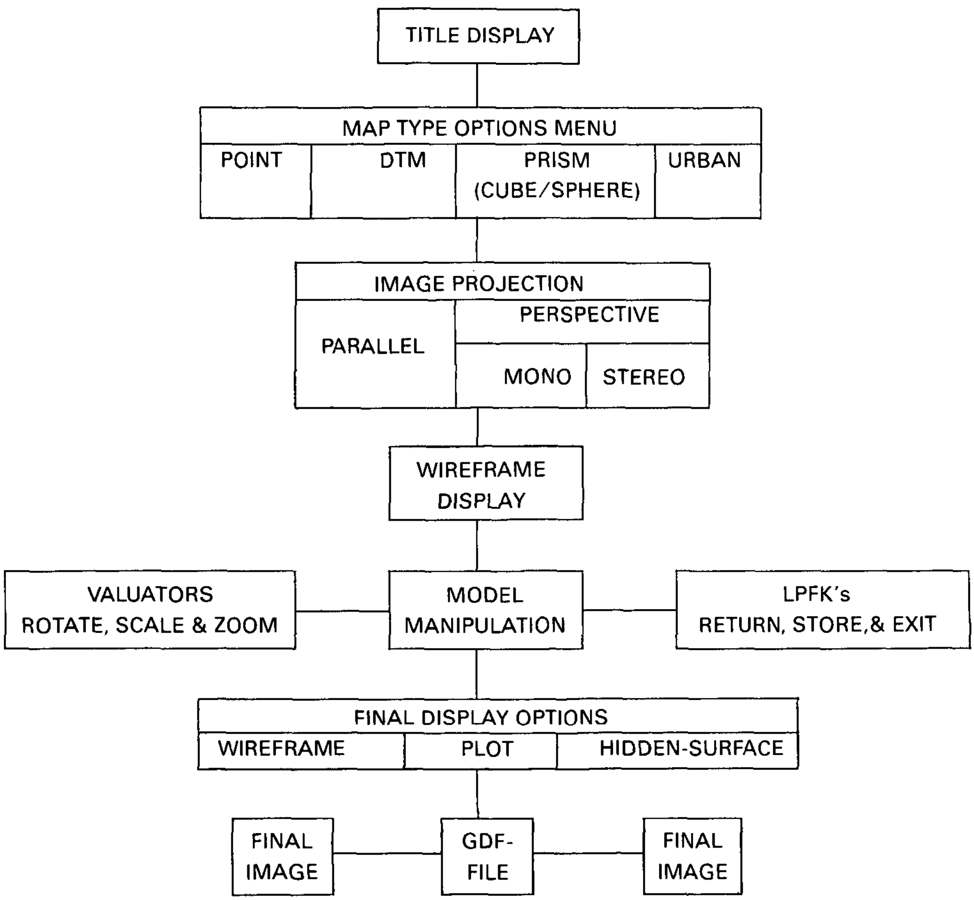


Figure I-2. Working with the program.

to store the image. Another menu to show the final display options will appear. If the user becomes confused by the model's orientation, key 29 can be used to return to the model's original position. If the user decides another map type, before storing the map image key 23 can be used to return to the menu with the map type options. Key 32 can always be used to quit the program.

In the menu with final display options the user can choose to re-display the wireframe model, to plot the wireframe model, or undertake a hidden-surface operation. From the menu it is also possible to return to the previous menu (the map type options) or leave the program. When the plot option has been chosen a GDF-file is produced. With GDDM this file can be displayed on a IBM 3270 terminal for instance, can and be plotted using a IBM 3852 inkjet printer. The program can be ended using the Enter key after the final results are displayed on the screen.

The scheme in Figure I-2 summarizes the use of the program.

The next pages (Figure I-3) present the structure of the program including the purpose of each sub-routine.

Program module 1

INTRO			prepare graPHIGS environment
	SPHIGS		install graPHIGS
	TITLE		display dynamic program title
		DRAW	draw 3d polygon
		ROTAT	rotate title's wireframe
	INDEF		install devices (valuator,lpfk,pick-device)

Program module 2

MAPTYP			chose maptype and display its wireframe
	MAPOPT		display menu with maptype options
		MAPCHO	get response from pick device
	CLOSE		close graPHIGS and exit program
	SCREEN		calculate window to centre map on screen
		CLASS	classify statistical data

MAPENV	establish view parameters for map(s)				
	STERPA	calculate stereo parameters			
LEGENV	establish view parameters for legend(s)				
MAPPIN	display chosen map type's wireframe				
	DIGTER	display digital terrain model			
		STAXIS	draw xyz-axis in wireframe		
		DRAW	draw 3d polygon		
		LEGDTM	display dtm legend		
	PRISM	display prism map			
		STAXIS	draw xyz-axis in wireframe		
		DRAW	draw 3d polygon		
		LEGPRI	display prism legend		
			CUBE	legend symbol	
			DRAW	draw 3d polygon	
	POINT	display point symbol map			
		STAXIS	draw xyz-axis in wireframe		
		DRAW	draw 3d polygon		
		CUBE	calculate cube symbol		
		SPHERE	calculate/display sphere		
			POLCAR	convert polar to cartesian coordinates	
			DRAW	draw 3d polygon	
		LEGPOI	display point legend		
			CUBE	legend symbol	
			SPHERE	calalculate & display sphere	
				POLCAR	convert polar to cartesian coordinates
				DRAW	draw 3d polygon
			DRAW	draw 3d polygon	
	URBAN	display urban map			
		STAXIS	draw xyz-axis in wireframe		
		DRAW	draw 3d polygon		
		LEGURB	display urban legend		
			CUBE	legend symbol	
			DRAW	draw 3d polygon	

Program module 3

MANIPU	manipulate the map's wireframe model	
	ROTAT	rotate the wireframe model
	ZOOM	zoom-in or -out on wireframe model
	SCALE	scale along the z-axis
	CLOSE	close graPHIGS and exit program
	FREMAP	store the map's wireframe model
	FRELEG	store the legend's wireframe model
	MESSAG	display message while storing wireframes

Program module 4

DISPLA	display final result					
	DISOPT	show final display options				
		MAPCHO	get response from pick device			
	WFRAME	re-display map model's wireframe				
		PERSPR	convert coordinates to perspective projection			
		LEGLAY	display legend text			
			STERPA	calculate stereoparameters		
	PLOT	prepare GDF-file (map's wireframe only)				
		PERSPR	convert coordinates to perspective projection			
	HSURF	display hidden-surface mapmodel				
		HIDDER	calculate hidden surfaces			
			READIN	input data for calculation		
			ADMI	check input & administer data		
			SHADOW	calculate shading parameters		
			SORT	sort polygons on z-min		
			TESTER	test polygon's visability		
				TEST1	boundary box xy	
				TEST2	plane p behind q	
					SNYVL	intersect line with plane
				TEST3	plane q front p	
					SNYVL	intersect line with plane
				TEST4	intersect projections p & q	
					SNYLL	intersect line with line

				TEST5	point p in q	
					SNYLL	intersect line with plane
					PBACKQ	point p behind q
						SNYVL
				SWAP	swap polygons p & q	
					SPLCAL	calculculate polygon split
						SNYVL
					SPLADM	administer polygon split
						ADMI
				OUTPUT	write results to output file	

Program module 5

CLOSE	close graPHIGS and exit program

Figure I-3. The program structure

APPENDIX II. THE INTRODUCTORY TEST

This appendix presents the introductory test. It includes all instructions, questions and illustrations of the test. This test was presented to the subjects to get them accustomed to the test environment, and to test their stereoscopic vision capabilities. It was also used to provide a link between the Spatial Map Images in the main test (see Appendix III) and two-dimensional cartography.

The instructions given to the subjects before the test started are given first, followed by the maps and the questions. The layout of each question follows the scheme below. The number after the title refers to the number of the illustration in this Appendix, and was not shown to the subjects:

MAP TITLE **[question number]**
Question
a) answer 1
b) answer 2
c) answer 3
d) answer 4

All text was originally presented in Dutch and on separate screens and is given below between quotation marks. The scheme below explains the location-indicators used in the questions, which are referring to the map on the screen.

UPPER LEFT	UPPER CENTRE	UPPER RIGHT
LEFT	CENTRE	RIGHT
LOWER LEFT	LOWER CENTRE	LOWER RIGHT

'The purpose of this introduction is to accustom you to the way of testing and to the use of the stereoscope as it will be used in the main test.'

'The main test consists of two sets (mono and stereo) of maps and accompanying questions. Several questions can be asked with a single map. After the answer has been given it can take some time before the next map will be displayed, because of the map complexity .'

'The questions in this test are of the multiple-choice type, and are shown in the upper right corner of the screen. Read the question and choose from the correct answer the options (A, B, C, or D). Point to the box concerned, using the locator, and press a locator button. Then the next question or map will appear.'

'In the questions locations in the map are related to their locations on the screen (such as centre, right, upper left, lower centre). When no legend is displayed the necessary information can be found in the questions. Now the first question will follow.'

'BENELUX **[Aa]**
What is the colour of the Netherlands?
a) blue
b) red
c) yellow'

Figure II-1. Question A.

'BENELUX **[Aa]**
Which country has the fewest provinces?
a) Netherlands
b) Belgium
c) Luxembourg'

'IRELAND POPULATION DENSITY **[Ba]**
To which class does the upper county belong?
a) highest (darkest)
b) lowest c)
middle'

'IRELAND POPULATION DENSITY **[Bb]**
Where is the population density the highest?
a) right
b) lower centre
c) centre'

Figure II-2. Question B.

Figure II-3. Question C.

'BENELUX **[Ca]**
What is the colour of the province of Groningen?
a) blue
b) green
c) yellow'

'BENELUX **[Cb]**
Where are most purple areas located?
a) upper centre
b) centre
c) left'

Figure II-4. Question D.

'PORTUGAL POPULATION **[D]**
Where is the lowest population density to be found?
a) right
b) below
centre c)
left'

'The following images are displayed in stereo. Please place the stereoscope in front of the screen.'

'CUBE **[E]**
Which figure on the cube is closest?
a) triangle
b) octagon'

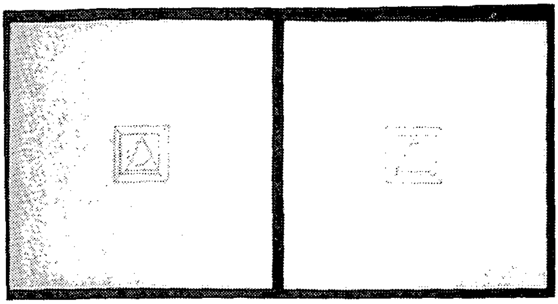


Figure II-5. Question E.

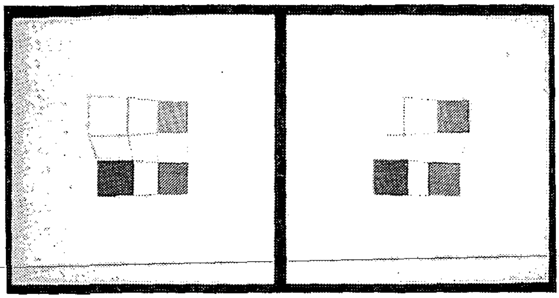


Figure II-6. Question F.

'FOUR PLANES I [F]
Which plane is third from the observer?
a) yellow
b) blue
c) red
d) green'

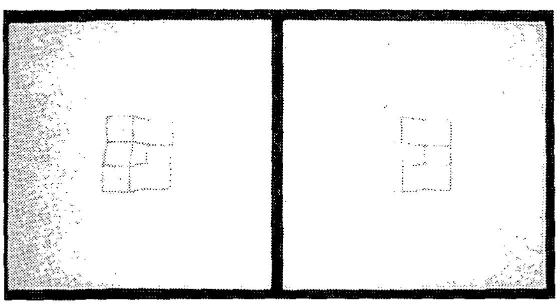


Figure II-7. Question G.

'FOUR PLANES II [G]
Which plane is closest to the observer?
a) plane 1
b) plane 2
c) plane 3
d) plane 4'

When the subject failed the stereoscopic test the following message appeared on the screen:

'The results of the stereo test indicate that your capability to see stereo is unsatisfactory, and since this can influence the test results negatively you can not participate further in the test. Thank you for your cooperation'

When stereoscopic vision was statisfactory the following message was displayed, indicating the main test was about to start:

'End of the introduction. Please remove the stereoscope. The main test is about to start.'

APPENDIX III. THE MAIN TEST

Appendix III presents the questions and Spatial Map Images of the main test. This part of the computer-assisted map user test was presented to the subjects in two sections. The first section consists of the mono maps whilst the second consists of the stereo maps. This was done to avoid a constant shifting of the stereoscope to and from the screen.

The layout of each question follows the scheme below. The number after the title refers to the question number, and was not shown to the subject. The order of the maps in the appendix does not necessarily correspond with their sequence in the test to avoid passing on of answers between subjects. The numbers correspond to the numbers in Figure 7-6 and the scheme in Appendix IV. Within the mono and stereo section of the main test the order of the maps was randomly changed for each new subject. All text was originally presented in Dutch.

MAP TITLE **[question number]**
Question
a) answer1
b) answer 2
c) answer 3
d) answer 4

The scheme below explains the location-indicators used in the questions, which are referring to the map on the screen.

UPPER LEFT	UPPER CENTRE	UPPER RIGHT
LEFT	CENTRE	RIGHT
LOWER LEFT	LOWER CENTRE	LOWER RIGHT

'AUSTRALIA - NUMBER OF SHEEP **[1a]**
Which state has most sheep?
a) upper centre
b) left
c) lower centre'

'AUSTRALIA - NUMBER OF SHEEP **[1b]**
How much less sheep does the island have as compared with the state with most sheep?
a) 50%
b) 90%
c) 25%'

'AUSTRALIA - NUMBER OF SHEEP **[1c]**
Where can the states with the fewest sheep be found?
a) centre
b) upper centre c)
lower centre'

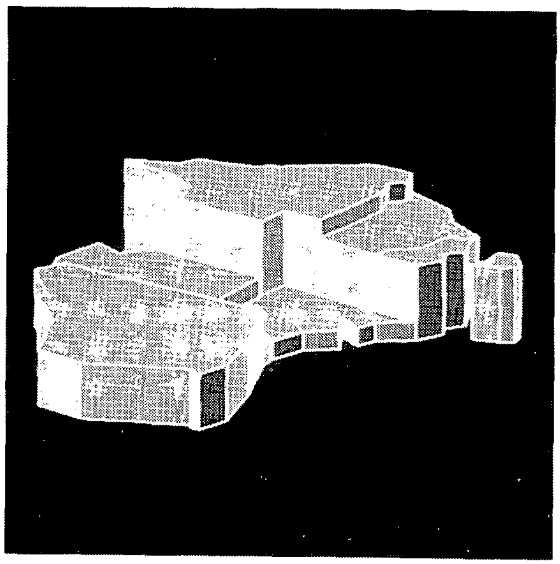


Figure III-1. Question 1.

'NEW MEXICO - NUMBER OF INHABITANTS AND PERCENTAGE OF INDIANS (the choropleth) **[2a]**
To which category does the percentage of Indians of the lower right county belong?
a) lowest
b) middle
c) highest'

'NEW MEXICO - NUMBER OF INHABITANTS AND PERCENTAGE OF INDIANS (the choropleth) **[2b]**
Does the upper right county have a higher or lower percentage than the county at the lower right?
a) lower
b) equal
c) higher'

'NEW MEXICO - NUMBER OF INHABITANTS AND PERCENTAGE OF INDIANS (the choropleth) **[2c]**
Where in New Mexico are the counties with the highest percentage of Indians to be found?
a) left
b) right
c) centre'

'WESTERN UNITED STATES - NUMBER OF FARMS [3a]
What value has the state furthest left?
a) high
b) low
c) middle'

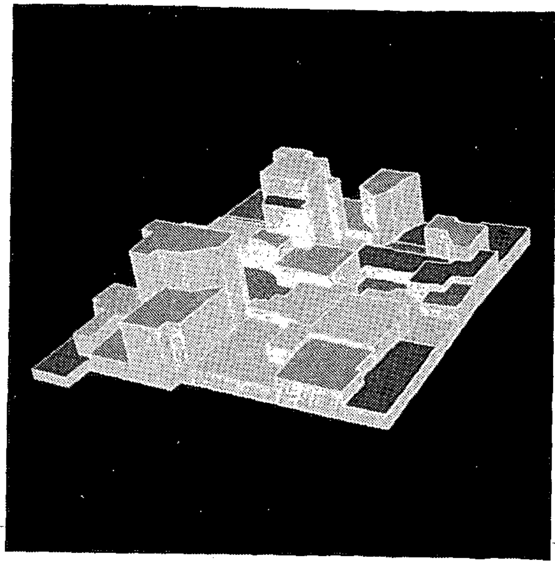


Figure III-2. Question 2.

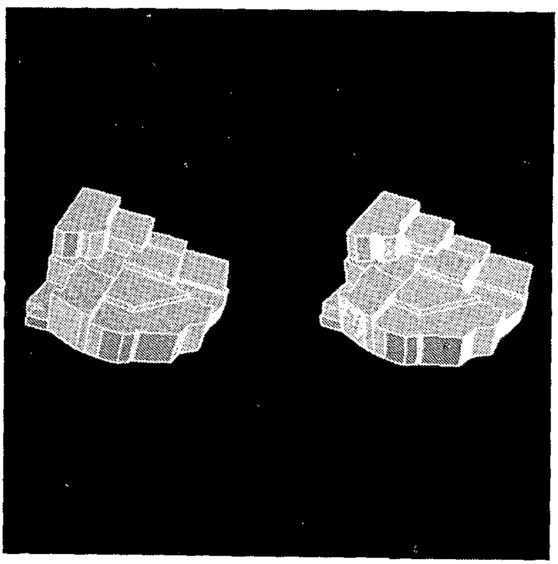


Figure III-3. Question 3.

'WESTERN UNITED STATES - NUMBER OF FARMS **[3b]**
How many other states have low values?
a) 3
b) 7
c) 5'

'WESTERN UNITED STATES - NUMBER OF FARMS **[3c]**
Which group of states dominate the map?
a) those with low values
b) those with high values
c) those with middle values'

'WESTERN UNITED STATES - NUMBER AND DENSITY OF HOUSES (the choropleth) **[4a]**
To which class does the house density of the lower most state belong?
a) lowest
b) highest (darkest)
c) middle'

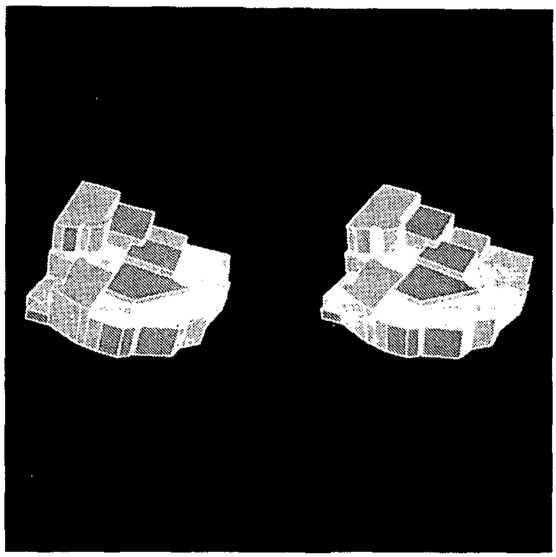


Figure III-4. Question 4.

'WESTERN UNITED STATES - NUMBER AND DENSITY OF HOUSES (the choropleth) **[4b]**
Does the upper most state have a higher or lower density then the lower most state?
a) higher
b) lower
c) equal'

'WESTERN UNITED STATES - NUMBER AND DENSITY OF HOUSES (the choropleth) **[4c]**
How many states belong to the highest density class?
a) 2
b) 3
c) 5'

'BELGIUM ARDENNES - OURTHE VALLEY **[5a]**
Where is the lowest point in the valley?
a) lower centre
b) upper centre
c) right'

'BELGIUM ARDENNES - OURTHE VALLEY **[5b]**
Looking from the middle of the area, where is the highest point to be found?
a) lower right
b) upper left
c) upper right'

'BELGIUM ARDENNES - OURTHE VALLEY **[5c]**
How can the area be characterized?
a) a plain
b) mountainous
c) hilly'

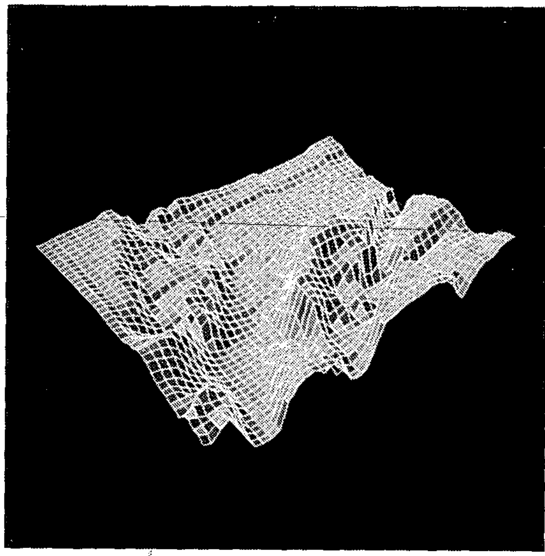


Figure III-5. Question 5.

'SAN FRANCISCO - LAND USE **[6a]**
What is the land use type along the coast on the right?
a) built-up area (yellow)
b) park (green)
c) industry (brown)'

'SAN FRANCISCO - LAND USE **[6b]**
Where else, in addition to the coast on the right, can industry (brown) be found?
a) upper centre
b) lower centre
c) nowhere'

'SAN FRANCISCO - LAND USE **[6c]**
Which land use category covers the smallest area?
a) park (green)
b) built-up area (yellow)
c) industry (brown)'

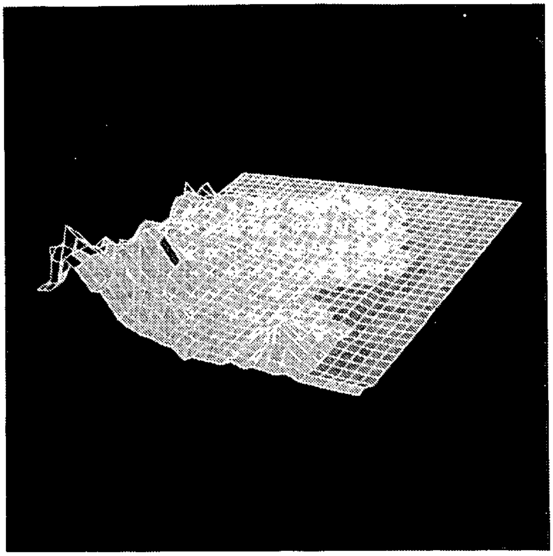


Figure III-6. Question 6.

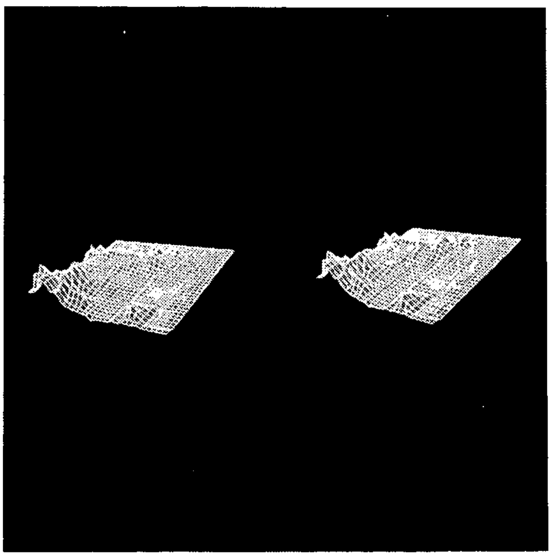


Figure III-7. Question 7.

'SAN FRANCISCO - LAND USE **[7a]**
What is the land use type on the highest point?
a) built-up area (yellow)
b) park (green)
c) industry (brown)'

'SAN FRANCISCO - LAND USE **[7b]**
Where else, in addition to lower left, can park (green) be found?
a) upper centre
b) lower centre
c) centre '

'SAN FRANCISCO - LAND USE **[7c]**
Which land use category dominates the map?
a) water (blue)
b) built-up area (yellow)
c) industry (brown)'

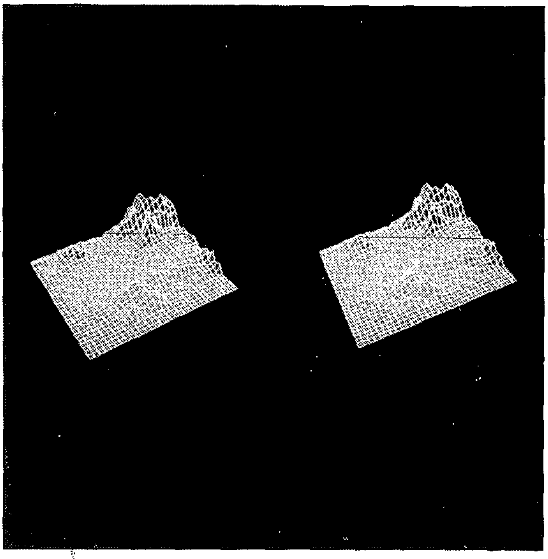


Figure III-8. Question 8.

'SAN FRANCISCO - PRECIPITATION **[8a]**
What is the amount of precipitation on the highest point?
a) much (dark)
b) few
c) mean'

'SAN FRANCISCO - PRECIPITATION **[8b]**
Is the precipitation in the lower left higher or lower than on the highest point?
a) more
b) less
c) equal'

'SAN FRANCISCO - PRECIPITATION **[8c]**
Is there a relation between the precipitation pattern and the relief?
a) yes
b) no
c) not clear'

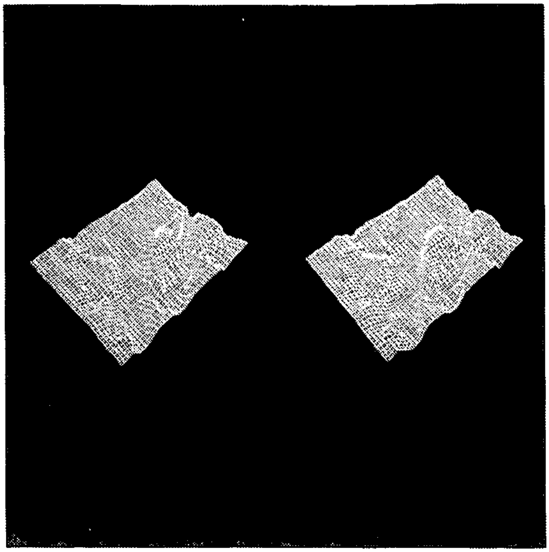


Figure III-9. Question 9.

'BELGIUM ARDENNES - OURTHE VALLEY **[9a]**
Where is the lowest point in the valley?
a) lower centre
b) upper centre
c) right'

'BELGIUM ARDENNES - OURTHE VALLEY **[9b]**
Looking from the middle of the area, where is the highest point to be found?
a) lower right
b) upper left
c) upper right'

'BELGIUM ARDENNES - OURTHE VALLEY **[9c]**
How can the area be characterized?
a) a plain
b) mountainous
c) hilly'

'GREAT BRITAIN - A NIGHT OUT IN THE CITIES **[10a]**
What is the most prominent type of entertainment in the upper left city?
a) museum (red)
b) theatre (yellow)
c) cinema (blue)'

'GREAT BRITAIN - A NIGHT OUT IN THE CITIES **[10b]**
Are there in the lower right area more or less 'cinema-cities' than in the upper left?
a) more
b) equal
c) less'

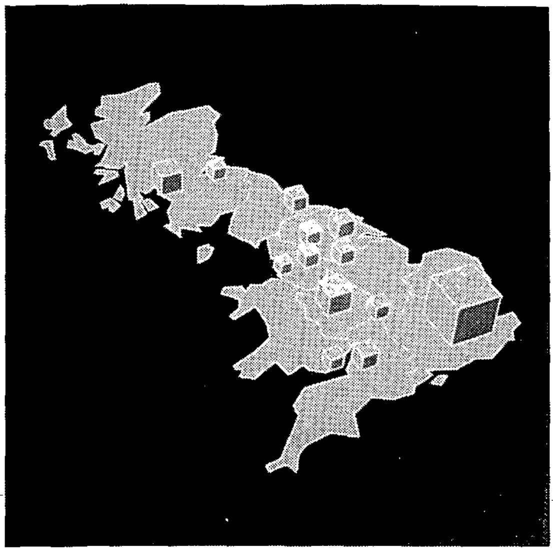


Figure III-10. Question 10.

'GREAT BRITAIN - A NIGHT OUT IN THE CITIES **[10c]**
Which type of entertainment predominates most cities?
a) museum (red)
b) theatre (yellow)
c) cinema (blue)'

'BENELUX - INHABITANTS PER PROVINCE' **[11a]**
How many inhabitants has the lower most province compared to the others?
a) many
b) mean
c) few'

'BENELUX - INHABITANTS PER PROVINCE' **[11b]**
How many provinces have about the same number of inhabitants as the lower most province?
a) 5
b) 10
c) 18'

'BENELUX - INHABITANTS PER PROVINCE' **[11c]**
Where are the provinces with the lowest number of inhabitants concentrated?
a) lower centre & upper right
b) left & lower right
c) right & upper left'

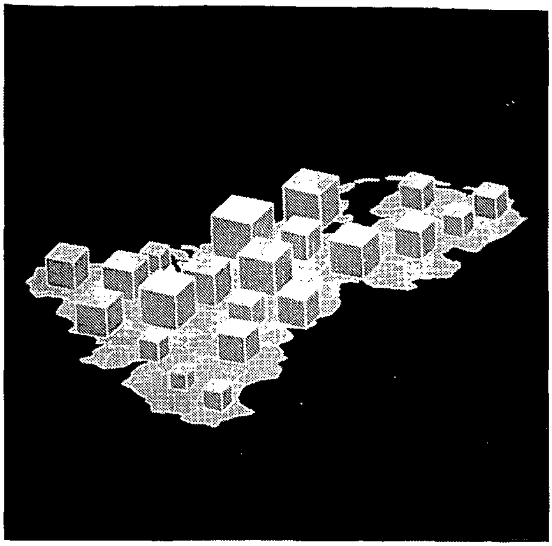


Figure III-11. Question 11.

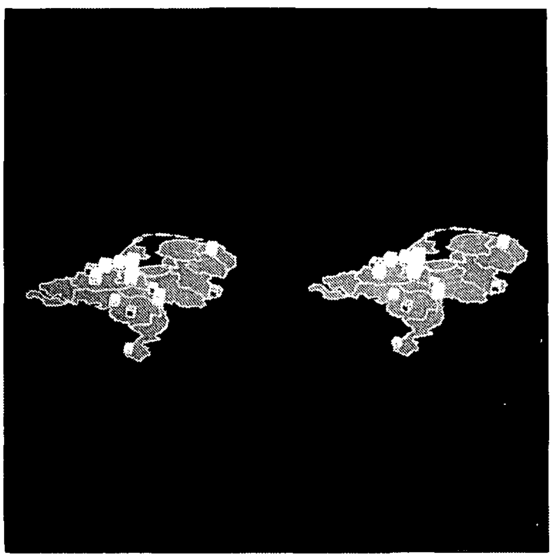


Figure III-12. Question 12.

'DUTCH UNIVERSITIES - TYPES AND NUMBER OF STUDENTS **[12a]**
To which category does Maastricht University belong?
a) ordinary (yellow)
b) agriculture (green)
c) technical (blue)'

'DUTCH UNIVERSITIES - TYPES AND NUMBER OF STUDENTS **[12b]**
How many other universities have about the same number of students as Maastricht?
a) 8
b) 3
c) 1'

'DUTCH UNIVERSITIES - TYPES AND NUMBER OF STUDENTS **[12c]**
To which category does the university with most students belong?
a) agriculture (green)
b) technical (blue)
c) ordinary (yellow)'

'GREAT BRITAIN - LARGE CITIES **[13a]**
How can the left-most city in the country be described?
a) large
b) small
c) middle'

'GREAT BRITAIN - LARGE CITIES **[13b]**
How many other of those cities are there?
a) 1
b) 2
c) 3'

'GREAT BRITAIN- LARGE CITIES **[13c]**
Where in the country is the largest city located?
a) right
b) left
c) below '

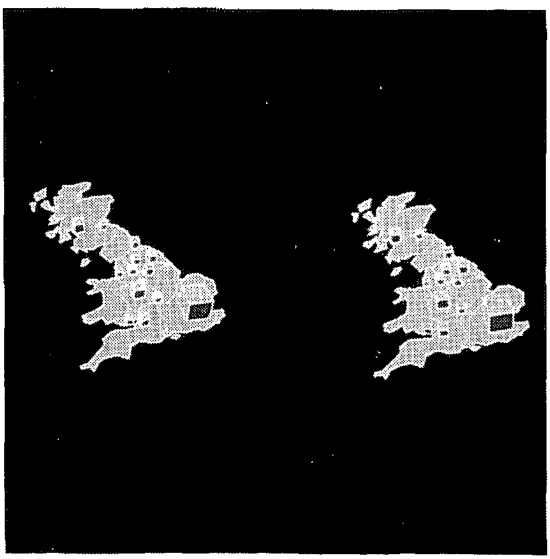


Figure III-13. Question 13.

'OLDTOWN - CENTRE **[14a]**
Where can the highest building be found?
a) centre
b) right
c) lower centre'

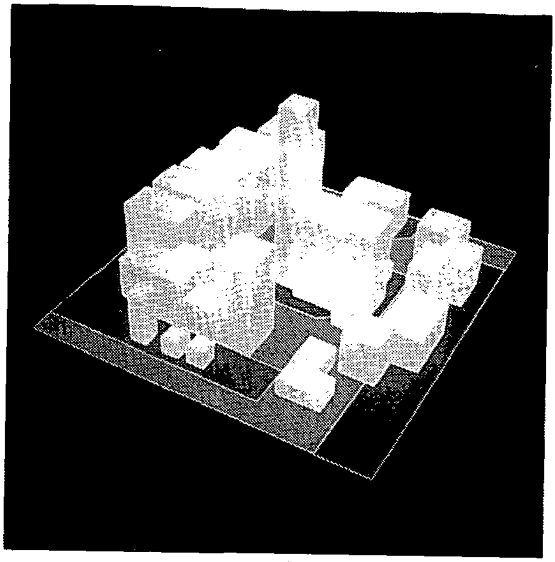


Figure III-14. Question 14.

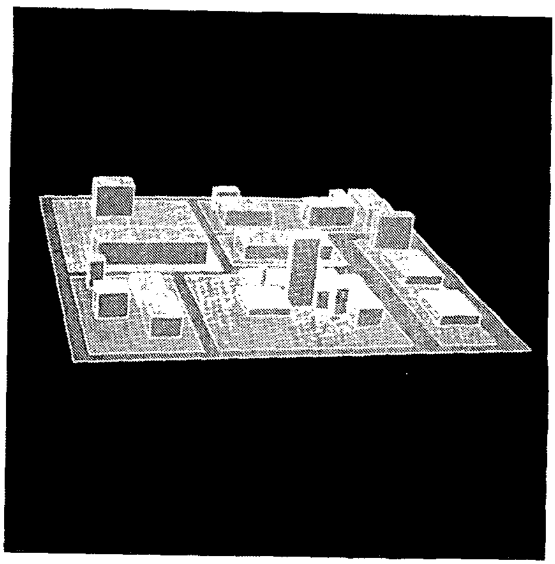


Figure III-15. Question 15.

'OLDTOWN - CENTRE **[14b]**
Which land use category dominates the upper half of the map?
a) street (gray)
b) park (green)
c) houses (yellow)'

'OLDTOWN - CENTRE **[14c]**
How can the land use in the map be characterized?
a) city centre
b) suburban
c) rural

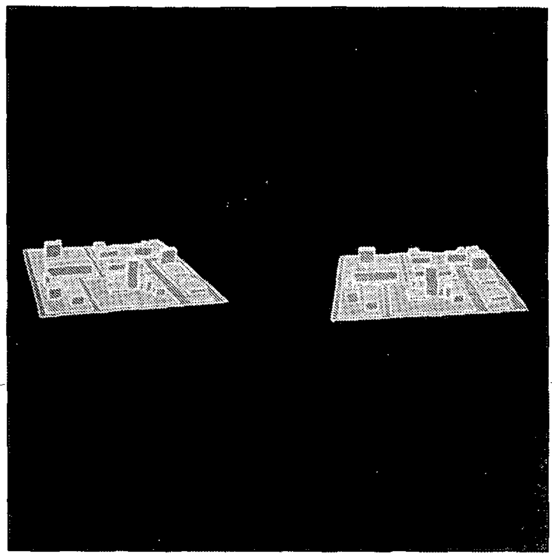


Figure III-16. Question 16.

'INDUSTRIAL ESTATE **[15a & 16a]**
Where is the highest building to be found?
a) lower half of the map
b) upper half of the map'

'INDUSTRIAL ESTATE **[15b & 16b]**
Are there more buildings with about the same height as the tallest?
a) yes
b) no'

'INDUSTRIAL ESTATE **[15c & 16c]**
Are there more higher or lower buildings?
a) more lower
b) more higher'

'NEW TOWN - LAND USE **[17a]**
What is the land use category of the right-most buildings?
a) offices (grey)
b) housing (yellow)
c) shops (brown)'

'NEW TOWN - LAND USE **[17b]**
In which part of the town are most houses to be found?
a) upper left
b) upper right
c) below left'

'NEW TOWN - LAND USE **[17c]**
Which land use category dominates the map?
a) built-up area (grey/yellow/brown)
b) parks (green)
c) water (blue)'

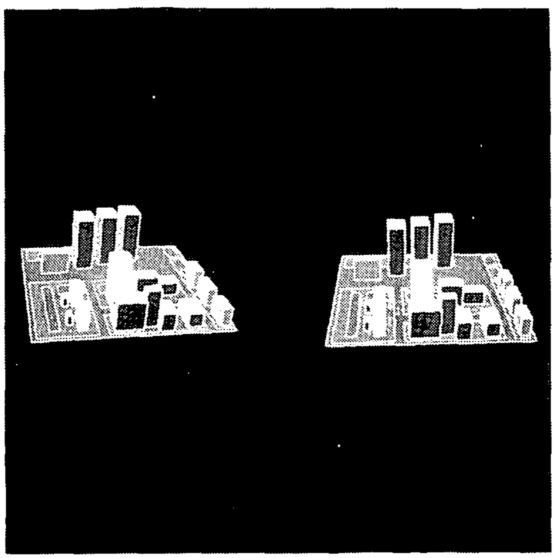


Figure III-17. Question 17.

'GREAT BRITAIN'S CITIES - NUMBER OF INHABITANTS (x1000) **[18]**
How many inhabitants has the upper left city?
a) 342
b) 220
c) 865
d) 458'

'WALES - PERCENTAGE SPEAKING WELSH [19]
What percentage of the people speak Welsh in the lower right county?
a) 8%
b) 22%
c) 15%
d) 2%'

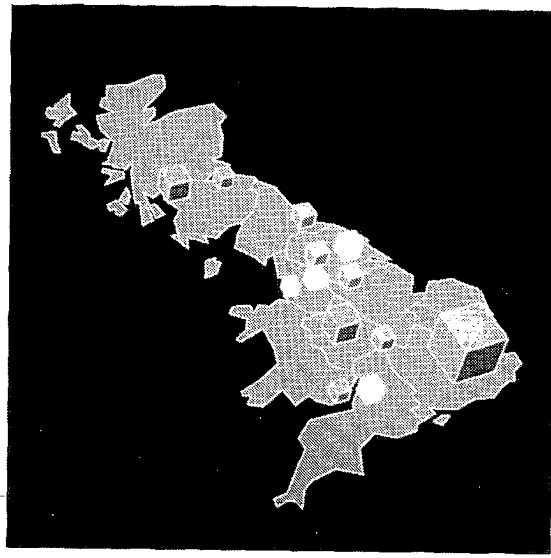


Figure III-18. Question 18.

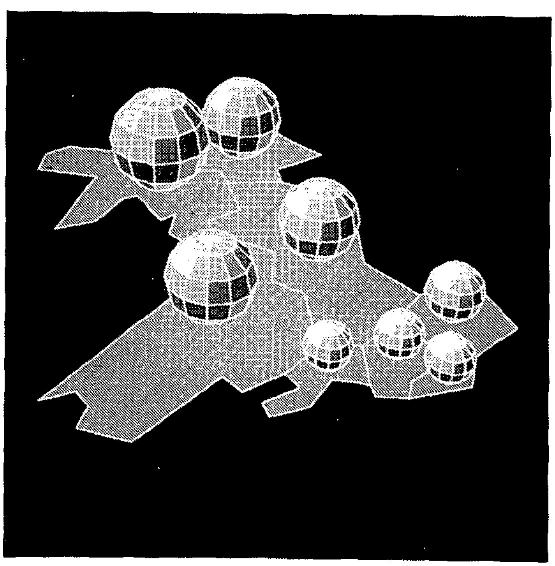


Figure III-19. Question 19.

'SOUTH WEST UNITED STATES - NUMBER OF INDIANS **[20]**
In which state live most Indians?
a) right
b) left
c) upper centre
d) lower centre'

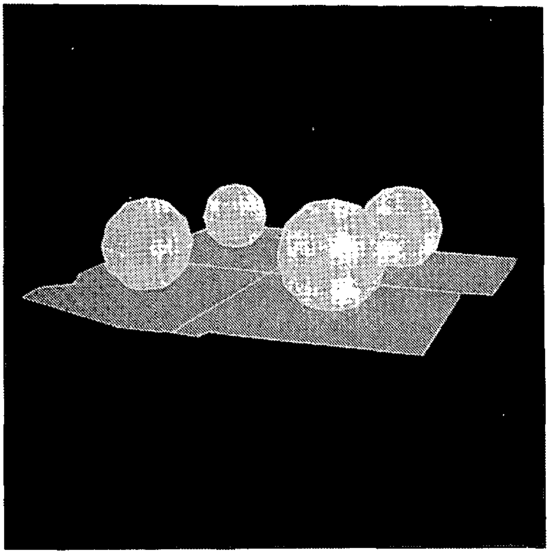


Figure III-20. Question 20.

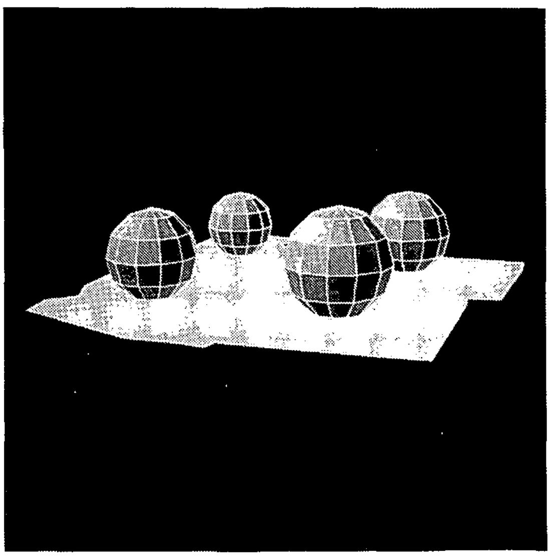


Figure III-21. Question 21.

'SOUTH WEST UNITED STATES - NUMBER OF INDIANS **[21]**
How many times more Indians live in the lower right state compared with the upper left state?
a) 1
b) 2
c) 3
d) 4'

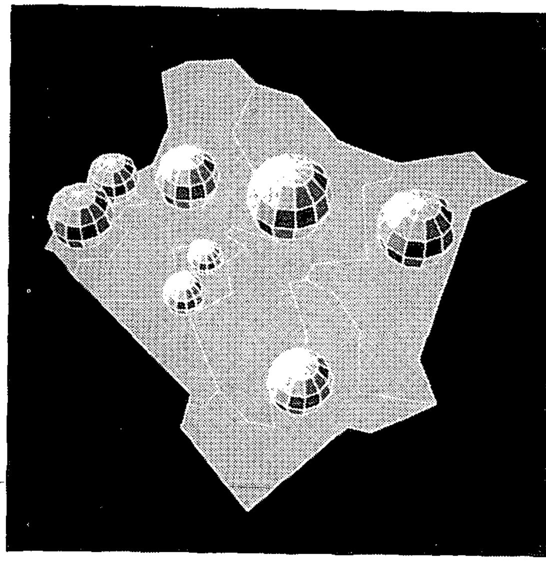


Figure III-22. Question 22.

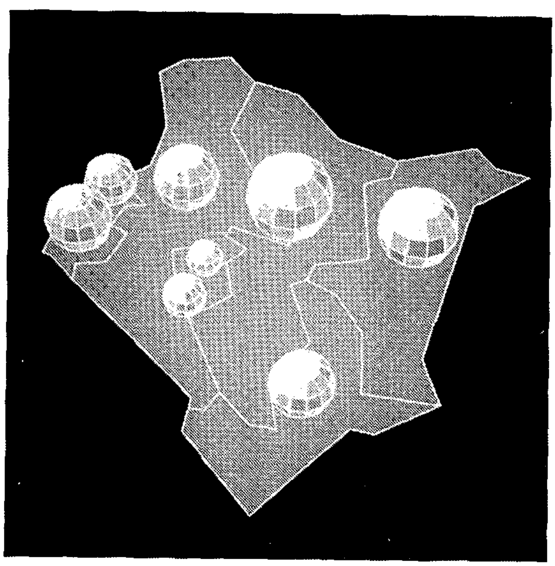


Figure III-23. Question 23

'KENYA - NUMBER OF MASAI [22]
Which province has the highest number of Masai?
a) right
b) centre
c) lower centre
d) left'

'KENYA - NUMBER OF MASAI [23]
In which part of the country live the fewest number of Masai?
a) lower left
b) upper centre
c) left'

'BENELUX - INHABITANTS PER PROVINCE' [24]
How many inhabitants does the left-most province have?
a) 1082
b) 560
c) 1710
d) 2370'

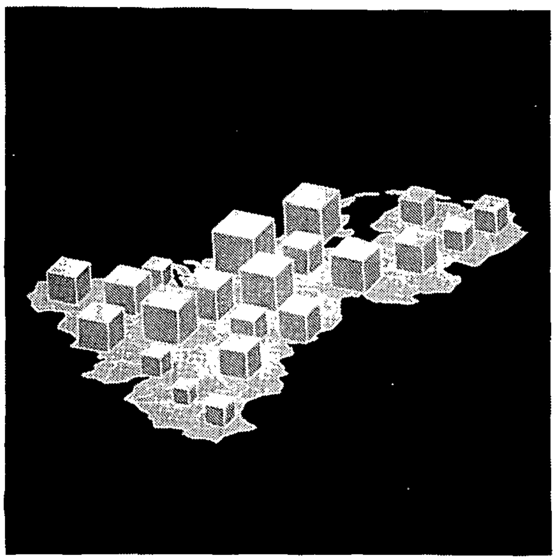


Figure III-24. Question 24.

'GREAT BRITAIN'S CITIES - NUMBER OF INHABITANTS (x1000) [25]
How many inhabitants has city in the upper left?
a) 342
b) 220
c) 865
d) 458'

'WALES - PERCENTAGE SPEAKING WELSH [26]
What percentage of the people speak Welsh in the upper right county?
a) 10%
b) 50%
c) 40%
d) 30%'

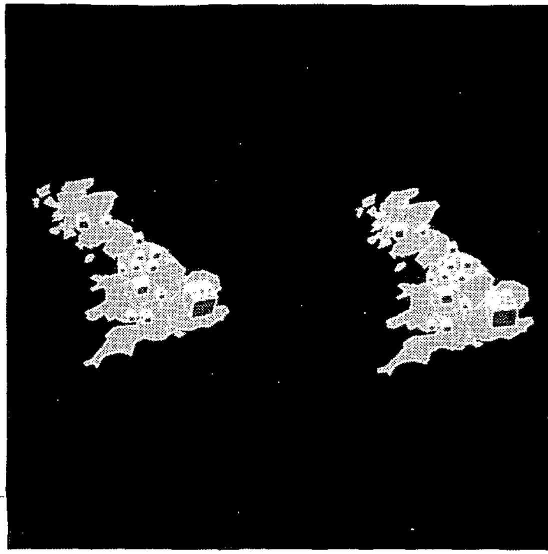


Figure III-25. Question 25.

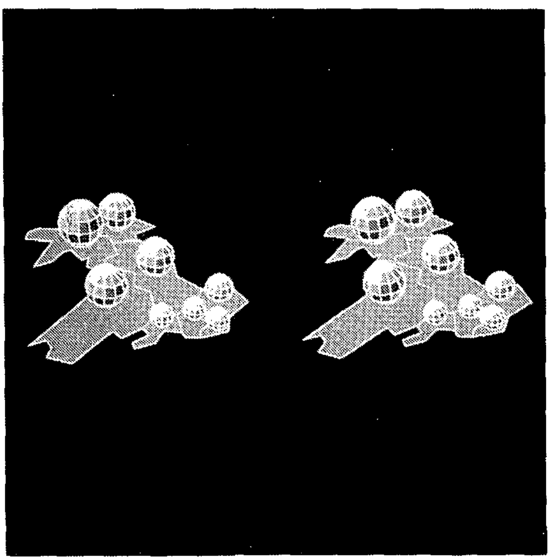


Figure III-26. Question 26.

'CANADA - ALLOCHTONOUS AND BILINGUALS (the choropleth) [27]
In which part of the country can the province with the highest percentage bilinguals be found?
a) left
b) centre
c) middle'

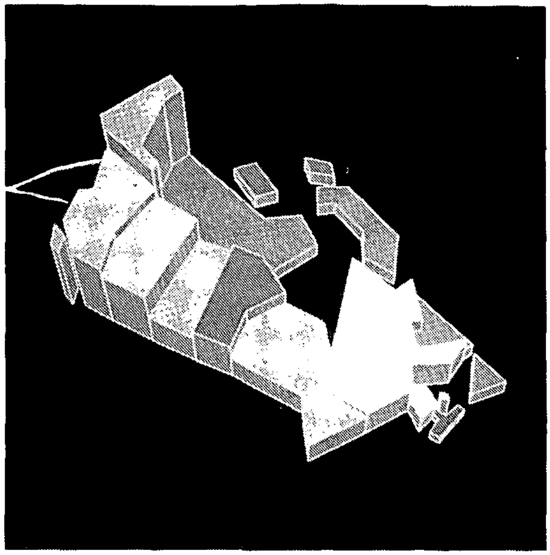


Figure III-27. Question 27.

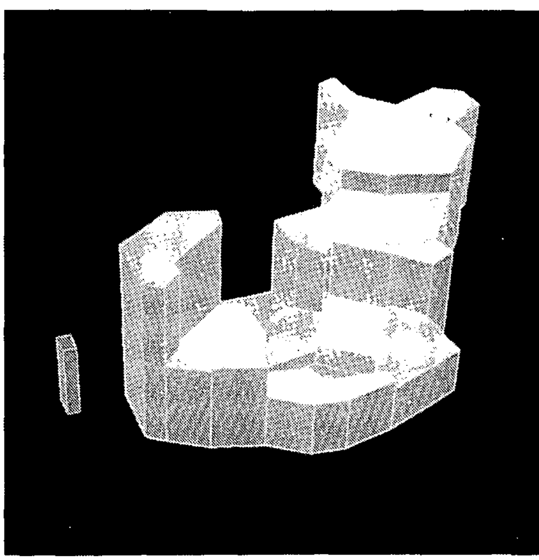


Figure III-28. Question 28.

'FINLAND - WOOD PRODUCTION AND PERCENTAGE SPRUCE (the choropleth) **[28]**
Has the upper province a higher or lower percentage spruce than the province with the highest wood production?
a) higher
b) lower
c) equal'

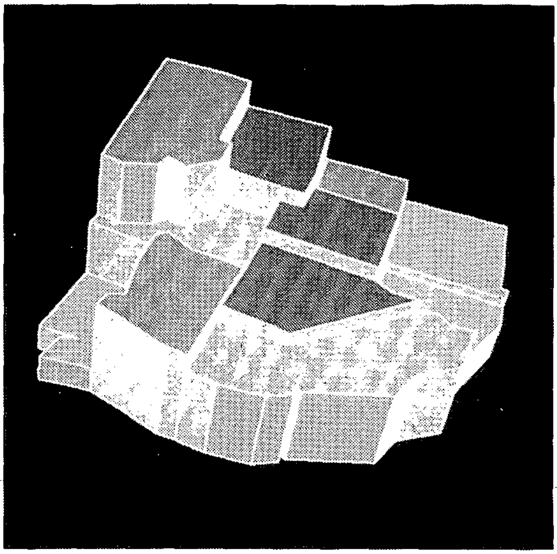


Figure III-29. Question 29.

'WESTERN UNITED STATES - TOURIST ATTRACTIONS AND AMUSEMENT PARKS (the choropleth) **[29]**
Which states have a high percentage of amusement parks?
a) those with many tourist attractions
b) there is no relation
c) those with few tourist attractions'

'NEW MEXICO - NUMBER OF INHABITANTS AND PERCENTAGE OF CATHOLICS (the choropleth) **[30]**
Is the percentage of Catholics in the county with most inhabitants higher or lower than in the county furthest left below?
a) higher
b) lower
c) equal

'AUSTRALIA - MARSUPIALS AND PERCENTAGE OF KANGAROOS (the choropleth) **[31]**
What is the percentage of kangaroos in the state with most marsupials compared with the island?
a) higher
b) lower
c) equal'

'AUSTRALIA - MARSUPIALS AND PERCENTAGE OF KANGAROOS (the choropleth) [32]
In which part of Australia can the states with the highest percentage of kangaroos be found?
a) left
b) right
c) below centre'

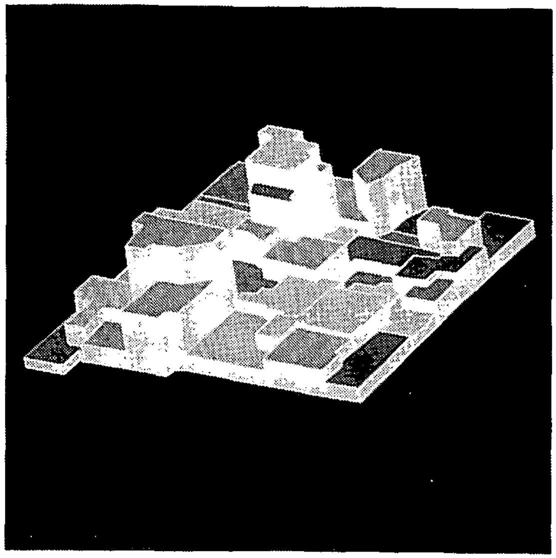


Figure III-30. Question 30.

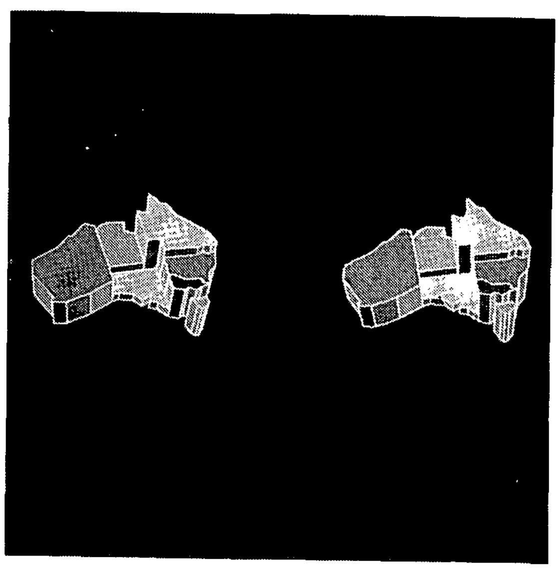


Figure III-31. Question 31.

'NEW MEXICO - CROPS AND PRODUCTION [33]
Which crop (patterns) has the highest production in the lower left of the state?
a) sisal (horizontal cross)
b) cassava (waves)
c) corn (diagonal cross)'

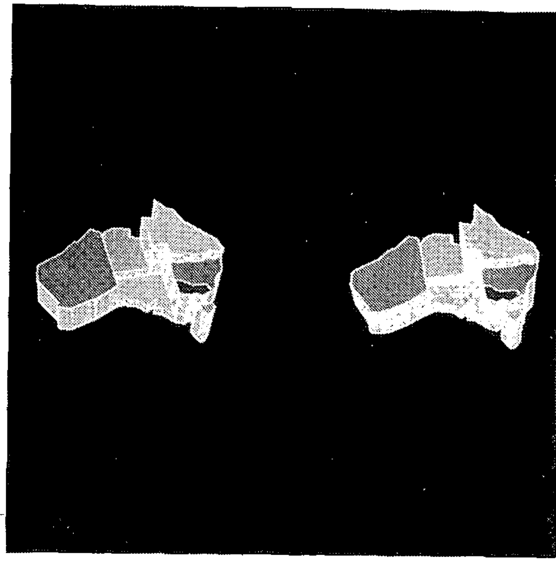


Figure III-32. Question 32.

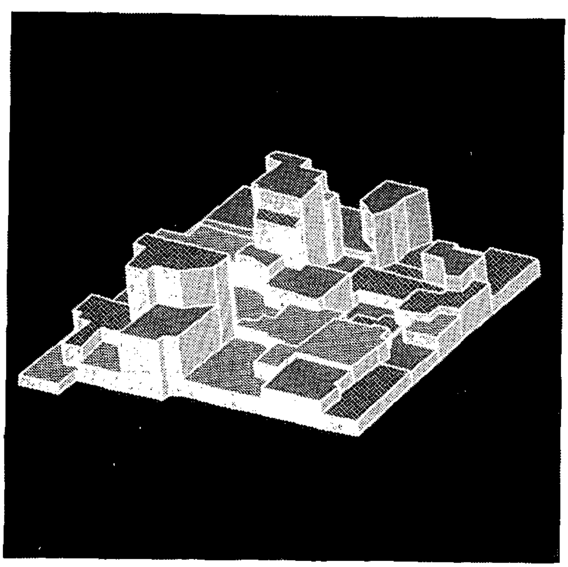


Figure III-33. Question 33.

'NEW MEXICO - CROPS AND PRODUCTION **[34]**
Which crop (patterns) in the upper part of the map has the lowest production?
a) sisal (horizontal cross)
b) cassava (waves)
c) corn (diagonal cross)'

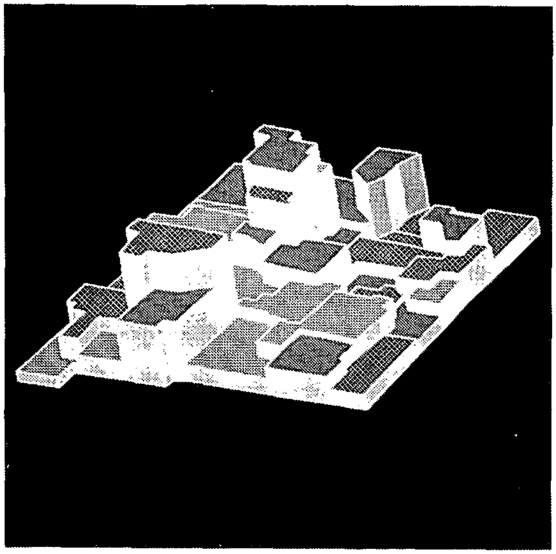


Figure III-34. Question 34.

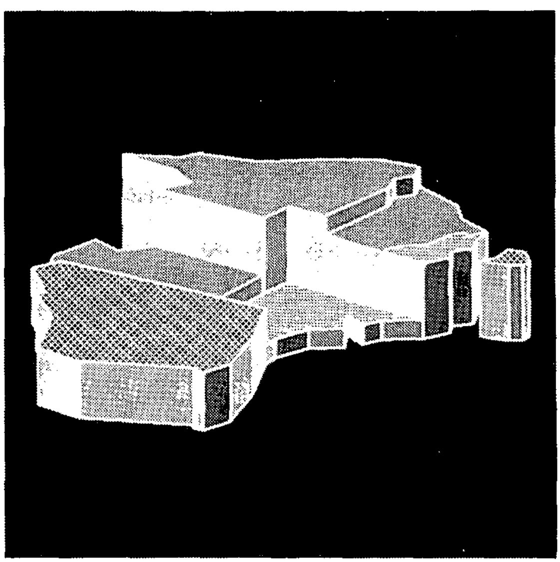


Figure III-35. Question 35.

'AUSTRALIA - NUMBER OF IMMIGRANTS AND THEIR ORIGINS [35]
Which population group (patterns) dominates the lower part of the map?
a) Scottish (horizontal cross)
b) Welsh (diagonal cross)
c) English (waves)

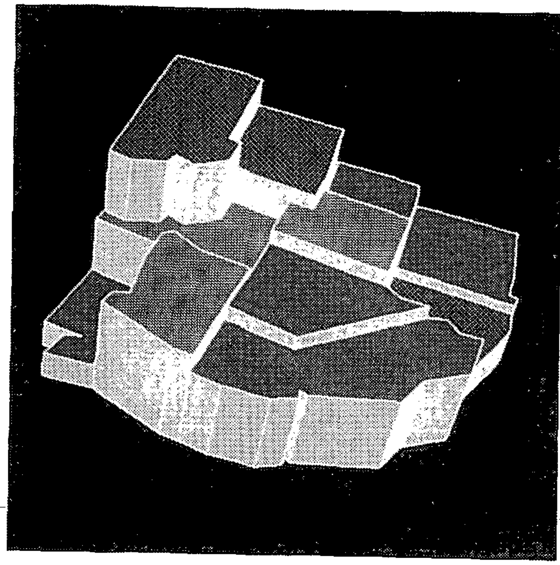


Figure III-36. Question 36.

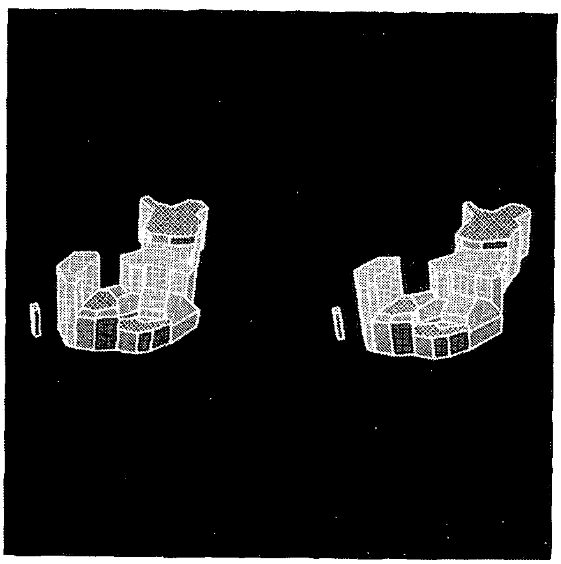


Figure III-37. Question 37.

'WESTERN UNITED STATES - MINERALS AND PRODUCTION **[36]**
Which state has the lowest coal production (coal=waves)?
a) left
b) right
c) lower centre'

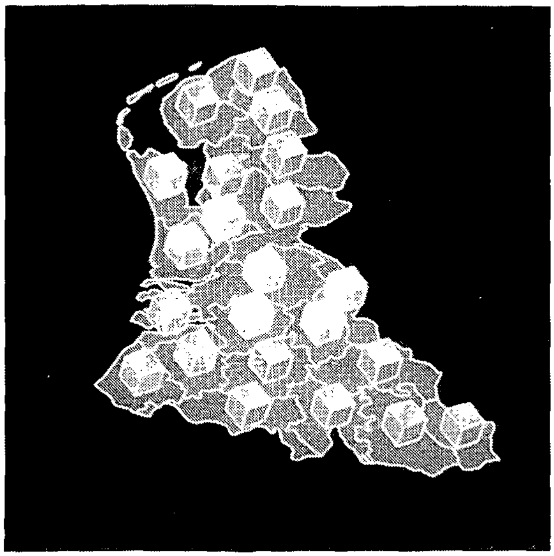


Figure III-38. Question 38 and 39.

'FINLAND - SWEDISH SPEAKING INHABITANTS AND THEIR ORIGINAL LOCATION IN SWEDEN **[37]**
From which part of Sweden are the Swedish in the right of the map?
a) Middle (waves)
b) North (diagonal cross)
c) South (horizontal cross)'

'BENELUX - POLITICAL PREFERENCES **[38]**
Which party captured most provinces?
a) liberals (blue)
b) socialists (red)
c) equal'

'BENELUX - POLITICAL PREFERENCES **[39]**
Which group liberals (blue) has most votes?
a) no difference
b) northern group
c) southern group'

'BENELUX - POLITICAL PREFERENCES [40]
Which group socialists (red) has most preferences?
a) no difference
b) northern group
c) southern group'

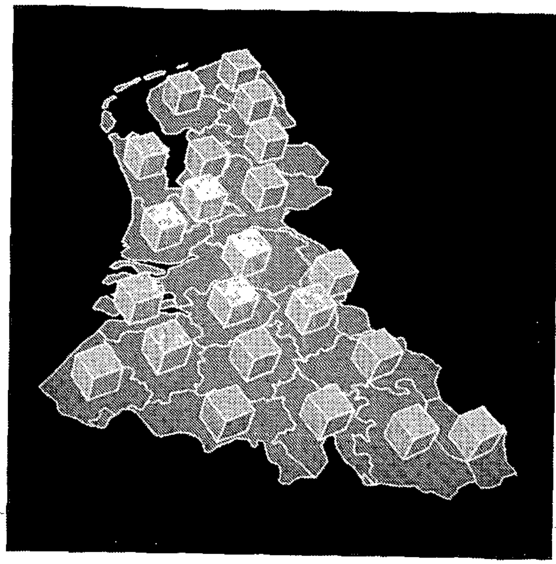


Figure III-39. Question 40.

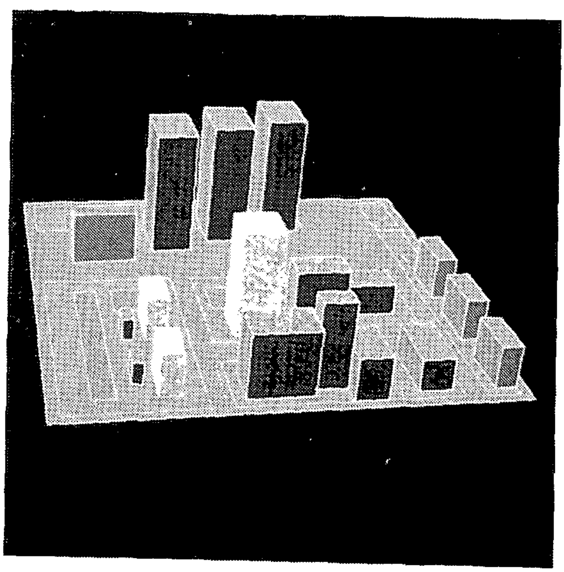


Figure III-40 . Question 41.

'NEWTOWN - LAND USE [41]
Which land use category covers the least area in the upper half of the map.
a) street (grey)
b) park (green)
c) water (blue)'

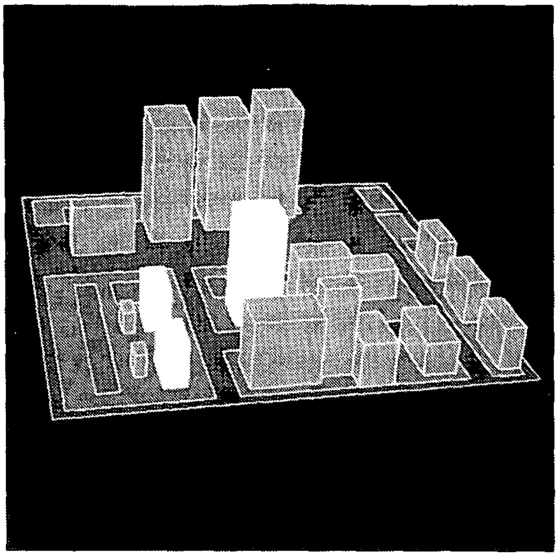


Figure III-41. Question 42.

Figure III-42. Question 43.

'NEWTOWN - LAND USE [42]
Which building type can only be found in the lower left in the map?
a) shops (brown)
b) housing (yellow)
c) offices (grey)'

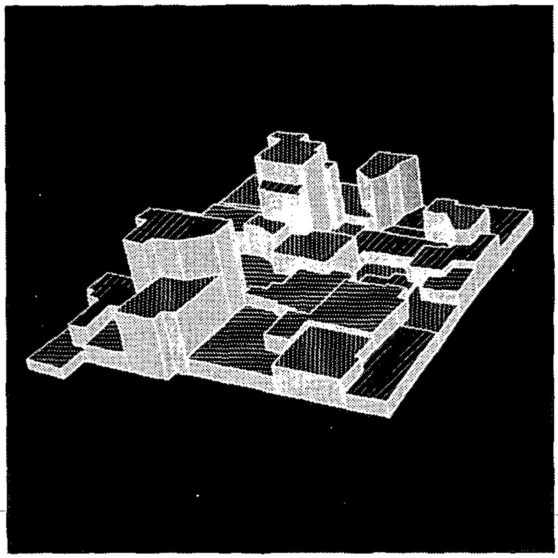


Figure III-43. Question 44.

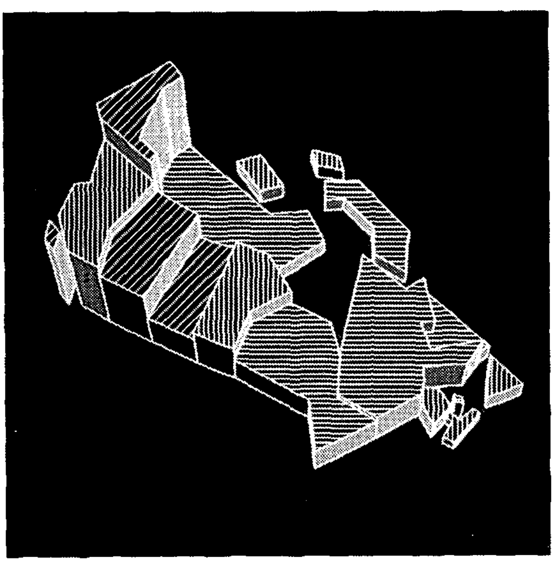


Figure III-44. Question 45.

'GREAT BRITAIN - TYPES OF CHINA [43]
Which type of china is being produced at most places?
a) abc (purple)
b) klm (brown)
c) xyz (yellow)'

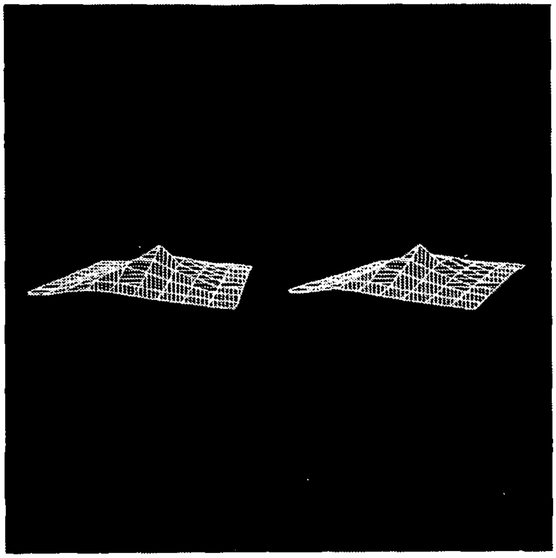


Figure III-45. Question 46.

'NEW MEXICO - NUMBER OF CARS AND MAKES [44]
Which make (the patterns) can be found most in the county with fewest cars?
a) Ford (horizontal lines)
b) Fiat (diagonal lines)
c) Opel (vertical lines)'

'CANADA - NUMBER AND TYPES OF TREES [45]
Which kind of tree (patterns) dominates the state with most trees?
a) spruce (horizontal lines)
b) pine (vertical lines)
c) birch (diagonal lines)'

'KILIMANJARO - AGRICULTURE [46]
Which type of farming (patterns) dominates the right side of the mountain?
a) corn (horizontal lines)
b) rice (vertical lines)
c) no dominant crop

APPENDIX IV. THE TEST RESULTS

This Appendix provides the numerical results of the computer-assisted map user test. Figure IV-1 presents some descriptive statistics for each single question. The Figures IV-2 and IV-3 provide the tables necessary to judge the results of the tests of significance. Figure IV-2 presents the 'table' for the t-test and Figure IV-3 for the Mann-Whitney test. At the end of this Appendix the numbers of the questions which made up the samples of a set used in the tests of significance can be found.

introduction

QN	RT	SD	A	B	C	D	G	NS	%G	NG	%W	NW
Aa	12.1	3.5	45	0	0	0	A	45	100	(45)	0	(0)
b	10.6	5.6	7	0	38	0	C	45	84	(38)	16	(7)
Ba	25.2	14.6	5	36	4	0	B	45	80	(36)	20	(9)
b	12.9	4.5	41	0	4	0	A	45	91	(41)	9	(4)
Ca	11.0	5.6	2	0	43	0	C	45	96	(43)	4	(2)
b	13.9	9.0	1	43	1	0	B	45	96	(43)	4	(2)
D	15.3	7.0	42	0	3	0	A	45	93	(42)	7	(3)
E	81.3	40.8	45	0	0	0	A	45	100	(45)	0	(0)
F	32.1	18.3	28	5	1	10	A	44	64	(28)	36	(16)
G	25.8	28.6	0	0	6	39	D	45	87	(39)	13	(6)

QN: question number
SD: standard deviation of RT (sec)
B: answer B
D: answer D
NS: number of subjects
NG: number of correct answers
NW: number of wrong answers
RT: mean response time (sec)
A: answer A
C: answer C
G: correct answer
%G: % correct answers
%W: % wrong answers

Figure IV-1a. Questions referring to the introductory test.

QN	RT	SD	A	B	C	D	G	NS	%G	NG	%W	NW
prism maps												
1A	15.7	6.4	44	1	0	0	A	45	98	(44)	2	(1)
B	30.4	11.8	1	8	36	0	C	45	80	(36)	20	(9)
C	11.2	4.3	40	1	4	0	A	45	89	(40)	11	(5)
2A	30.4	11.4	1	3	41	0	C	45	91	(41)	9	(4)
B	21.6	7.2	0	45	0	0	B	45	100	(45)	0	(0)
C	24.5	18.7	2	43	0	0	B	45	96	(43)	4	(2)
3A	30.1	15.9	2	42	1	0	B	45	93	(42)	7	(3)
B	26.1	12.2	42	0	3	0	A	45	93	(42)	7	(3)
C	22.2	12.8	2	25	18	0	C	45	40	(18)	60	(27)
4A	31.4	16.4	36	0	9	0	A	45	80	(36)	20	(9)
B	17.1	6.9	42	1	2	0	A	45	93	(42)	7	(3)
C	16.7	9.8	1	40	3	0	B	44	91	(40)	9	(4)
digital terrain models												
5A	57.1	13.9	33	1	6	0	C	40	15	(6)	85	(34)
B	67.2	13.8	18	2	20	0	A	40	45	(18)	55	(22)
C	52.1	11.5	0	11	29	0	C	40	73	(29)	27	(11)
6A	27.8	11.9	1	2	37	0	C	40	92	(37)	8	(3)
B	24.6	10.2	2	0	38	0	C	40	94	(38)	6	(2)
C	22.0	9.7	33	6	1	0	A	40	82	(33)	18	(7)
7A	36.4	16.2	20	24	0	0	A	44	45	(20)	55	(24)
B	19.3	7.9	41	2	1	0	A	44	93	(41)	7	(3)
C	14.0	6.1	0	44	0	0	B	44	100	(44)	0	(0)
8A	37.2	14.7	45	0	0	0	A	45	100	(45)	0	(0)
B	23.0	11.2	0	45	0	0	B	45	100	(45)	0	(0)
C	24.5	17.8	38	3	4	0	A	45	84	(38)	16	(7)
9A	38.6	16.1	11	0	28	0	C	39	72	(28)	28	(11)
B	30.3	12.9	11	5	23	0	A	39	28	(11)	72	(28)
C	17.4	11.5	0	17	22	0	C	39	56	(22)	44	(17)

QN: *question number*
SD: standard deviation of RT (sec)
B: answer B
D: answer D
NS: number of *subjects*
NG: number of correct answers
NW: number of wrong answers
RT: mean response time (sec)
A: answer A
C: answer C
G: correct answer
%G: *% correct answers*
%W: % wrong answers

QN	RT	SD	A	B	C	D	G	NS	%G	NG	%W	NW
three-dimensional point symbol maps												
10A	21.4	8.6	0	0	45	0	C	45	100	(45)	0	(0)
B	24.1	9.9	0	2	43	0	C	45	96	(43)	4	(2)
C	16.8	5.6	44	1	0	0	A	45	98	(44)	2	(1)
11A	23.5	8.3	0	3	42	0	C	45	93	(42)	7	(3)
B	31.6	12.8	45	0	0	0	A	45	100	(45)	0	(0)
C	31.0	13.4	44	1	0	0	A	45	98	(44)	2	(1)
12A	25.0	10.8	45	0	0	0	A	45	100	(45)	0	(0)
B	36.3	20.8	2	29	14	0	B	45	64	(29)	36	(16)
C	17.6	8.2	0	0	45	0	C	45	100	(45)	0	(0)
13A	20.3	11.8	35	8	2	0	A	45	78	(35)	22	(10)
B	13.8	5.1	36	1	8	0	A	45	80	(36)	20	(9)
C	39.2	18.2	21	22	2	0	B	45	49	(22)	51	(23)
three-dimensional urban maps												
14A	16.4	7.8	45	0	0	0	A	45	100	(45)	0	(0)
B	43.8	20.7	10	3	32	0	C	45	71	(32)	29	(13)
C	17.9	12.2	43	2	0	0	A	45	96	(43)	4	(2)
15A	21.5	8.2	43	2	0	0	A	45	96	(43)	4	(2)
B	21.0	9.3	13	32	0	0	B	45	71	(32)	29	(13)
C	16.9	6.6	5	40	0	0	B	45	89	(40)	11	(5)
16A	18.5	12.7	42	3	0	0	A	45	93	(42)	7	(3)
B	16.2	10.4	1	44	0	0	B	45	98	(44)	2	(1)
C	20.0	11.2	41	4	0	0	A	45	91	(41)	9	(4)
17A	17.8	5.3	0	0	44	0	C	44	100	(44)	0	(0)
B	17.9	9.5	0	0	45	0	C	45	100	(45)	0	(0)
C	36.2	21.1	24	21	0	0	B	45	47	(21)	53	(24)

QN: question number
SD: standard deviation of RT (sec)
B: answer B
D: answer D
NS: number of subjects
NG: number of correct answers
NW: number of wrong answers
RT: mean response time (sec)
A: answer A
C: answer C
G: correct answer
%G: % correct answers
%W: % wrong answers

Figure IV-1b. Questions referring to the geographical component.

QN	RT	SD	A	B	C	D	G	NS	%G	NG	%W	NW
size												
18	48.7	19.6	13	1	3	28	D	45	62	(28)	38	(17)
19	43.2	16.7	21	2	21	1	A	45	47	(21)	53	(24)
20	21.1	10.2	0	0	45	0	C	45	100	(45)	0	(0)
21	27.0	11.3	2	20	23	0	C	45	51	(23)	49	(22)
22	38.4	22.7	4	41	0	0	B	45	91	(41)	9	(4)
23	35.7	14.3	35	4	6	0	A	45	78	(35)	22	(10)
24	50.7	16.4	23	21	1	0	A	45	51	(23)	49	(22)
25	22.7	9.6	1	3	41	0	C	45	91	(41)	9	(4)
26	48.6	15.8	2	33	4	6	B	45	73	(33)	27	(12)
value												
27	51.8	24.1	26	1	18	0	C	45	40	(18)	60	(27)
28	62.1	28.2	6	24	14	0	B	44	55	(24)	45	(20)
29	62.7	27.1	19	24	2	0	A	45	42	(19)	58	(26)
30	58.4	26.7	0	43	2	0	B	45	96	(43)	4	(2)
31	52.2	21.8	7	34	4	0	B	45	76	(34)	24	(11)
32	29.9	11.9	2	17	25	0	B	44	39	(17)	61	(27)
texture												
33	39.7	15.7	13	0	32	0	C	45	71	(32)	29	(13)
34	42.8	14.7	16	6	23	0	A	45	36	(16)	64	(29)
35	36.0	10.5	2	31	12	0	B	45	69	(31)	31	(14)
36	47.2	19.5	40	0	5	0	A	45	89	(40)	11	(5)
37	64.3	29.3	12	24	8	0	B	44	55	(24)	45	(20)
colour												
38	34.5	19.8	38	5	2	0	A	45	84	(38)	16	(7)
39	18.9	7.7	27	2	16	0	A	45	60	(27)	40	(18)
40	39.0	16.3	42	1	2	0	A	45	93	(42)	7	(3)
41	35.8	15.0	0	1	44	0	C	45	98	(44)	2	(1)
42	47.8	29.9	0	40	5	0	B	45	89	(40)	11	(5)
43	25.7	9.7	44	1	0	0	A	45	98	(44)	2	(1)
orientation												
44	63.7	24.1	15	12	18	0	A	45	33	(15)	67	(30)
45	28.7	13.0	2	3	40	0	C	45	89	(40)	11	(5)
46	39.8	20.3	14	27	4	0	A	45	31	(14)	69	(31)

QN: question number
RT: mean response time (sec)
SD: standard deviation of RT (sec)
A: answer A
B: answer B
C: answer C
D: answer D
G: correct answer
NS: number of subjects
%G: % correct answers
NG: number of correct answers
%W: % wrong answers
NW: number of wrong answers

Figure IV-1c. Questions referring to the graphical variables

VALUES OF t FOR SELECTED DEGREES OF FREEDOM (df) AND PROBABILITY P

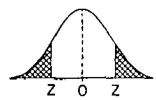
df \ P	.20	.10	.05	.02	.01	.002	.001	.0002	.0001	.00002	.00001	.000002	.000001	.0000002
1	3.078	6.314	12.706	31.821	63.657	318.309	636.619	3,183.099	6,366.198	31,830.989	63,661.977	318,309.886	636,619.772	3,183,098.862
2	1.886	2.920	4.303	6.965	9.925	22.327	31.598	70.700	99.992	223.603	316.225	707.106	999.999	2,236.068
3	1.638	2.353	3.182	4.541	5.841	10.214	12.924	22.204	28 000	47.928	60.397	103.299	130.155	222.572
4	1.533	2.132	2.776	3.747	4.604	7.173	8.610	13.034	15.544	23.332	27.771	41.578	49.459	73.986
5	1.476	2.015	2.571	3.365	4.032	5.893	6.869	9.678	11.178	15.547	17.897	24.771	28.477	39.340
6	1.440	1.943	2.447	3.143	3.707	5.208	5.959	8.025	9.082	12.032	13.555	17.830	20.047	26.286
7	1.415	1.895	2.365	2.998	3.499	4.785	5.408	7.063	7.885	10.103	11.215	14.241	15.764	19.932
8	1.397	1.860	2.306	2.896	3.355	4.501	5.041	6.442	7.120	8.907	9.782	12.110	13.257	16.320
9	1.383	1.833	2.262	2.821	3.250	4.297	4.781	6.010	6.594	8.102	8.827	10.720	11.637	14.041
10	1.372	1.812	2.228	2.764	3.169	4 144	4.587	5.694	6.211	7.527	8.150	9.752	10.516	12.492
11	1.363	1.796	2.201	2.718	3.106	4.025	4.437	5.453	5.921	7.098	7.648	9.043	9.702	11.381
12	1.356	1.782	2.179	2.681	3.055	3.930	4.318	5.263	5.694	6.756	7.261	8.504	9.085	10.551
13	1.350	1.771	2.160	2.650	3.012	3.852	4.221	5.111	5.513	6.501	6.955	8.082	8.604	9.909
14	1.345	1.761	2.145	2.624	2.977	3.787	4.140	4.985	5.363	6.287	6.706	7.743	8.218	9.400
15	1.341	1.753	2.131	2.602	2.947	3.733	4.073	4.880	5.239	6.109	6.502	7.465	7.903	8.986
16	1.337	1.746	2.120	2.583	2.921	3.686	4.015	4.791	5.134	5.960	6.330	7.233	7.642	8.645
17	1.333	1.740	2.110	2.567	2.898	3.646	3.965	4.714	5.044	5.832	6.184	7.037	7.421	8.358
18	1.330	1.734	2.101	2.552	2.878	3.610	3.922	4.648	4.966	5.722	6.059	6.869	7.232	8.115
19	1.328	1.729	2.093	2.539	2.861	3.579	3.883	4.590	4.897	5.627	5.949	6.723	7.069	7.905
20	1.325	1.725	2.086	2.528	2.845	3.552	3.850	4.539	4.837	5.543	5.854	6.597	6.927	7.723
21	1.323	1.721	2.080	2.518	2.831	3.527	3.819	4.493	4.784	5.469	5 769	6.485	6.802	7.564
22	1.321	1.717	2.074	2.508	2.819	3.505	3.792	4 452	4.736	5.402	5.694	6.386	6.692	7.423
23	1.319	1.714	2.069	2.500	2.807	3.485	3.768	4.415	4.693	5.343	5.627	6.297	6.593	7.298
24	1.318	1.711	2.064	2.492	2.797	3.467	3.745	4.382	4.654	5.290	5.566	6.218	6.504	7.185
25	1.316	1.708	2.060	2.485	2.787	3.450	3.725	4.352	4.619	5.241	5.511	6.146	6.424	7.085
26	1.315	1.706	2.056	2.479	2.779	3.435	3.707	4.324	4.587	5.197	5.461	6.081	6.352	6 993
27	1.314	1.703	2.052	2.473	2.771	3.421	3.690	4.299	4.558	5 157	5.415	6.021	6.286	6.910
28	1.313	1.701	2.048	2.467	2.763	3.408	3.674	4.275	4.530	5 120	5.373	5.967	6.225	6.835
29	1.311	1.699	2.045	2.462	2.756	3.396	3.659	4.254	4.506	5.086	5.335	5.917	6.170	6.765
30	1.310	1.697	2.042	2.457	2.750	3.385	3.646	4.234	4.482	5.054	5.299	5.871	6.119	6.701
35	1.306	1.690	2.030	2.438	2.724	3.340	3.591	4.153	4.389	4.927	5.156	5.687	5.915	6.447
40	1.303	1.684	2.021	2.423	2.704	3.307	3.551	4.094	4.321	4.835	5.053	5.554	5.768	6.266
45	1.301	1.679	2.014	2.412	2.690	3.281	3.520	4.049	4.269	4.766	4.975	5.454	5.659	6.130
50	1.299	1.676	2.009	2.403	2.678	3.261	3.496	4.014	4.228	4.711	4.914	5.377	5.573	6.025
55	1.297	1.673	2.004	2.396	2.668	3.245	3.476	3.986	4.196	4.667	4.865	5.315	5.505	5.942
60	1.296	1.671	2.000	2.390	2.660	3.232	3.460	3.962	4.169	4.631	4.825	5.264	5.449	5.873
70	1.294	1.667	1.994	2.381	2.648	3.211	3.435	3.926	4.127	4.576	4.763	5.185	5.363	5.768
80	1.292	1.664	1.990	2.374	2.639	3.195	3 416	3.899	4.096	4.535	4.717	5.128	5.300	5.691
90	1.291	1.662	1.987	2.368	2.632	3.183	3.402	3.878	4.072	4.503	4.682	5.084	5.252	5.633
100	1.290	1.660	1.984	2.364	2.626	3.174	3.390	3.862	4 053	4.478	4.654	5.049	5.214	5.587
200	1.286	1.652	1.972	2.345	2.601	3.131	3.340	3.789	3.970	4.369	4.533	4 897	5.048	5.387
500	1.283	1.648	1.965	2.334	2.586	3.107	3.310	3.747	3.922	4.306	4.463	4.810	4.953	5.273
1,000	1.282	1.646	1.962	2.330	2.581	3.098	3.300	3 733	3 906	4.285	4.440	4.781	4.922	5.236
2,000	1.282	1.645	1.961	2.328	2.578	3 094	3.295	3 726	3.898	4.275	4.428	4 767	4.907	5.218
10,000	1.282	1.645	1 960	2.327	2.576	3.091	3.292	3 720	3.892	4.267	4.419	4.756	4.895	5.203
∞	1.282	1.645	1.960	2 326	2.576	3.090	3.291	3.719	3.891	4 265	4.417	4.753	4.892	5.199

Values of P are for a two-tailed test. For a one-tailed test they should be halved.

Figure IV-2. The 't-table' [Williams, 1984, p.327].

AREAS UNDER THE NORMAL CURVE IN THE TWO TAILS

Entries in the body of the table refer to the shaded areas in the diagram. These areas are listed as proportions of the total area under the normal curve.



Second decimal place of Z

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	1.0000	.9920	.9840	.9761	.9681	.9601	.9522	.9442	.9362	.9283
0.1	.9203	.9124	.9045	.8966	.8887	.8808	.8729	.8650	.8572	.8493
0.2	.8415	.8337	.8259	.8181	.8103	.8026	.7949	.7872	.7795	.7718
0.3	.7642	.7566	.7490	.7414	.7339	.7263	.7188	.7114	.7039	.6965
0.4	.6892	.6818	.6745	.6672	.6599	.6527	.6455	.6384	.6312	.6241
0.5	.6171	.6101	.6031	.5961	.5892	.5823	.5755	.5687	.5619	.5552
0.6	.5485	.5419	.5353	.5287	.5222	.5157	.5093	.5029	.4965	.4902
0.7	.4839	.4777	.4715	.4654	.4593	.4533	.4473	.4413	.4354	.4295
0.8	.4237	.4179	.4122	.4065	.4009	.3953	.3898	.3843	.3789	.3735
0.9	.3681	.3628	.3576	.3524	.3472	.3421	.3371	.3320	.3271	.3222
1.0	.3173	.3125	.3077	.3030	.2983	.2937	.2891	.2846	.2801	.2757
1.1	.2713	.2670	.2627	.2585	.2543	.2501	.2460	.2420	.2380	.2340
1.2	.2301	.2263	.2225	.2187	.2150	.2113	.2077	.2041	.2005	.1971
1.3	.1936	.1002	.1868	.1835	.1802	.1770	.1738	.1707	.1676	.1645
1.4	.1615	.1585	.1556	.1527	.1499	.1471	.1443	.1416	.1389	.1362
1.5	.1336	.1310	.1285	.1260	.1236	.1211	.1188	.1164	.1141	.1118
1.6	.1096	.1074	.1052	.1031	.1010	.0989	.0969	.0949	.0930	.0910
1.7	.0891	.0873	.0854	.0836	.0819	.0801	.0784	.0767	.0751	.0735
1.8	.0719	.0703	.0688	.0672	.0658	.0643	.0629	.0615	.0601	.0588
1.9	.0574	.0561	.0549	.0536	.0524	.0512	.0500	.0488	.0477	.0466
2.0	.0455	.0444	.0434	.0424	.0414	.0404	.0394	.0385	.0375	.0366
2.1	.0357	.0349	.0340	.0332	.0324	.0316	.0308	.0300	.0293	.0285
2.2	.0278	.0271	.0264	.0257	.0251	.0244	.0238	.0232	.0226	0220
2.3	.0214	.0209	.0203	.0198	.0193	.0188	.0183	.0178	.0173	.0168
2.4	.0164	.0160	.0155	.0151	.0147	.0143	.0139	.0135	.0131	.0128
2.5	.0124	.0121	.0117	.0114	.0111	.0108	.0105	.0102	.00988	.00960
2.6	.00932	.00905	.00870	.00854	.00829	.00805	.00781	.00759	.00736	.00715
2.7	.00693	.00673	.00653	.00633	.00614	.00596	.00578	.00561	.00544	.00527
2.8	.00511	.00495	.00480	.00465	.00451	.00437	.00424	.00410	.00398	.00385
2.9	.00373	.00361	.00350	.00339	.00328	.00318	.00308	.00298	.00288	.00279

First decimal place of Z

Z	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
3	.00270	.00194	.00137	$.0^{3}967$	$.0^{3}674$	$.0^{3}465$	$.0^{3}318$	$.0^{3}216$	$.0^{3}145$	$.0^{4}962$
4	$.0^{4}633$	$.0^{4}413$	$.0^{4}267$	$.0^{4}171$	$.0^{4}108$	$.0^{5}680$	$.0^{5}422$	$.0^{5}260$	$.0^{5}159$	$.0^{6}958$
5	$.0^{6}573$	$.0^{6}340$	$.0^{6}199$	$.0^{6}116$	$.0^{7}666$	$.0^{7}380$	$.0^{7}214$	$.0^{7}120$	$.0^{8}663$	$.0^{8}364$
6	$.0^{8}197$	$.0^{8}106$	$.0^{9}565$	$.0^{9}298$	$.0^{9}155$	$.0^{10}803$	$.0^{10}411$	$.0^{10}208$	$.0^{10}105$	$.0^{11}520$

Figure IV-3. The 'Z-table' [Williams, 1984,p.325].

Set 1: * Sample A (GEO3):
1c, 3c, 5c, 9c, 11c, 13c, 15c, 16c
* Sample B (GEO3+C):
2c, 4c, 6c, 7c, 10c, 12c, 14c, 17c

Set 2: * Sample A (GEO3):
1c, 3c, 5c, 9c
* Sample B (GEO3+C - topographic):
2c, 4c, 6c, 7c

Set 3: * Sample A (GEO3):
11c, 13c, 15c, 16c
* Sample B: GEO3+C - thematic):
10c, 12c, 14c, 17c

Set 4: * Sample A (CONTS C):
7c
* Sample B (CONTS B):
8c

Set 5: * Sample A (2D MAP):
Bb
* Sample B (3D MAP):
1c

Figure IV-4a. Question numbers for which the tests of significance were used for the geographical component (see Figure 8-4).

Set 1: * Sample A (size with the depth cue retinal image size applied): 18
* Sample B (size without the depth cue retinal image size applied): 24

Set 2: * Sample A (size with the depth cue shading applied): 19
* Sample B (size without the depth cue shading applied): 20

Set 3: * Sample A (size with the depth cue colour applied): 22
* Sample B (size without the depth cue colour applied): 23

Set 4: * Sample A (size with the depth cue texture applied): 22
* Sample B (size without the depth cue texture applied): 21

Set 5: * Sample A (value with the depth cue shading applied): 31, 29
* Sample B (value without the depth cue shading applied): 32, 27

Set 6: * Sample A (value with the depth cue texture applied): 29
* Sample B (value without the depth cue texture applied): 28

Set 7: * Sample A (value with the depth cue retinal image size applied): 29
* Sample B (value without the depth cue retinal image size applied): 30

Set 8: * Sample A (texture with the depth cue retinal image size applied): 36
* Sample B (texture without the depth cue retinal image size applied): 35

Set 9: * Sample A (texture with the depth cue colour applied): 33
* Sample B (texture without the depth cue colour applied): 34

Set 10: * Sample A (colour with the depth cue retinal image size applied): 38
* Sample B (colour without the depth cue retinal image size applied): 40

Set 11: * Sample A (colour with the depth cue texture applied): 38
* Sample B (colour without the depth cue texture applied): 41

Set 12: * Sample A (colour with the depth cue shading applied): 38
* Sample B (colour without the depth cue shading applied): 42

Figure IV-4b. Question numbers for which the tests of significance were used for the graphical variables (see Figure 8-6).

Set 1: * Sample A (mono):
1a, 1b, 1c, 2a, 2b, 2c, 5a, 5b, 5c, 6a, 6b, 6c, 10a, 10b, 10c, 11a, 11b, 11c, 14a, 14b, 14c, 15a, 15b, 15c
* Sample B (stereo):
3a, 3b, 3c, 4a, 4b, 4c, 7a, 7b, 7c, 8a, 8b, 8c, 12a, 12b, 12c, 13a, 13b, 13c, 16a, 16b, 16c, 17a, 17b, 17c

Set 2: * Sample A (mono - prism):
1a, 1b, 1c, 2a, 2b, 2c
* Sample B (stereo - prism):
3a, 3b, 3c, 4a, 4b, 4c

Set 3: * Sample A (mono - dtm):
5a, 5b, 5c, 6a, 6b, 6c
* Sample B (stereo - dtm):
7a, 7b, 7c, 8a, 8b, 8c

Set 4: * Sample A (mono - point):
10a, 10b, 10c, 11a, 11b, 11c
* Sample B (stereo - point):
12a, 12b, 12c, 13a, 13b, 13c

Set 5: * Sample A (mono - urban):
14a, 14b, 14c, 15a, 15b, 15c
* Sample B (stereo - urban):
16a, 16b, 16c, 17a, 17b, 17c

Set 6: * Sample A (mono - GEO3):
1a, 1b, 1c, 5a, 5b, 5c, 11a, 11b, 11c, 15a, 15b, 15c
* Sample B (stereo - GEO3):
3a, 3b, 3c, 9a, 9b, 9c, 13a, 13b, 13c, 16a, 16b, 16c

Set 7: * Sample A (mono - GEO3+C):
2a, 2b, 2c, 6a, 6b, 6c, 10a, 10b, 10c, 14a, 14b, 14c
* Sample B (stereo - GEO3+C):
4a, 4b, 4c, 7a, 7b, 7c, 12a, 12b, 12c, 17a, 17b, 17c

Set 8: * Sample A (mono - size):
18, 19
* Sample B (stereo - size):
25, 26

Set 9: * Sample A (mono - value):
29
* Sample B (stereo - value):
31

Set 10: * Sample A (mono - texture):
35
* Sample B (stereo - texture):
37

Set 11: * Sample A (mono - colour):
38
* Sample B (stereo - colour):
43

Set 12: * Sample A (mono - orientation):
44
* Sample B (stereo - orientation):
46

Figure IV-4c. Question numbers for which the tests of significance were used for mono versus stereo (see Figure 8-8).

CURRICULUM VITAE

Menno-Jan Kraak took his secondary education (VWO) at the Erasmus College in Zoetermeer. In 1976 he started his study of Physical Geography at the State University of Utrecht, where he graduated - cum laude - in 1981 with a specialization in Cartography. During his study in Utrecht he was a student-assistant in Computer-assisted Cartography for two years, and after his graduation he worked at the Utrecht Geographical Institute for two months. From the end of 1981 until the beginning of 1983 he worked in the army (military service) as a terrain analysis officer. From 1983 onwards he works at the Faculty of Geodesy at the Delft University of Technology as a Lecturer in Cartography.