Lehrstuhl für Kartographie

Attention-Guiding Geovisualisation

A cognitive approach
of designing relevant geographic information

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Abstract

It is a delicate task to design suitable geovisualisations that allow users an efficient visual processing of the depicted geographic information. In digital era, such a design task is subject to three major challenges: the ever growing amount of geospatial data at various levels of detail, the diversified applications of that data, and the continuously expanding range of display sizes. These challenges are guided by the same cognitive scope. Users face an increasing level of cognitive workload that has a substantial impact on decision-making while processing complex visual environments.

This work tends to enhance the visualisation of relevant geographic information by proposing a conceptual framework for the development of attention-guiding geovisualisation. The main challenge is to stimulate a users decision-making and to reduce the cognitive workload by providing high responsiveness in specific visual brain areas that are involved in visual geographic information processing. Based on theories and research findings in GIScience and cognitive neuropsychology the research basis of this work is formed by combining utility and usability issues of system engineering.

The relevance of information is considered as an utility criterion and its cognitively adequate visualisation as an usability criterion of a system’s acceptability. To enhance utility, irrelevant information is separated from relevant information by implementing relevance as a filter. To enhance usability the design of attention-guiding geovisualisation is adapted to internal visual characteristics of visual information processing.

Based on the internal structure of visual information processing and biological mechanisms involved in visual attention, appropriate cognitive principles and a design methodology are presented and applied to pixel-based remote sensing satellite image and vectorised maps. A pre-evaluation with a computational attention-model serves as a knowledge base for designing vectorised attention-guiding geovisualisations that are evaluated with a paper and pencil test and the eye-movement recording method.

The evaluation results reveal that the proposed attention-guiding design approach significantly enhances visual geographic information processing and contribute to the overall acceptability of geographic information systems and geovisualisations that are needed for fast and accurate decision-making processes.

Zusammenfassung

Aufgrund der steigenden Anzahl geographischer Daten in verschiedenen Auflösungen, ihrer vielfältigen Anwendungsbereiche und der variierenden Größe ihrer Visualisierungen ist es notwendig Geovisualisierungen zu gestalten, welche dem Anwender eine effektive visuelle Informationsprozessierung geographischer Phänomene erlaubt. Die Gestaltung solcher kognitiv adäquaten Geovisualisierungen wird von einem wesentlichen kognitiven Aspekt bestimmt. Anwender von Geovisualisierungen müssen zusehends höhere Kapazitäten ihrer limitierten kognitiven Ressourcen verwenden was die Entscheidungsfindung bei der Prozessierung komplexer Informationen beeinträchtigt.

Diese Studie beabsichtigt eine Optimierung der Visualisierung relevanter geographischer Information und erstellt einen konzeptuellen Rahmen auf dem die Entwicklung aufmerksamkeitslenkender Geovisualisierung basiert. Die wesentliche Herausforderung ist die Erleichterung der Entscheidungsfindung und die Verringerung der kognitiven Belastung indem visuelle Gehirnareale aktiviert werden, welche in der visuellen Prozessierung geographischer Information involviert sind.

Auf der Basis von kognitiven Theorien und Forschungsergebnissen aus der Geoinformationswissenschaft und der kognitiven Neuropsychologie wird eine theoretische Forschungsgrundlage vorgestellt welche sich an der Nützlichkeit (utility) und der Brauchbarkeit (usability) eines Systems orientiert. Die Relevanz einer Information wird als Beurteilungskriterium für die Nützlichkeit eines Systems verwendet. Die kognitiv-adäquate Visualisierung dient der Beurteilung der Brauchbarkeit eines Systems. Um die Nützlichkeit des Systems zu verbessern wird irrelevante Information gemäß der Anfrage an ein System nach ihrem Relevanzgrad gefiltert und visualisiert. Die Brauchbarkeit des Systems wird durch die Gestaltung der aufmerksamkeitslenkenden Geovisualisierung optimiert indem sich ihre Gestaltung an interne zerebrale Prozesse der visuellen Informationsverarbeitung orientiert.

Anhand neurokognitiver Verarbeitungsprozesse visueller Information und biologischer Aufmerksamkeitsmechanismen werden kognitive Gestaltungsprinzipien formuliert, welche der Erstellung einer kognitiven Gestaltungsmethodik dienen. Diese wird am Beispiel von pixelbasierten Satellitenbildern und vektorisierten Geovisualisierungen umgesetzt und mit einem computerisierten Aufmerksamkeitsmodell prä-evaluiert. Mittels der Testergebnisse wird eine Sammlung von optimierten Geovisualisierungen zusammengestellt und mittels eines Aufmerksamkeitstest und der Blickregistrierungsmethode evaluiert.

Die statistische Analyse der Ergebnisse offenbart eine signifikante Optimierung der visuellen Informationsverarbeitung mittels aufmerksamkeitslenkender Geovisualisierungen. Diese Studie liefert somit einen Beitrag zur Verbesserung der visuellen Prozessierung von geographischer Information und der Erhöhung der Akzeptanz eines geographischen Informationssystems welches der schnellen und präzisen Entscheidungsfindung dient.

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1. Introduction

Geovisualisations are visual representations of geographic space that serve as tools for generating hypotheses, developing solutions and constructing spatiotemporal knowledge. To support these mental processes, cartographers design geovisualisations by means of graphical variables with the objective to enable user's efficient knowledge acquisition from geographic phenomena.

However, there exists a large capability discrepancy between users and geovisualisation systems: while a user is able to visually process geographic information faster and more accurate than a computational system, a system is able to process a huge amount of geographic data much faster than a user. This work gives a try to link users' cognitive skills to computers' calculation capability by designing an external aid to visual information processing in form of attention-guiding geovisualisations. Geovisualisation is here understood as any kind of visualisation that promptly directs users' attention to relevant geographic information for rapid and accurate decision making.

From the point of view of engineering, it is necessary to conduct a user-centred approach, i.e. to pay attention to the user's skill of visual information processing and to place the corresponding investigations in the centre of the research. A basic challenge is to enhance visual geographic information processing by adapting a system's external design of geographic information visualisation to user's internal skill of visual information processing. This cognitive approach involves the investigation, standardisation and use of evaluation methods.

The rapid advances in computer technology have led to the development of many interactive tools which tend to facilitate visual processing of geographic information but underlying comprehensive cognitive theories for the effective design of geovisualisations are still missing. In a digital era, cognitive theories for geovisualisation design need to adhere to the diversity of applications, the continuously expanding range of display sizes and the increasing quantity of geographic data at various granularity degrees and diverse levels of information abstraction.

Mobile devices, for example, may communicate known geographic information on miniaturised displays in mobile environments to individual users for private use, and with a low degree of human-computer interaction. On the other hand, explorative systems may reveal unknown geographic phenomena on large desktop displays in static environments for private use, and via high human-computer interaction. Although these systems differ in their design constraints, they are guided by a similar cognitive scope that is accomplished by the human functional system of visual information processing. In complex visual environments users face an increasing level of cognitive workload that has a substantial impact on the effectiveness of visual information processing. While exploring users have to visually process a large amount of information that may include distractive irrelevant geographic information, mobile users are additionally affected by distractive visual stimuli located in their egocentric geographic space.

A successful usage of all these systems depends on the cognitive skill of visual attention which reflects the efficiency of mental processes. To enable users an effective visual processing of geographic information in complex visual displays, adapting the design of geovisualisations to a users' capability of visual attention is necessary. This work follows basic recommendations of recent research agendas (MacEachren & Kraak 2001, Slocum et al. 2001, Chinchor et al. 2005) by focusing on the cognitive perspective of geovisualisations for relevant information. It is predominantly based on the knowledge of how the human brain processes visual information and tries to elaborate design principles, methodologies and evaluations of geovisualisations. While traditional cartographic research is focused on the role of maps as information storage and communication devices, geovisualisation is used for geographic data exploration. In the context of exploratory analysis, this work puts an emphasis on the user's skill of visual scanning which is often referred to as visual exploration of geographic information. This is in contrast to algorithmic data explorations performed by the computer system.

Two scientific areas, geovisualisation and cognitive psychology are principally interwoven in this work:

First, geovisualisation draws upon theories from many research disciplines that investigate the visualisation of geographic phenomena ”... *to provide theory, methods and tools for the visual exploration, analysis, synthesis and presentation of data that contains geographic information”* (Dykes et al. 2005,4). It originates amongst other scientific areas from traditional cartography which is “*... the art, science and technology of making and using maps”* (International Cartographic Association, 1999). Within geovisualisation the focus of this work is dedicated to cognitive and usability issues of visualisation design.

Second, cognitive psychology embraces human cognition in interaction with the physical world and deals with “*... perception, learning, memory, language, emotion, concept formation, and thinking”* (Eysenck & Keane 2000,1). As a research discipline of cognitive psychology, cognitive neuroscience unifies approaches concerning functions of perception, thinking, and memory (Gazzaniga 1984) by investigating the basic processing units of the brain, namely the neurons. The knowledge of the selectivity and connectivity of visual neurons as well as their functions in major visual information processing systems plays a decisive role in adapting the design of geovisualisation to the functional partition of visual information processing.

In addition the work is based on two assumptions formulated by MacEachren with respect to his conceptualisation of communicating geographic information through the use of maps (MacEachren 1995).

- Maps do not contain nor transmit geographic messages.
- Maps do stimulate inferences of users by interacting with prior beliefs.

It is argued that reasoning processes in geographic tasks result from specific relationships between visual brain areas and take place in different visual areas of the human brain. Accordingly, the cognitive approach of this work addresses the underlying brain functions involved in visual geographic information processing. In contrast to the traditional behaviourist view that regards the human mind as a black-box (Slocum et al. 2005) and concentrates on external and observable behavioural aspects, this work also takes internal cognitive processes between stimulus-input and behavioural-output into account. The objective is not to find out which geovisualisation works the best by solely concentrating on external behaviour of users. Here, the focus is rather on understanding how and why people visually process geovisualisations by considering cerebral processes of visual information processing. Knowledge from these internal correlations of visual information processing constitutes the scientific base for the development and evaluation of design principles geovisualisation methods.

By considering knowledge and methods of geovisualisation and cognitive psychology, this work is based on the hypothesis that a function-driven relation of graphical variables, design principles and methodologies with mental processes of users offers the opportunity (1) to adapt the design of geovisualisations to users’ capability of visual information processing more precisely and (2) to facilitate executive functions in geographic tasks.

The objective is to present a cognitive framework to optimise the design of geovisualisations so that they can support users in rapid and accurate visual analytical tasks. The analytical tasks are monitored by user’s working memory system that has a limited capacity of attentional resources (Baddeley 2003). The cognitive design approach of attention-guiding geovisualisation tends to reduce the cognitive workload by stimulating user’s attentional performance to afford an effective monitoring of speed and accuracy during visual analytical tasks. The proposed design aims at guiding visual attention to geographic information of interest in terms of attracting and directing gazes to classified geographic information. Unclassified visualisations are visually too complex (Dobson 1979, Muller 1979) and run the risk of provoking users' false visual selection of geographic information that leads to wrong decisions in geographic relevant tasks.

Attention-guiding geovisualisations are considered as representations that support users in processing relevant information with little effort (fast and accurate locating and decoding of information) to obtain large effect (precise decision-making). The emphasis is put on the theoretical approach for designing attention-guiding geovisualisation. This work demonstrates the application of these theories by proposing designed geovisualisations rather than automatically adapting representations of geographic information.

Some of the involved major tasks are:

- Illustrating the visual processing of geographic information from the cognitive perspective with emphasis on cerebral visual information processing systems.

- Formulating design principles and developing a design methodology for geovisualisation that are based on visual attention.

- Evaluating the effectiveness of adapted geovisualisations by analysing the attentional performance of users.

The work is structured as follows:

Chapter 1 outlines the capability discrepancy between computational and human geographic information processing and the necessity of designing attention-guiding geovisualisations. and briefly illuminated the role of visual attention in geovisualisation design. It introduces the recommendations of two research agendas and the involved scientific areas. The interdisciplinary perspective of this research is reiterated. Finally, it elucidates the objectives and the associated research tasks.

Chapter 2 is dedicated to 'external geographic information visualisation'. It gives an overview of the scientific development and overlaps of involved theories. The interdisciplinary theoretical background is predominantly composed of communication theory, relevance theory, and usability with a strong emphasis on visual information processing.

An overview of cognitive foundations of visual information processing which is termed 'internal visual information processing' is given in chapter 3. Following an introduction of approaches and research findings from neurocognitive psychology, it puts the emphasis on the analytical strength of sophisticated functions of information processing pathways and corresponding visual brain areas. In this context, it is argued that designing cognitively adequate geovisualisations requires the understanding of underlying functions of visual brain areas by retracing the information processing pathways in the brain.

A conceptual framework for developing attention-guiding geovisualisation is presented and analysed in detail in chapter 4. The framework consists of five major challenges that are considered to be of prime importance when designing geovisualisations from a cognitive perspective. The main foundation of this framework is the integration of cognitive and usability issues in geovisualisation research. Cognitive design principles for attention-guiding geovisualisation that integrates cognitive and usability issues are formulated.

Chapter 5 demonstrates the application of the design methodology in pixel-based satellite images that users can retrieve from large image data bases by using image information mining systems. For a proof of concept these satellite images are pre-evaluated with a computational attention model.

Chapter 6 describes the application of the design methodology to vectorised maps configured in ArcGIS. For a proof of concept these maps are pre-evaluated with the computational attention model.

Chapter 7 formulates basic cognitive research questions when evaluating the attention-guiding design approach with a paper-and-pencil test. A statistical analysis is conducted on the test results. The subsequent discussions are devoted to the cognitive adequacy of the attention-guiding design approach, its impact on the task difficulty, and the properties of proposed variables.

Chapter 8 describes the evaluation of the attention-guiding geovisualisation with the eye movement recording method. A statistical analysis is conducted to prove the efficiency of the proposed attention-guiding geovisualisation when processed by users.

Chapter 9 summarises the main achievements of this work that essentially result from the hypothesis that combining cognitive and usability issues in geovisualisation design can significantly improve the performance of visual geographic information processing. Finally, future cognitive research issues are discussed. They contribute to the overall acceptability of geographic information systems and geovisualisations that are needed for fast and accurate decision-making processes.

2. External geovisualisation

One component of the wider scope of this thesis is determined by the broad-sense term ‘external geovisualisation’. External geovisualisation deals with making geographic phenomena visible through external artefacts such as maps. ‘External’ as the visual representation of geographic information is opposed to ‘internal’ as the cerebral visual processing of geographic information. In other words, ‘external’ means ‘outside the brain’ and ‘internal’ is related to ‘inside the brain’. Within geovisualisation, this work is based on communication theory, relevance theory and usability with emphasis on visual information processing. This chapter gives an overview of the scientific development of these research fields and illuminates relevant scientific overlaps that characterises the interdisciplinary approach of this thesis.

2.1 GI science, cartography and geovisualisation

Among the concepts of the all-encompassing research fields that deal with the visualisation of geographic information, three areas that by themselves make intensive use of other theories are relevant for this thesis. Geovisualisation originates from cartography and both play a significant role in the multidisciplinary field of Geographic Information Science (GI science).

GI science. In the literature, more or less wide-ranging definitions of GI science can be found. GI science can be considered as the “*… science which deals with generic issues that surround the use of GIS technology, hamper its successful implementation, or contribute to the understanding of its capabilities*” (Goodchild 1992,41). Montello and Freundschuh (2005,61) consider GI science as a multidisciplinary field *“ ... concerned with the collection, storage, processing, analysis, and depiction and communication of digital information about spatiotemporal and thematic attributes of the earth, and the objects and events found there*”.

As a research area of GI science, cognition can be on the one hand related to the area of ‘Cognitive models of geographic phenomena’ that “... *involves the study of human perception, learning, memory, reasoning, and communication of and about geographic phenomena* …” (Mark 2003,8). On the other hand, cognition can be attributed to the field of ‘Human interaction with geographic information and technology’ that deals with “… *Human-computer interaction (HCI) for geographic information systems, and the design of user interfaces for GIS* …” (Mark 2003,8). Montello and Freundschuh (2005,61) suggest that “... *many aspects of GIS usability, efficiency, and profitability can be improved by greater attention to cognitive research.*” They consider research in cognition as relevant to “... *data collection and storage, graphic representation and interface design, spatial analysis, interoperability, decision-making, the social context of GIS, and more*.”

Cartography. As the earliest player involved in GI science, cartography is defined by the International Cartographic Association (ICA) as “... *the art, science and technology of making and using maps*” or more detailed as the *“… unique facility for the creation and manipulation of visual and virtual representations of geospace – maps – to permit the exploration, analysis, understanding and communication of information about that space*” (ICA, 1999).

During the last forty years, cartography was influenced by changing map making methods and moved from pen and ink to computer technologies. Without any doubt, the coming up of printing technologies and geographic information systems (GIS) has changed theoretical and practical approaches of representing geographic data. Because of the widespread access to hardware and software, map production is no longer a privileged task of professional cartographers. These technology-driven aspects tend to degrade cartography to a craftsmanship. Meng (2003) suggests that cartography can loose its scientific value due to the lack of guiding cognitive theories and methods that provoke a mismatch between technology-driven and user-centred cartographic research. On the other hand, cartography benefits from its multidisciplinary interactions. Because of scientific exchanges with land surveying and psychology, cartographers are specialised in designing visualisations that precisely represent geographic information to support users in locating and decoding geographic phenomena. In particular the goal of optimising the design of geovisualisation by investigating the human cognitive skills is one of the strengths of cartographers.

One of the first attempts in cartographic design research in the twentieth century may be dated back to the German geographer Eckert who set principles for map creation and cartographic perception (Eckert 1908). He established the scientific foundation for cartography as an academic discipline at the Department of Geography at the 'Rheinisch-Westfälische Technische Hochschule' in Aachen, Germany (Eckert 1921, 1925). Since then, cartographic design research was conducted with a varying intensity (Gilmartin 1992, Montello 2002) and was accompanied by forward-looking callings for more research on visual information processing and usability of geovisualisations (Slocum et al. 2001, Meng 2003, Lobben 2004).

Particularly with regard to technological advances, cartographers have realised that technology-driven solutions for decision making in geographic tasks should be combined with user-centred cartographic research. They state that geovisualisations do not only lead to information satisfaction but also to frustration (Dykes et al. 2005). Therefore, cartographers reinforced research on the design of geovisualisations and intensified studies on visual geographic information processing (e.g. Brodersen et al. 2002, Fabrikant et al. 2006, Griffin et al. 2006, Mac Aoidh & Bertolotto 2007, Lobben 2007).

This work follows a multidisciplinary-driven perspective of cartography and is highly influenced by statements like "*Should cartographers be collaborating with colleagues in other disciplines to carry out work of this sort?" and "So what?" We argue that yes, we should be so involved, even if in the end we find little useful. There could be important implications for some very hard questions that overlap between psychology, physiology, and cartography/GIS ...*" (Lobben et al. 2005,1).

Geovisualisation. Geovisualisation, that is sometimes referred to as geographic visualisation, integrates approaches from visualisation "… *in cartography, scientific visualisation, image analysis, information visualisation, exploratory data analysis (EDA), and GI science to provide theory, methods, and tools for the visual exploration, analysis, synthesis, and presentation of data that contain geographic information*" (Dykes et al. 2005,4). Since 1995, geovisualisation is one of the basic research topics promoted by the ICA-Commission on Visualisation and Virtual Environments (MacEachren & Kraak 2001). The Commission on Geovisualisation laid down an agenda in 2007 to (1) promote, develop and report upon the use of cartography in its broadest sense in the exploration and analysis of spatial information through interactive visual interfaces, to (2) define short and medium term research goals that address key issues associated with geovisualisation and its application, and to (3) encourage a multi-disciplinary and international approach to geovisualisation that draws upon and contributes to the efforts of relevant stakeholders, cognate disciplines and ICA commissions and working groups.

Geovisualisation is a young research discipline and has its scientific roots in traditional cartography that regarded maps as an information storage to communicate information to users. With the coming up of computational systems and the rising growing availability of geographic data, researchers began to study the use of animations and interactive visualisations to explore spatiotemporal phenomena (e.g. Karl 1992). Theoretical and practical interactive possibilities, communicative and evaluation aspects of visualising spatiotemporal processes through animations were frequently reported (e.g. Shepherd 1995, Dransch 1997, Cartwright et al. 1999, Andrienko et al. 2002, Ogao 2002, Blok 2005). The general idea of enabling knowledge discovery in large databases through interactive analyses for complex problem solving inspired MacEachren (1994, 2001) and other researchers to consider geovisualisation as a tool for knowledge construction (MacEachren & Kraak 1997). By suggesting that maps rather stimulate knowledge construction than transferring information to users, MacEachren (1995) regarded the concept of geovisualisation as a method that goes beyond information presentation. Geovisualisation deals with the representation of geospatial dynamics by investigating the design of visualisations that support users in visually extracting geographic information of interest.

2.2 Visualisation and geographic information

Although GI science, cartography, and geovisualisation consist of loosely bound areas with fuzzy scientific overlaps, they are reconciled with each other by investigating aspects of visual information processing and usability issues with regard to geovisualisation.

Geographic information. In this work, the term ‘geographic information’ is used for geographic data that can be visualised to gain knowledge from phenomena located in the geosphere. Sometimes, ‘geographic’ that implicates the consideration of at most three dimensions, is referred to as ‘geospatial’, even though ‘spatial’ includes multiple dimensions. To handle these multidimensional data various methods of visualisation were realised in sciences that aim to depict geographic data.

Visualisation of geographic information. The notion of visualisation and the main subcategories in the light of geographic information are presented in the following.

Scientific visualisation. The term ‘visualisation’ was probably popularised outside geography by McCormick and colleagues (Slocum et al. 2005). They related visualisation to computational advances in sciences and minted the term ‘scientific visualisation’ that has the objective “*... to leverage existing scientific methods by providing ... insight through visual methods*” (McCormick et al 1987,3). The wide application area of scientific visualisation includes amongst others the visualisation of molecular structures, medical imaging and fluid flows (e.g. Keller & Keller 1993, Nielson et al. 1997).

In recent years, *visualisation* moved from “*… being an internal construct of the mind*” to “*… an external artefact supporting decision making*” (Ware 2004,2). Ware (2004) stated that in the beginning of the 1970s, visualisation was related “*… to constructing a visual image in the mind*” and nowadays is “*… something more like a graphical representation of data or concepts*” (Ware 2004,2). A more general definition of visualisation as a representation process was given by Buttenfield and Mackaness (1991) who consider visualisation as “... *the process of representing information synoptically for the purpose of recognizing, communicating and interpreting patterns and structure. Its domain encompasses the computational, cognitive, and mechanical aspects of generating, organizing, manipulating and comprehending such representations*” (Buttenfield & Mackaness 1991,432).

Information visualisation. Information visualisation tends to represent and analyse nonnumeric abstract information like web-based frequencies of document retrieval. In contrast to scientific visualisation that needs two or three dimensions to represent surfaces and volumes, information visualisation deals with a larger number of more categorical items to discover trends, patterns, and relationships in large databases (e.g. Card 2002, Chen 2003). The primary goal of visualising these numbers of data is “... *to reduce complexity, while loosing the least amount of information*” (Fayyad & Grinstein 2002,5). Shneiderman & Plaisant (2004,580) proposed a more cognition-oriented definition of information visualisation. They defined information visualisation as “*... the use of interactive visual representation of abstract data to amplify cognition*”.

Spatialisation. To visualise and analyse nonnumeric information, some researchers use spatial metaphors by visualising for instance online news on a topographic surface through ‘spatialisations’ (Skupin 2000). These researchers use the multidimensional scaling method to convert nonnumeric information into spatialisations (Skupin & Fabrikant 2003). Being aware of the fact that users are familiar with topographic surfaces, Fabrikant & Buttenfield (2001) designed 2D and 3D spatialisations to allow users the discovery of relationships between documents through the use of distance similarity and height grading. In two experiments Fabrikant et al. (2006) found out that distance and region membership of depicted information largely stimulates a user's judgement of information similarity. They concluded "*… that the spatial metaphor region is a useful concept of depicting clusters of similar documents in an information space*" (Fabrikant et al. 2006,43).

Exploratory geovisualisation. The availability of large databases has stimulated researchers to develop data mining techniques of knowledge discovery in databases to detect possible useful patterns for knowledge acquisition (Miller & Han 2001). As one category of data mining tasks, exploratory data mining tends to detect and identify structures or discover similarities and differences of data (Freitas 2002, Ye 2003) that can be visualised e.g. by methods of hierarchical clustering (e.g. Stasko & Hang 2000, Müller-Hannemann 2001) or self organising-maps (e.g. Kohonen 1997, Takatsuka 2001).

However, large geographic databases contain heterogeneous and multidimensional geospatial data that cannot be explored with classic data mining algorithms which are used to detect patterns in identically distributed data. Therefore, researchers focused on 'spatial data mining' and developed spatially aware algorithms that tend to explore spatial data (e.g. markov random fields, bayesian classifier, spatial outlier detection) or modelled spatial properties and relationships before using classic data mining algorithms (Shekhar & Vatsavai 2003). Typical applications of spatial data mining methods are for instance extracting spatiotemporal patterns in geographic space or extracting information from remotely sensed imagery (Miller & Han 2001).

The change from maps that communicate static messages to maps that dynamically support data exploration of multiple perspectives has forced researchers to focus on 'exploratory geovisualisation'. Exploratory geovisualisation as a subset of the wider concept of geovisualisation aims at representing geographic data in a way that allow users the effective exploration of complex geographic information. To gain insight into unknown geographic data (e.g. detecting trends, correlations or patterns), experts employ exploratory geovisualisations as tools for discovery (Kraak 1998). This exploration process is characterised by a highly interactive search for e.g. patterns to come up with hypotheses about so far unknown geographic phenomena. Several exploratory geovisualisation methods were implemented in the world wide web to allow public users the exploration of geographic data through dynamic variables (Dykes 1997, Andrienko & Andrienko 1999). Recent work included visualisations of spatiotemporal data such as mobile trajectories (Dykes & Mountain 2003, Mountain 2005), health and demographic survey data (Koua & Kraak 2004a,b; Robinson 2005) and timing of protective action in relationship to the distance of wildfire (Kim et al. 2006).

Statistical visualisation of geographic information. Visualising geographic information does not automatically include the cartographic depiction of geographic phenomena. For instance, histograms (graphs) display statistical measures like the spatial distribution of geographic information. In addition to these methods that analyse the distribution of geographic attributes and those that investigate the relationships among parameters (e.g. scatterplots), methods of exploratory data analysis became popular with the increasing acquisition of geographic data that need to be explored.

Exploratory data analysis differs from other statistical methods in so far that it is used for developing new hypotheses instead of analysing and confirming (or invalidating) existing suspects. Being invented, developed, elaborated and promoted by John Tukey (1977) exploratory data analysis tends to detect data properties in large data bases to formulate hypotheses and identify unknown patterns. The concept of (exploratory) geovisualisation which is built on Tukeys' work allows users to explore data through the brushing technique in an interactive way. The brushing technique was picked up by Monmonier (1989) who proposed to visualise changing data properties in maps. Systems of exploratory spatial data analysis (Anselin 1998) or geographic data mining (Miller & Han 2001) consist of brushing and linking techniques to manipulate numerical and graphical procedures. A well-known geospatial data mining system that merges the idea of geovisualisation and spatial analysis is the GeoVISTA Studio (Gahegan et al. 2002). It combines multivariate clustering, visualisation with parallel coordinate plots, self-organising maps, and maps. Using the GeoVISTA Studio, Demšar (2006) recently combined automatic data mining with visual data mining methods to support users in geospatial data exploration.

Remotely sensed images. Like graphs and tables, remotely sensed images may not be considered as geovisualisations from a cartographic point of view. However, geoscientists do benefit from the accessibility and actuality of satellite images and cooperate increasingly with remote sensing engineers. One of the typical collaborative tasks is to derive semantic information from images by developing semantic concepts in visual databases for the retrieval of earth observation data (Schröder et al. 2000). Different technical methods serve to bridge the semantic gap, i.e. linking the algorithmic and clearly defined low-level features of a system with the complex high-level semantic concepts that humans associate with images. For instance, the present configuration of Image Information Mining (IIM) systems is predominantly concentrated on developing algorithms for the search of information. Techniques like content-based image retrieval (CBIR) are characterised by focussing on the system's ability to retrieve information rather than the human ability to visually detect relevant information. In addition to the need of developing algorithms for pattern exploration (e.g. Hinz & Baumgartner 2003) and object extraction (e.g. Weihing et al. 2007), a major challenge is to effectively visualise the results (Swienty et al. 2007a, Zhang et al. 2001).

3D visualisations. As a result from the abovementioned growing multi-sensor technology, 3D visualisations have become wide spread to process various geographical tasks (e.g. urban planning, civil engineering, and navigation) and are realised in research prototypes like GeoZui3D (Ware et al. 2001) as well as common GIS such as ArcGIS (ESRI 2006). 3D visualisations are suggested to provoke a user's intuitive organisation of spatial objects by reflecting the physical world (Meng & Forberg 2007) through stimulating the user's cognitive capability of spatial information processing (Germanchis & Cartwright 2003). Wood et al. (2005,295) postulate that 3D visualisation is a "*… new and exciting way*" that provides the ability to design *"… more information rich, interactive, realistic and dynamic visualisations processes*".

One current research issue in the configuration and design of 3D visualisations is to enhance the efficiency of representations through modelling and generalising the level of details (LOD's) in rural and urban areas. For example, Wang et al. (2007) tackled the problem of visualising the distance of landscape terrains simultaneously without limiting LOD's. Users face this problem that particularly occurs when applying different zoom-levels to process geographic information on small screen spaces such like mobile devices. They have developed a so called 'collapsing functionality' that enhances vertex dependencies to overcome fuzzy geographic information caused by inconsistencies between LOD's.

Meng and Forberg (2007) claimed that unlike 2D topographic maps, the visualisation of 3D buildings is not grounded on standard official scale series. They proposed to extend 2D operations (e.g. typification and landmark exaggeration) to tackle 3D generalisation problems. A step towards the generalisation of 3D buildings was done by Forberg and Mayer (2003) by extending the approach of scale spaces in image analysis. They separately applied the 3D version of mathematical morphology and the 3D curvature space to simplify parallel structures of 3D buildings. Forberg (2004) unified both approaches into a parallel shift of different buildings facets to simplify their adjustment.

One form of 3D visualisation is 'virtual environment' that is believed to be a potential mean for simulating spatial or temporal distances of geographic information. The main difference between virtual environments and non-virtual geovisualisations can be made by relating them to tangible and non-tangible aspects (MacEachren et al. 1999). Maps may be assigned to 'tangible' in the sense of 'visible' because they visualise information that physically exists. On the contrary, virtual environments are rather non-tangible because they offer the possibility to show multivariate relationships of non-visible data. Virtual environment is not on par with virtual space. While virtual space deals with spatiality, construction and representation of space through a specific optic (e.g. virtual worlds), virtual environment is "*... about modelling and simulation of a specific domain within a specific scientific field. These include the generalization, visualisation, manipulation, perception and interpretation of these virtual environments*" (Bodum 2005,390).

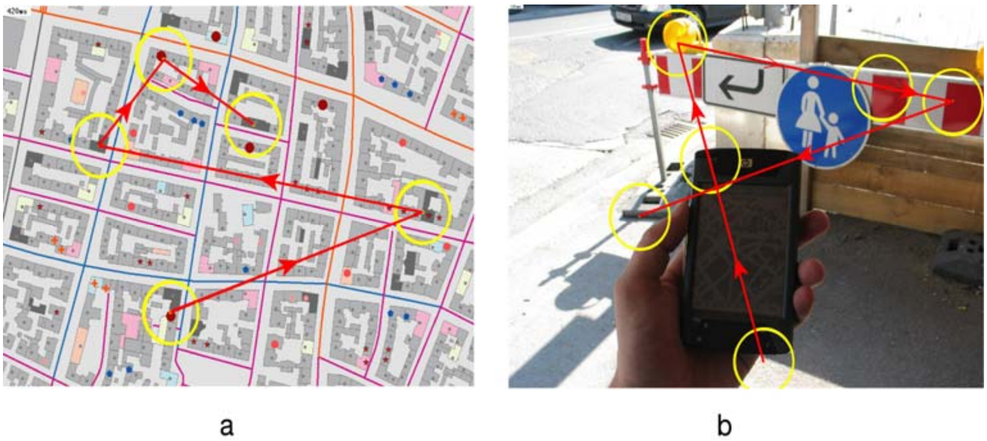


Figure 1. Deviated scan paths in a) complex geovisualisations and b) mobile usage. Scan paths were predicted with a computational attention-model (Itti et al. 1998).

Amongst the diversity of geographic information visualisation, mobile and topographic geovisualisations serve as examples for the development of the cognitive approach of attention-guiding geovisualisation. Due to their distinctive usage characteristics, these examples are ideal candidates to illustrate the universality of attention-guiding geovisualisation, because both methods represent two opposed cartographic visualisations that are affected by the same cognitive challenges. The focus of attention of explorative users that is indicated by gaze fixations can be misguided by the representation of irrelevant geospatial objects and information processing resources of mobile users can additionally be affected by non-targets like distractive stimuli that are located in geographic space (Figure 1). The pre-evaluation of the design methodology also includes examples of remotely sensed images to prove its application in pixel-based geovisualisations. The main evaluation with the eye-movement recording method was conducted with geovisualisations that were configured with a geographic information system representing different complexities of geographic information.

2.3 Perspectives on cognition

Two research areas that deal with cognition are principally involved in this work: geovisualisation design and psychology. In spite of their scientific overlaps, they evolved more or less independently. With regard to relevant theoretical perspectives for conducting past and future research of cognitive phenomena in GI science, Montello and Freundschuh (2005) named seven major theoretical perspectives of cognition.

Constructivism assumes that information located in the geographic space is memorised in form of so called 'internal representations' of the world that help humans to retrieve gained knowledge for constructing sense. These mental representations are often referred to as 'cognitive maps', a term that was invented by Tolman (1948) after having studied spatial abilities of rats and humans.

The ecological perspective suggests that information is processed through an interaction of the environment and the human organism. Accordingly, humans rather process something in the kind of ‘values’ and ‘meanings’ than dimensions or properties of environmental information.

The information-processing perspective believes that humans acquire knowledge over a period of time through strategies. Hence, theorists who follow this perspective take into account the function of memory in the learning process. Such a theoretical background is often used to generate computer processors.

Connectionism suggests that human information processing is based on complex interconnected neural networks for generating computational models.

The linguistic perspective considers the linguistic structure as the basis for human information processing. In other words, the meaning of information is expressed by the metaphorical content of language.

The perspective of situated cognition argues that information processing takes place in a specific ‘situated’ context that is characterised by particular cultural backgrounds.

The evolutionary perspective hypothesises that human’s diver in their way of information processing depending on their evolutional background. In other words, human information processing is affected by the way evolution has formed the mind and behaviour.

Additionally, variations of these seven perspectives on cognition are suggested by Montello and Freundschuh (2005) to yield knowledge for designing geovisualisations. Due to the manifold common characteristics of these perspectives, it is beyond the scope of this work to discuss its content in relation to the before mentioned perspectives, which vary in specific psychological subjects. For instance, the fact that connectionists study the neural network to develop computational models can entice someone to relate this approach automatically to the theoretical perspective of cognitive neuroscience without making relevant distinctions. Although both areas investigate characteristics of the neural network involved in human information processing, they differ in their approach to develop computational architectures for attention. Connectionists are interested in interconnecting units. They assume that these units correspond nearly to neurons or groups of neurons that exchange information about for example pointers or abstract addresses. Connectionist studies and paradigms (e.g. Fukushima et al. 1983, Humphreys & Müller 1993) differ from other approaches in cognitive neuroscience having a clear relation to the biological substrate of neurons. Accordingly, main functions in various connectionist networks differ from those of biological neurons. Another important difference is that investigations done by connectionists are limited in the data set they consider. “*These differences make it difficult to compare predictions of connectionists architectures with physiological observations*” (Niebur & Koch 2000,164).

To position this work within the scope of psychological research, cognitive aspects in this work are related to more widespread psychological perspectives of cognition, namely the behaviouristic approach and the cognitive approach. In order to investigate the design of geovisualisations, this work borrows approaches and findings from cognitive neuroscience. Cognitive neuroscience can be considered as a discipline of cognitive psychology. It investigates amongst other things internal phenomena of visual information processing and has considerably contributed to the understanding of the complexity of visual information processing. Cognitive psychology embraces human cognition in interaction with the physical world and deals with “*... perception, learning, memory, language, emotion, concept formation, and thinking*” (Eysenck & Keane 2000,1). Cognitive neuroscience results from the scientific connection of neurobiology with research of cognition (Thompson 2001) and deals with patterns of cognitive performance (Eysenck & Keane 2000). Cognitive neuroscience unifies approaches concerning functions of perception, thinking, and memory as well as their reproduction by computational programs, for example in fields of application dealing with artificial intelligence, robot design and programming, or expert systems (Fröhlich 1997, Gazzaniga 1984).

The overall goal of cognitive neuroscience is to investigate classic philosophical and psychological topics of mental functions with neurobiological terms. As a result of this account, a frequently asked question is formulated and answered by Kandel et al. (1996,326): "*How can we reason about mental processes from a biological perspective?*"

Previous success in understanding the most important functional systems (sensor, motor, motivation and attentional systems) results from a reductive approach by using the analytical strength of the cellular neurobiology to investigate cognitive psychological research questions. This approach assumes that mental functions result from biological characteristics and activity of neurons which are the basic processing units of the brain. Accordingly, the human mind corresponds to a collection of functions which are executed by the interaction of a vast quantity and variety of firing neurons in the human brain. Knowledge of this specificity, selectivity, and connectivity of visual neurons offers the possibility to gain new knowledge for designing geovisualisations. In this work, particularly the functionality of neurons in major visual brain areas play a decisive role in adapting the design of geovisualisation to the functional fractionation of visual information processing.

Cognitive psychologists consider the entire process of handling information as cognition. "*Cognition refers to all the processes by which sensory input is transformed, reduced, elaborated, stored, recovered, and used*" (Neisser 1967,4). GI scientists make a distinction between 'perception' (initial processing of visual information) and 'cognition' (continuative processing of visual information including memorised information). As Slocum (2005,14) documented, "*Understanding the role that cognition plays in cartography requires contrasting it with perception. Perception deals with our initial reaction to map symbols. In contrast, cognition deals not only with perception but also with our thought processes, prior experience, and memory*".

Cognitive aspects in this work are explicitly related to the human skill of visual information processing, often referred to as visual cognition. To avoid a misleading usage of the term 'visual cognition', the human ability of handling visual information is here referred as to 'visual information processing'. Visual information processing is the functional system of behaviour (Lezak et al. 2004), ranging from cognitive functions such as memory to behaviour characteristics like visual attention.

The term 'perception' as it is used in GI science is specified as 'bottom-up' or 'low-level' processing. Bottom-up processing is characterised by the exogenous stimulus-driven control of attention. In other words, attention is spontaneously oriented towards an oncoming stimulus. The term 'cognition' as it is used in GI science is defined as 'top-down' or 'high-level' processing. Top-down processing is characterised by the endogenous intentional control of attention. In other words, attention is directed by knowledge, expectations and current goals (e.g. Desimone & Duncan 1995, Egeth & Yantis 1997).

Both, bottom-up factors (sensory stimulation) and top-down-factors (e.g. knowledge) control visual attention. The interaction of these factors determines where humans pay attention in their visual environment, how they do it and to what information they direct their focus of attention (Corbetta & Shulman 2002). In the work hereafter, the terms 'cognitive' and 'cognition' are related to visual information processing without any distinction between bottom-up and top-down processing.

2.4 The behaviouristic and the cognitive approach

GI scientists aim at depicting geographic data to support users in geographic relevant tasks through geovisualisations. Geovisualisations are powerful and efficient means by abstracting and simplifying the amount of information that is located in the geographic space to scale. When designing geovisualisations it can be advantageous to consider them as ‘external’ artefacts that graphically represent geographic data to prompt a user’s ‘internal’ mental processes. To effectively adapt the external geographic information presentation to a user’s internal geographic information representation, some GI scientists study the design of geovisualisations with respect to a user’s physical and mental ability of visual information processing.

Visual information processing as a functional system for the organisation of visual information comprises a set of functions characterising a part of human behaviour. Theoretically and empirically, psychologists approach such behaviour by investigating subjects from various scientific perspectives. Among these views, the ‘behaviouristic approach’ and the ‘cognitive approach’ have been discussed in cartographic design and psychology. Although it is stated that any “*... approach in the history of cognitive cartography has ever relied much on behaviorism as a theoretical framework*“ (Montello 2002,295), differences of the behaviouristic and the cognitive approach are presented in the following to point out the ‘cognitive focus’ of this work, that is characterised by putting emphasis on internal processes of visual information processing.

In GI science the behaviouristic approach investigates which geographic information presentation (e.g. a cartographic symbol) works best through the observation of a subjects’ behaviour. The cognitive approach additionally deals with how and why this specific information is processed by the user. With regard to cognitive issues in cartography Slocum (2005) distinguishes between a traditional behaviouristic view and a trend towards a cognitive view. *“Traditionally, cartographers were not so concerned with why symbols worked but rather with determining which worked best. This was known as a behaviorist view, in which the human mind was treated like a black box. The trend today is toward a cognitive view, in which cartographers hope to find why symbols work effectively”* (Slocum 2005,14).

In psychology, the basic difference between the behaviouristic and the cognitive approach is deeply rooted in taking or not taking into account cerebral processes for understanding characteristics of visual information processing. “*Behaviourists regarded any processes between the stimulus-input and the behaviour-output as being irrelevant for scientific behaviour research. Constructive cerebral processes which form the basis of perception, action, planning, thinking, attention and complex forms of memory were ignored nearly in their entirety*” (Kandel et al. 1996,329). For this reason, behaviourists *“... regarded the brain as an unapproachable black box and denied the usefulness of studying mental processes because they were basically unobservable*” (Kandel et al. 1991,3). The non-consideration of internal processes by behaviourists can reveal some shortcomings for e.g. concepts of association. This is the case when relations that occur in learning should be related to the functionality and execution of the nervous system (Weiten 1989). Currently, psychology has a different perspective on visual information processing. *“Most psychologists now want to look into the black box and understand how mental processes function”* (Kandel et al. 1991,3). In contrast to the behaviouristic approach, cognitive psychologists study internal processes to understand how and why humans internally represent external visual information. “*Cognitive psychologists analyse cerebral processes between stimuli and behaviour, i.e. they investigate exactly the domain that was considered as being of no importance by behaviourists*” (Kandel et al. 1996,329).

Until the nineteenth century, research of mental activity belonged to the scientific area of philosophy where psychologists acquired knowledge through self-monitoring. In the mid-century, this introspection was superseded by empirical studies and has offered the possibility to find experimental psychology as an independent discipline. In the beginning of experimental psychology, researchers predominantly investigated sensory perception, i.e. they studied patterns of events by which a stimulus excited a subjective reaction or behaviour. This trend was accompanied by the establishment of the already existing research discipline of psychophysics that aims at describing, quantifying and interpreting characteristics of information processing. Psychophysics dates from the beginning of the eighteenth century and is mostly related to the work of the German scientists Weber (1795-1878) and Fechner (1801-1871). While Weber predominantly studied the haptic and auditive information processing, Fechner can be considered as the founder of psychophysics as a new technique for conducting experiments (Guski 1996). In his approach of psychophysics, Fechner was one of the first scientists who considered internal processes as being relevant for investigating interactions between objective physical and subjective mental processes. Particularly with regard to his concept of internal psychophysics, the brain is considered as a connected system between the processing of external stimuli and the behaviour of humans.

At the end of the nineteenth century, psychologists increasingly began to analyse these subjective experiences by investigating aspects of learning, memory and attention. Experimental methods for investigating learning capabilities were founded for humans and animals. Hence, experimental psychology extended its research field to higher mental processes. At this time, such a development towards an objective psychology peaked out in a rigorous empirical tradition of behaviourism (Kandel et al. 1996).

The behaviouristic approach is based on the assumption that human behaviour can be studied by solely concentrating on observable phenomena of behaviour and by abandoning non-observable mental activities. As a result, experimental psychology was dominated by exclusively measuring observable reactions to controlled stimuli. In behaviourism, internal cerebral processes between the stimulus-input (entering of a stimulus on the retina) and the behaviour-output (ranging from executive functions like decision-making to motor output like eye-movements) were considered as irrelevant for investigating the humans capability of visual information processing (Kandel et al. 1996). This perspective of visual information processing is comparable with a functionalist approach to the philosophy of mind, implying that neural structure characteristics have no impact on theories of mental functioning (Dennet 1991). In the 1950s, the behaviouristic perspective has led to the notion in experimental psychology that the observable behaviour of humans represents their whole mental life (Kandel et al. 1996).

The somewhat ‘scientific autarchy’ of behaviourism has been increasingly criticised by psychologists and provoked polemic remarks such like Chomskys “... *defining psychology as the science of behavior was like defining physics as the science of meter reading*” (in Miller 2003). As a result, founders of cognitive psychology in the 1950s and 1960s (e.g. Bartlett 1958, Miller 1956, Neisser 1967) have aimed at demonstrating a scientific narrowness of behaviourism and herald the cognitive era. By the mid-1950s psychologists realised failures of behaviourism and except for some experimentalists in the United States, it had become obvious that the behaviouristic perspective on its own could not succeed (Miller 2003). Conducted cognitive research as well as former references from gestalt psychologists, psychoanalysts and European neurologists suggested that visual information processing ‘forms’ the behaviour of humans. Consequently, visual information processing itself can be regarded as a constructive process that not only depends on the encoded information of a given stimulus but that it is also closely related to the mental structure of humans (Kandel et al. 1996).

2.5 Low-level-and high-level visual processing

Eckert was probably the first scientist in the twentieth century who put emphasis on visual information processing in map-design research. In the work *On the nature of maps and map logic* (Eckert 1908) he set principles for map creation and cartographic perception. In his agenda for cartographic science *The science of maps* (Eckert 1921, 1925) he stated that “… *It* *is the subtle teasing out and determining of aesthetic, psychological and physiological laws … that make it* (cartography) *a science"* (1925,5).

Nearly at the same time, Gulliver (1908) presented results in *The orientation of maps* from experiments done with school children. He investigated cognitive issues of map-reading with a focus on the influence of map orientation on the study of geography. A few years later, Wright (1942) was inspired by Speiers (1941) work on using maps for propaganda purposes and discussed the cartographers' subjective perspective of the world and the objective reality of the physical geographic environment. He suggested that both cognitive aspects have an impact on the design of maps and stressed out the subjective contents of maps.

Being influenced by these studies and research questions about psychological effects of maps in the report of the *US National Society for the Study of Education* (1933), Robinson appealed to cartographers in 1952 to conduct systematic investigations on how users visually process maps in *The Look of Maps* (Robinson 1952). He stated that to optimise the function of maps, it is favourable to investigate the communication process between maps and their users. In doing so, Robinson supported the perspective of map functionality as communication device and later proposed maps as channels of information transmission between the geographic space and the map user (Robinson & Petchenik 1976).

During the twentieth century, studies in cartographic design were conducted with a varying intensity having heydays in the 1970s and downs in the 1980s (Gilmartin 1992, Montello 2002). First empirical research with the eye movement recording method caused a sensation due to its novelty in cartographic science (Jenks 1973). Jenks conducted eye movement recordings of users while processing thematic maps. He was probably the first cartographer who investigated user's capabilities in processing visual geographic information from the cognitive perspective with respect to internal neural activity because recording eye-movements means collecting data about neural responses of the eyes retina that exhibits a vast number of nerve cells. Anatomically speaking these cells represent the basic units of the brain, namely the neurons (e.g. Guski 1996, Thompson 2001). Unfortunately, these promising first steps towards investigating map-design with the eye movement recording method were not crowned with success. Several researchers found fault with inconsistent results (Chang 1980, Petchenik 1983) and missing grounding theories for analysing eye movement parameters (Castner 1983).

Instead of studying these low-level tasks that are driven by bottom-up factors, cartographers then called for more investigations of high-level tasks that are driven by top-down-factors. They assumed that studying the visual processing of spatial relations on maps would provide more knowledge on map-design than investigating isolated symbols (Montello 2002). As a result, cartographic research was characterised by a somewhat separation of the purely stimulus-driven low-level and the knowledge-based high-level processing of geographic information. Cartographers believed that it could be more favourable to put the research focus on the investigation of a users' performance when processing spatial relationships instead of understanding visual scanning strategies when processing single map symbols (Petchenik 1975, Gilmartin 1981, Olson 1984). Consequently, two main research topics evolved to investigate the design of geovisualisations.

On the one hand cartographers concentrated on the understanding of a user's capability of visual information processing with respect to high-level tasks such as the influence of knowledge, the ability of spatial orientation and the impact of memory (Olson 1975, 1979; Gilmartin 1981, Blades & Spencer 1986). On the other hand, intensive investigations were conducted on the design of symbols like for instance graduated circles (Chang 1977, 1980), point symbols (Flannery 1971) and squares (Crawford 1973), colour (Olson 1981) and colour scales (Crawford 1971), pattern complexity (Monmonier 1974), contours (Griffin & Lock 1979) and shaded reliefs (Philips et al. 1975) with the purpose to optimise geographic information transmission.

These approaches studied bottom-up and top-down tasks almost independently from each other. By analysing the characteristics of visual information processing, it becomes clear that such a separation is not advantageous.

Any geovisualisation depicts potentially interesting geographic information at many locations. Relevant geographic information cannot be effectively analysed during a single gaze fixation because visual acuity outside the centre of this fixation (fovea) is poor. To process geographic phenomena, humans have to bring each piece of relevant geographic information onto the fovea through a sequence of saccadic eye movements. Such a strategy of processing geographic information implies the existence of a parallel bottom-up and top-down driven selection process within the brain. Hence, to optimise the design of geovisualisations, it may be desirable to study the interplay of high- and low-level processing in geographic tasks.

Visual information processing can be described by hierarchical patterns, processing sequences and pathways, functions of visual brain areas, and the role of mental maps.

Hierarchical patterns of visual processing. In the 1970s and 1980s, scientists found out that detailed processed sensory input is transmitted to higher cerebral areas for binding single features into larger units (Eriksen & Hoffmann 1973, Treisman 1982, Crick 1984). Studies revealed that the visual analysis of information consisting of the hierarchical patterns ‘local view’ (e.g. a symbol, letters, and numbers) and ‘global view’ (the entire geovisualisation) necessitates humans to process different spatial-frequency scales simultaneously. The results of these studies revealed that bottom-up factors are closely interrelated with top-down factors (Wilson 1978, Ginsburg 1986). In view of that, cognitive design research cannot base on significantly separating the bottom-up processing of visual stimuli from the top-down driven decoding of geographic phenomena because information is encoded via sensory input.

Visual information processing sequences and pathways. In the 1980s and 1990s psychologists found evidence for a ’where’ and ’what’ visual information processing stream enabling humans to locate and decode information of interest for decision-making (Ungerleider & Mishkin 1982, Ungerleider 1985, Ungerleider & Haxby 1994) (Figure 2). These observations correspond to prominent visual information processing models. Such models suppose that observers implement a filter as an ’information processing bottleneck’ (Peterson & Juola 2000, Wolfe & Horowitz 2004) or benefit from a ’shifting attention window’ to filter out irrelevant information (Kosslyn 1994). Such a filtering mechanism reduces the complexity of visual information by dissociating the recognition of an object (what) from its localisation (where). These objectives are reflected in basic factors of visual attention that are controlled by stimulus-driven bottom-up factors and goal-driven top-down factors. Only the interaction of these factors generates eye movements in high-level and low-level tasks according to where, how and what attention is paid to (Corbetta & Shulman 2002, McCarley & Kramer 2007).

Visual information processing sequences and pathways in the brain were frequently discussed (e.g. Merigan & Maunsell 1993) and evidence for their validity is given by excellent studies (e.g. Goodale & Milner 1992, Thorpe & Fabre-Thorpe 2001, Fang & He 2005). For instance, in *Seeking Categories in the Brain*, Thorpe & Fabre-Thorpe (2001) could show that primates can categorise complex visual stimuli very quickly and that involved visual brain areas chronologically respond to sensory input. Nowadays psychologists are able to roughly retrace the information flow ranging from sensory input through decision-making to controlled motor-output (e.g. Ungerleider 1995).

In visual search tasks, it is well-known that conspicuous features commonly attract eye gazes (Yarbus 1967, Engel 1971) and that these features are processed through the visual system before neurons fire to higher visual brain areas (e.g. to the prefrontal cortex-PFC) where they are combined into meaningful information (Figure 2). Finally, relevant signals are sent from cerebral association areas through motor areas like the motor cortex (MC) to the spinal cord

(SPC) for innervating skeletal muscles to execute decisions (e.g. activating finger muscles to click and move the mouse or triggering eye muscles to direct gazes).

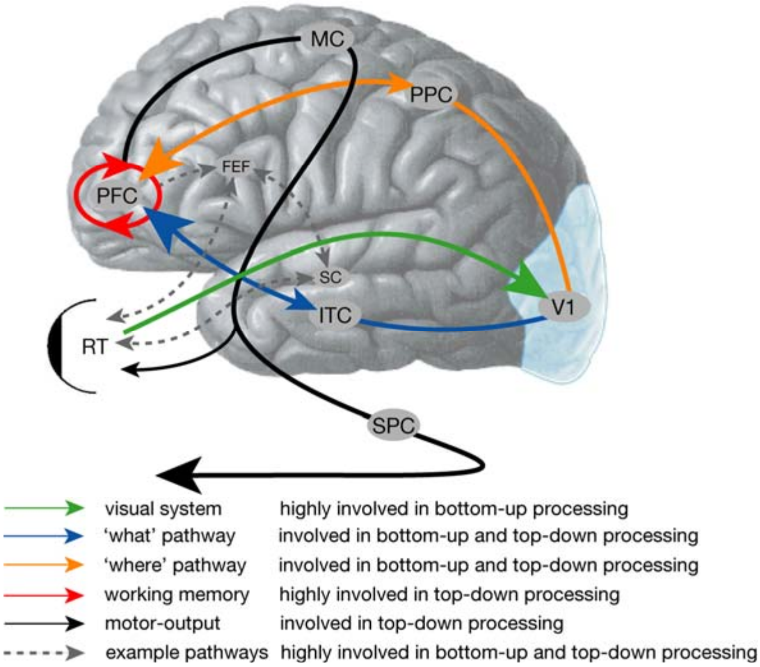


Figure 2. Bottom-up and top-down processing of visual information. Abbreviations: retina (RT), primary visual cortex (V1), posterior parietal cortex (PPC), inferior temporal cortex (ITC), prefrontal cortex (PFC), frontal eye field (FEF), superior colliculus (SC), motor cortex (MC), spinal cord (SPC).

Following this well-structured and rather feed-forward scheme, it seems to be critical to answer the question of how the brain selects relevant information to guide eye-movements. This perspective on visual information processing neglects that the physical salience of objects is only partly responsible for shifting eye gazes to relevant information in a purely bottom-up manner. Thus, the human brain must consist of higher visual brain areas that are simultaneously involved in visual tasks and show neural response during or even before low-level processing occurs.

Functions of visual brain areas. Four visual brain areas are presented in the following. Their functional characteristics illustrate that visual geographic information processing cannot be stiffly separated into purely bottom-up or top-down sequences. The posterior parietal cortex (PPC) and inferior parietal cortex (ITC) are located on the 'where' and 'what' pathways (Figure 2), that seem to be solely involved in bottom-up processing by sending signals about the location and semantics of geographic information to association areas. However, these areas are also highly influenced by top-down signals. The posterior parietal cortex is selectively activated when either voluntary allocation of attention is required via top-down orienting of attention or during target detection without knowing the targets spatial location depending on bottom-up processes (Kastner et al. 1999, Corbetta et al. 2000). The inferior parietal cortex relates colour to objects by retrieving top-down factors that are stored in memory (Zeki & Marini 1998). Gibson and Maunsell (1997) found out that, behaviourally relevant visual information is represented in this visual brain area and that it plays a major role in separating important from unimportant information.

The frontal eye field (FEF), a small but influential visual area that is located in the frontal part of the brain (Figure 2), is involved in converting electrical impulses from higher visual brain areas into motor commands to e.g. allow humans the generation of about three saccades a second. Accordingly, it plays a prominent role in the control of saccadic eye-movements during visual search tasks and initiates eye-movements that are relevant to behaviour before saccades occur. In other words, after the presentation of a visual search array, but before gaze shifts, the frontal eye-field generates intentional eye-movements (e.g. Schall & Hanes 1993, Thompson et al. 1996, Murthy et al. 2001, Sato et al. 2003) independent of where that target is located in space. These eye-movements are experience-dependent (Bichot et al. 1996) and do not solely respond to stimulus properties such as colour and orientations (Mohler et al. 1967). Thompson et al. (2005) stated that neural responses in the frontal eye field have to be related to previous knowledge and sensory input. They pointed out that they use the term ‘salience’ for representing visual conspicuousness depending on interrelations of bottom-up and top-down processing. This corresponds to Sommer and Wurtz (2001) who suggested that the interconnection between the frontal eye field and other brain areas largely depends on signals related to bottom-up processed movement and top-down processed memorised information.

The function of another visual brain area that is connected to the frontal eye-field is inconsistent with the assumption that low-level tasks represent the indispensable prerequisite for visually processing geographic information. The superior colliculus (SC) (Figure 2) receives on one hand bottom-up driven inputs directly from the retina and indirectly from the primary visual cortex (Wurtz & Goldberg 1972, Meredith & Stein 1985). On the other hand, the superior colliculus consists of neurons that initiate commands for driving saccades by relating sensory input to appropriate associations (Horowitz & Newsome 2001). This interplay of bottom-up and top-down processing serves to generate a topographic map of visual space and to code gaze commands in retinal coordinates (Klier et al. 2001).

The role of mental maps. Psychological research on visual information processing revealed that bottom-up and top-down processing coexists by simultaneously influencing relevant action of behaving humans. This fact also becomes obvious by analysing the function of cognitive maps as internal representations of the geographic space. It is clear that humans do not store one single photographic-like picture of what they see. They rather use fragmented collections of abstract or symbolic representations. Due to their multiple character, these representations are often referred to as a ‘cognitive atlas‘ (Kuipers 1982) or a ‘cognitive collage‘ (Tversky 1993).

Such a multitude of mental representations implies that e.g. spatial relations between geographic information are not represented in association brain areas like spatial relations between neurons. Accordingly, the two-dimensional representation of spatial information on the retina is different from copies stored in higher association brain areas that are for instance involved in the working memory system. To estimate spatial distances or to navigate in space, humans use the bottom-up driven retinal image and the top-down driven selected portions of memorised visual information. As a result, one might argue that visual information processing is a creative process that results from matching two-dimensional images projected onto the retina with mental representations of the visual field stored in higher association areas. Only the conjunction of these bottom-up and top-down generated information allows humans to effectively direct their visual attention to information of interest.

A theoretical separation of bottom-up and top-down processing is favourable for developing models of visual information processing. It helps to illuminate the retracing and understanding of the sophisticated information processing ’flows’ but without anticipating predefined processing ’steps’.
However, the division of bottom-up and top-down processing can lead to the faulty assumption that low-level processing represents the essential precondition of high-level processing and can probably entice someone to study geovisualisation design by concentrating on one of these interrelated functions. To conclude that high-level tasks result from low-level tasks or that bottom-up processing is an essential prerequisite of top-down processing, or in turn that humans perceive information in a clearly defined first step before they make decisions in a second step can probably lead to the faulty assumption that visual information processing is a feed-forward two-part procedure. Such an approach implies that someone can determine the beginning and the end of high- and low-level internal correlations. For developing effective

computational architectures of attention, Ballard (1991) and Niebur and Koch (2000) considered yet another theoretical challenge. They are interested in detecting the boundary between the end of cerebral information processes (interplay of bottom-up and top-down processing) and the beginning of corresponding motor-control (action).

Even though the notion of hierarchical visual information flow organisations were successfully investigated (e.g. Ungerleider & Mishkin 1982, Mesulam 1998, Webster & Ungerleider 2000, Pollmann 2003), psychologists noticed that principles of concurrent processing streams and distributed networks of information flow are far away from being exhaustive. To illustrate, about 305 major pathways are estimated to transmit visual information mostly in a bidirectional way through 32 visual areas (Felleman & Van Essen 1991). Assuming that visual areas were a fully interconnected matrix, about 992 pathways related to visual information processing would exist (Van Essen & Anderson 1995), without taking unknown visual areas and pathways into consideration.

Although some psychologists suggested that visual tasks are under top-down-control (e.g. Folk et al 1992) and others stated that visually capturing salient information is predominantly bottom-up controlled (e.g. Nothdurft 1993, Kim & Cave 1999, Itti & Koch 2000), in this work a distinction between bottom-up and top-down processing is intentionally exclusively drawn to facilitate the understanding of internal visual information processing. Hence, no emphasis is put on bottom-up or top-down processing to formulate design principles and develop a design methodology. Visual geographic information processing is regarded as a consistent cognitive process.

2.6 User-centred research

Rapid advances in computer technology have led to the development of many interactive tools which tend to facilitate visual processing of geographic information but underlying cognitive theories for the effective design of appropriate visualisations are still missing (Meng, 2003). With regard to navigational map-reading tasks, Lobben (2004) suggested that a possible reason for missing psychological theories could be, that most psychological or cartographic researchers "*... borrow theories and study results from one another's discipline, but with a few exceptions, most of the cognitive research has been conducted either by psychologists or by cartographers but not by both in collaboration*" (Lobben 2004,271). Beside many research calls in published papers, the need for more research in psychological issues is documented in research agendas that attempt to enforce research on visual geographic information processing.

Four working groups of the *ICA-Commission on Visualisation and Virtual Environments* have formulated the exploratory focus of geovisualisation (MacEachren & Kraak 2001) entitled: (1) Geospatial information visualisation user interface issues (Cartwright et al. 2001), (2) Integration of geographic visualisation with knowledge discovery in databases and geocomputation (Gahegan et al. 2001), (3) Representation and its relationship with cartographic visualisation (Fairbain et al. 2001), and (4) Cognitive and usability issues in geovisualisation (Slocum et al. 2001). The common ground of these research areas is the call for studies that investigate the abilities of visual information processing in the context of designing geovisualisations.
In particular research area (4) recommends the investigation of design approaches that are based on gained knowledge of visual information processing to optimise knowledge acquisition in geographic tasks. A major research challenge is to investigate the potential of geovisualisations to enable decision-making by tackling cognitive and usability aspects (Dykes et al. 2005). In this connexion, it is of prime importance to create or advance cognitive design theories as well as to consider ergonomic design principles. These aspects represent the scientific foundation wherefrom new design methodologies can be developed.

Before and since then, many powerful tools have been implemented to facilitate visual information processing tasks like exploring geographic information (e.g. Gahegan et al. 2002, Demšar 2007), route planning and way finding (e.g. Coors et al. 2005). An important aspect of current research is the accumulation of geographic databases with spatiotemporal information (e.g. Honsby & Egenhofer 2000, Worboys 2005). The dedicated task of designing geovisualisations that enables users an effective visual processing of these amounts of data still lags behind the ongoing geographic data acquisition.

The rather technology-driven evolution in the history of geographic information can amongst other things probably be attributed to the more profitable economic focus of map production and the sometimes lucrative development of GIS tools. This can entice GI scientists to first code vast amount of geographic information into complex visualisations and then to require appropriate cognitive skills from users to visually process these products. In doing so, they obligate users to adapt their powerful capability of visual information processing to the comparably limited ability of computational geographic information design. Contrariwise, to enhance a system's acceptability GI scientists should first investigate a user's cognitive skills and then adapt the visualisation design to the user's need in a second step.

In the course of threat of terrorism, the US Department of Homeland Security (DHS) defined a research agenda for visual analytics to facilitate advanced analytical insight through visual analytics tools. To bridge the gap between technology-driven and user-centred research, the US *National Visual Analytic Center* (NVAC) has to some extent advanced the *ICA-agenda* in collaboration with researchers of geovisualisation (Chinchor et al. 2005). This agenda reveals a lack of research to develop scientifically testable design principles for visual representations. As a substantial request, the optimisation of cognitive analytical processes in complex geographic tasks is considered by the NVAC. For this purpose, the agenda calls for research in new design approaches that allow users to apply as much visual information processing abilities as possible for effective decision-making. It specifies the suggestion of the 4th ICA-working group by recommending that representation principles "*… must address information complexity, enable knowledge discovery through information synthesis, and facilitate analytical reasoning"*. The goal of this recommendation is to '*… expose all relevant data in a way that facilitates the reasoning process to enable action'* (Chinchor et al. 2005, 98).

In the 1980s, computational advances in GIS-technology have directed the focus of research to the automated treatment of geographic data. This technology-driven approach decreased cognitive research and became a mainstream. Resulting from this trend, geographic information engineering concentrated on fulfilling the objective and purpose-driven pragmatic requirements (e.g. technical quality) of users and abandoned the personal, more diffuse and subjective hedonistic quality (e.g. quality of performance influencing a users emotion) of geovisualisations (Meng 2004).

In a digital era, the design of geovisualisation faces a three-fold challenge: (1) the expanding range of display sizes, (2) the increasing quantity of geographic data at various granularity degrees, and (3) different levels of information abstraction. Resulting from this development, Meng (2003,1) stated that "*... today's mapmaking activities tend to be more and more technique-oriented and cartographic products have become more and more functional"*. She called cartographers for *"… more attention to usability study and more effort towards the design of geo-services*". Recommendations like these probably evolve from the absence of standardised empirical evaluations to test Bertin's well-known set of fundamental graphic variables (Bertin 1967, 1983). Although Bertin's work still influences cartographic design research, it can be scientifically questioned due to the missing empirical evidence of his conceptualisations that do not result from cognitive research (MacEachren 2001).

User-centred studies in the recent decade have come more and more to the fore of cartographic research via new psychological approaches of visual geographic information processing. The rudimentary shifting of the research focus is characterised by the issue *From geovisualisation toward geovisual analytics* of the annual *ICA-Commission on Visualisation and Virtual Environments* meeting that was held on August 2, 2007 in Helsinki, Finland.

Recent publications prove the increasing awareness among GI scientists that technology-driven development needs to be accompanied by profound empirical research on cognitive skills. Psychological research in geovisualisation has experienced a renaissance in the latest years. GI scientists recognised that technology-driven solutions for decision making in geographic tasks should be based on user-centred research. Therefore, GI scientists and other interface designers shifted the focus of research to the user by intensifying cognitive studies for empirically investigating the design of geovisualisation.

Various studies on visual search processes during map-reading tasks have been conducted and discussed visual search theories in map-reading context (e.g. Bartz 1970, Beller 1972, Treisman 1988, Duncan & Humphreys 1989, Cave & Wolfe 1990). For example, in *Visual Search Processes Used in Map Reading* (Lloyd 1997), various objects were designed that differed in size, colour, orientation, and shape to investigate their supporting character of spatial search. The study revealed that objects with unique characteristics visually ‘popped out’ from information density. This was especially the case when ‘colour’ has been used to provide differences between attractors and distractors. Another result was that the spatial locations of relevant objects have influenced visual search strategies.

Visual information processing was also investigated by using statistical maps (Herrmann & Pickle 1996) as well as scatterplots. In Kosara et al. (2002), a concept of semantic field of depth (SDOF) by blurring objects based on their relevance was tested by using scatterplots which are useful to present two data dimensions. In order to visualise large numbers of easily distinguishable cues, SDOF proved to be helpful for discriminating up to four classes. Another study tested the effectiveness of searching for information on maps with multivariate point symbols (Nelson & Gilmartin 1996). The authors embed variates in some symbols to investigate wether they attract attention more quickly and accurately than others. They found out that it is easier for subjects to search for symbols that consist of a single variate.

The rise of 3D visualisations afforded researchers to evaluate different cognitive aspects of their application, often in comparison to 2D visualisations. One study investigated the effectiveness of representing numeric information by means of bars and bar charts in desktop 3D environments (Bleisch & Dykes 2007). The authors demonstrated that it was easier for trained users to decode two classes of numeric values in 2D compared to 3D settings when processing bars of varying height and constant width. Other results revealed no significant differences in remembering tasks between 2D and 3D computerised visualisations, although subjects were better when using a 2D than a 3D physical model (Cockburn & McKenzie 2004). After evaluating the usability of the spatial metaphor ‘scale’ in a digital document collection, Fabrikant (2001) suggested that subjects were able to associate graphical changes in zooming spatialised views with changes in the hierarchical order of a document collection. She stated that the analysis of group membership was significantly different, but for some displays subjects needed more time for decision-making. An interactive spatial cognitive map was evaluated by Ramloll & Mowat (2001) to test its ability for supporting wayfinding in virtual environments.

In the mean time, GI scientists made more and more use of the eye recording method, also referred to as eye-tracking or gaze-tracking. While some researchers formerly were in doubt about eye-movement recording as an appropriate evaluation method, others sensed, documented and realised its potential to advance research in geographic information design (e.g. Keates 1982, Castner & Eastman 1984, 1985; Steincke 1987, Morita 1991, Lloyd & Hodgson 2002, Brodersen et al. 2002, Hermans & Laarni 2003, Fabrikant et al. 2006). Instead of ruling out the possibility to gain fundamental knowledge of how people process geographic information through eye-movement recordings, GI scientists nowadays benefit from their openness to experience that is grounded in the highly interdisciplinary research area of GI science. They do not simply hark back on tracking eye-movements as a research method. Instead they have recognised that analysing, interpreting and applying eye-movement data requires knowledge of visual information processing and therefore they pay a lot of attention to scientific progresses in cognitive research areas. Tracking visual parameters through sophisticated systems has previously been proved to be a substantial evaluation method in interdisciplinary research areas that study human behaviour in interaction with the physical world through external artefacts, like for instance in neuroergonomics (Parasuraman & Rizzo 2007).

Most recently, eye-movement recordings have evolved amongst a variety of other cognitive evaluation methods to a promising technique for investigating cognitive issues of geovisualisation design. It measures significant parameters of eye-movements as human's external manifestation of visual attention and describes individual scan paths in qualitative and quantitative terms (e.g. Zihl & Hebel 1997). Recording these visual scanning parameters allows to analyse user's visual scanning strategies during visual geographic information processing. Tracking gazes has not been 'simply' used to investigate bottom-up visual information processing tasks such as feature detection. Knowledge of interrelated high-level and low-level visual information processing has already been applied in the 1950s to reveal shortcomings in the design of cockpit displays. Fitts et al. (1950) filmed expert and novice pilots and collected data about duration and frequencies of looks in order to obtain information about patterns of visual information processing. The results of such circumstantial evaluation method have led to remarkable improvements in cockpit design (McCarley & Kramer 2007).

Eye-tracking has been applied to study cognitive processes in complex tasks such as defining differences between novices and experts in processing radiological images (Kundel & LaFolette 1972) or analysing visual strategies in airport security inspections (McCarley et al. 2004). It also serves to investigate the level of cognitive workload related to top-down task difficulty (e.g. Wickens & Hollands 2000), to gain knowledge about humans' visual imagery of presented visual information (e.g. Brandt & Stark 1997), and to predict high-level task-dependent future actions (e.g. Pelz & Canosa 2001a,b).

Eye-movement recording involves the recording of pupillary changes and the rate of eye-blinking as well as the analysis of visual scanning parameters (e.g. quantity, amplitude, and direction of saccades, the location, number, and duration of fixations as well as frequency and location of re-fixations). By measuring changes of a pupils diameter during mental activity an increase of the cognitive workload has been identified. Psychologists related pupillary dilation to task difficulties during short-term memorisation (Kahnemann & Beatty 1966, Kahnemann & Wright 1971), inference-making (Hunziker 1970, Lenhart 1983, Nakano, 1971) and decision-making (Simpson & Hale 1969), pitch discrimination (Kahnemann & Beatty 1967), and geometric and mechanic reasoning (e.g. Hegarty & Just 1993, Epelboim & Suppes 1997, Rozenblit et al. 2002). The increase of pupil diameter is considered as a valid parameter to measure mental efforts (Beatty 1978, 1982).

Several researchers found out that the decreased rate of eye blinking could be a possible indicator of mental effort (e.g. Wood & Hasset 1950, von Cramon & Shuri 1981, Stern & Skelly 1984). Other researchers investigated eye blinking and its relation to the cognitive workload of air traffic controllers during weather display interaction. Through eye movement activity measures that correlated with the cognitive workload, Ahlstrom et al. (2006) revealed significantly shorter blink durations when controllers operated traffic without weather displays. This indicates a higher workload level. A comparison of the pupil diameter during operations with a static storm forecast visualisation and a dynamic tool, showed that pupil diameter was larger in the first case than in the second one. Hence, cognitive load was higher when controllers used the static tool. May et al. (1990) observed that the range of saccadic extent decreased when humans faced an increasing workload during visual and auditory tasks. By comparing eye-movements on bottom-up stimulus-driven saliency maps and top-down task-dependent natural scenes, eye scan patterns showed that humans rather visually fixate task-relevant objects than focusing on low-level salient features (Canosa et al. 2003). Psychologists hypothesised that eye-movements are useful to investigate aspects of visual imagery (Neisser 1967, Hebb 1968). They suggested the reproduction of external visual information by means of eye movement during internal processes. In other words, when humans remember visual information while keeping their eyes open, they employ patterns of eye-movements like those originally made when the visual information was present. This hypothesis results from somnological research (research on the behaviour during sleep), where studies revealed that rapid eye-movements during dreaming could represent the visual content of dreamed scenes (e.g. Dement & Kleitman 1957, Herman et al 1984).

Based on the analysis of eye-movement patterns, Brandt and Stark (1997) concluded that scan paths during mental visual imagery re-enact those that where observed during visual processing of the same scene. They compared eye-movement patterns of complex diagrams with those of visual imagery and observed approximately the same scan-path sequences (Figure 3). This experiment was also conducted with images that contained semantic content like for instance pictures of animals (Laeng & Teodorescu 2002). Such studies revealed that the order of visual scanning as commands from higher brain areas to the eyes is stored in the limited capacity of humans' memory. Such investigations showed that eye-movement recordings are appropriate for acquiring knowledge about how long and how accurate humans are able to memorise complex information.

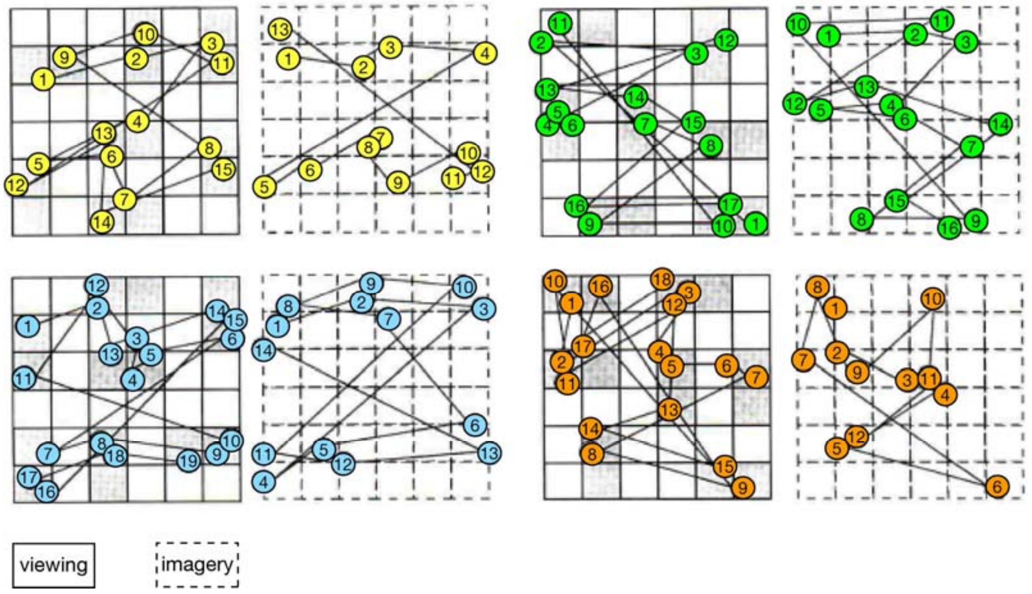


Figure 3. Scan paths during viewing and scan paths during imagery (modified from Brandt & Stark 1997).

Another study suggested that gaze tracking data can serve to determine levels of satisfaction in usability research upon eye tracking experiments using graphs and tables as stimuli (Renshaw et al. 2005). In the domain of human-computer interaction Hornof (2004) investigated cognitive strategies of humans when visually searching within computer displays. Amongst other determinants he used eye-movement parameters to create an ocular motor, a visual perceptual and a central cognitive processor to generate a predictive visual search tool. Finally, eye-movement recording has been proved to be an appropriate method even for identifying high-level task-dependent strategies of future relevance (Pelz & Canosa 2001a,b), i.e. eye-movement parameters can serve to indicate motor-controlled future actions like predicting mouse clicks and movements.

GI scientists and psychologists consider eye-movement recording as a 'window to the mind', and they therefore regard it as an objective method 'towards' understanding visual geographic information processing. They relate eye-movement parameters to the complex correlations of visual information processing for understanding internal representations of the geographic space. Hence, designers of geographic information do not expect concrete results - in terms of definite solutions - that pop-out through one mouse-click like mathematical problems solved through the usage of pocket calculators. These days, GI scientists keep an eye on consolidated findings in cognitive sciences and intensify cognitive studies. Being aware of these findings, GI scientists have been striving for collaborations with cognitive scientists to embed gained knowledge in design approaches, principles, methodologies and evaluations.

By comparing various types of high-level geographic tasks, Wiebe et al. (2005) studied the impact of focused and integrative question types on visual processing of 2D and 3D topographic maps. They found out that 3D maps do not positively or negatively influence users in processing geographic information. This outcome involves results from Savage et al. (2004) who additionaly revealed advantages in the use of 2D representations for focused questions.

With eye-movement recordings Hermans & Laarni (2003) investigated differences in search performance between different map user groups using zooming or scrolling to navigate in visualisation space. They concluded that experience with GIS has an impact on the search performance. Experts found objects and interpreted information more efficiently than novices and prefer scrolling to zooming.

Fabrikant et al. (2006) investigated the relationship of information relevance and salience in static weather maps. They investigated how users' visual scan path sequences vary when relevant items are designed more salient than irrelevant ones. First, they pre-evaluated a mass media map and a cartographically enhanced map by predicting possible scan paths with a saliency-based attention model (Itti et al. 1998). In an ongoing study, they use the eye-movement recording method in a second step, to study how users visually detect information of interest from weather maps and how they draw conclusions from static visualisations for knowledge construction of weather phenomena.

Another promising cognitive evaluation method for user-centred research is brain imaging. It permits to investigate and directly visualise ongoing brain activity and changing levels of cognitive workload during visual information processing. Functional brain imaging like functional magnetic resonance imaging (fMRI) allows researchers to analyse the activity of visual brain areas and to investigate neural substrates of visual attention at a given task. By visualising the changing blood oxygenation level dependent (BOLD) signal, degrees of (non)-activation of individual brain areas can be displayed. The visualisations map colour coded signal densities of activated visual brain areas into precise neuroanatomical images and support neuroscientists in retracing the information flow between connected areas. fMRI can provide evidence of the functional relationship of sensory input and corresponding executive functions (e.g. decision-making, concluding) while measuring the increase or decrease of a user's cognitive workload at a given task. Hence, conducting task-specific evaluations of visualisation designs with fMRI allows to gain fundamental knowledge of (1) why a variable, a principle or a methodology works more effectively than others do and (2) how this effectiveness is related to specific variables and design principles.

fMRI is moreover used to examine humans behaviour in spatial navigation tasks. In ergonomics, Hartley et al. (2003) investigated differences in spatial navigation between route following (taking a known route) and way finding (taking an unknown route in a familiar environment). Ruddle et al. (1997) found out that when designing virtual environments realistic landmarks optimise the ability of navigation while abstract landmarks (e.g. coloured patterns) do not.

During recent years, GI scientists have begun to study the design of geovisualisation from the cognitive perspective with emphasis on neural correlations (Lawrence 2004, 2005; Lobben et al. 2005, Olson et al. 2005, Lobben 2007). Using fMRI they investigate amongst others orientation and navigation capabilities of users when processing maps. In *The Neural Basis of Map Comprehension and Spatial Abilities*, Lawrence (2004) claimed that relations between spatial abilities and map comprehension are unknown. Using fMRI, she investigates the neurological basis of spatial relations and spatial scannings. Lobben et al. (2005) conducted exciting research in collaboration with neurocognitive scientists, neurologists and physiologists. In order to investigate aspects of spatial navigation and spatial attention they included fMRI to study map-rotation tasks.

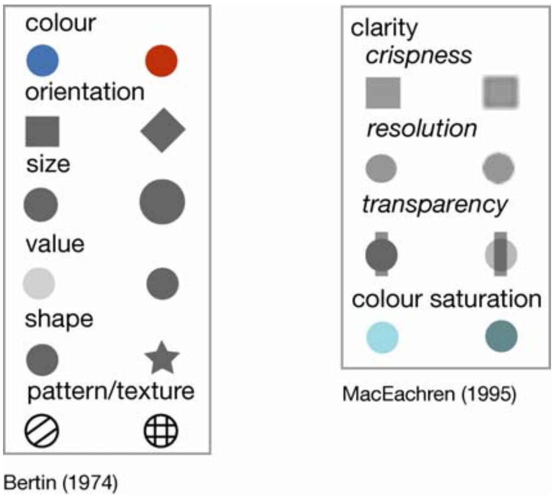
Conducting task-specific evaluations with both eye movement recording and fMRI simultaneously (e.g. Thiel et al. 2003) can reveal new fundamental insights into the design issues of geovisualisations. Moreover, these cognitive methods definitely benefit from a high level of emprical evidence and standardisation. Even though, GI scientists enforce cognitive research on geographic information processing, it must be noted that empirical evaluations have been conducted sporadically. As a result, test validity and reliability are underrepresented in GI science (Lobben 2004) and can be optimised via specific inclusion and exclusion criteria of performance. This includes conventional routine measures to exclude subjects with impaired visual functions. Subjects receiving medication that reduce velocity and accuracy of saccadic eye movements, increase saccadic latency, or impair visual scanning, can be easily excluded throughout simple interviews (Swienty 2005).

Finally, empirical test methods for cognitive studies were reported. To improve spatial data usability, Mac Aoidh & Bertolotto (2007) developed a flexible architecture for desktop and mobile systems to monitor user interactions through mouse movements. Recorded data allows a system to build up a session-dependent user profile. To optimise test validity and reliability in navigational map reading tasks, Lobben (2007) designed a Map Reading Ability Test (NMRAT) to measure five map-related abilities (map rotation, place recognition, self-location, route memory, way finding exercise). To assess the validity of the NMRAT, she additionaly developed a Real World Map Navigation Exercise that records data for task-specific criteria (number of map rotations, number and duration of stops, number of hesitancies, time spent to fulfil each task).

2.7 Communication, visualisation and visual scanning efficiency

There exist a number of models of the cartographic communication process. The theoretical background ranges from approaches that regard maps as channels between the source (geographic space) and its recipient (user) (e.g. Robinson & Petchenik 1976) to cognitive models that involve map production and use in the cartographic communication process (e.g. Koláčný 1969).

To optimise the communication of geographic information, Bertin (1967, 1983) proposed his concept of graphic semiology that is generally considered as the basis of the grammar of the so called cartographic language (e.g. Kraak & Ormeling 2003). Bertin put forward a set of fundamental graphic variables (luminance, texture, colour, orientation, shape, and size) to support users in processing the order, association, selection, and quantity of geographic information. These variables differ in their properties of perception. The ordered variables texture, luminance, and size are spontaneously perceived in a visual order. The associative variables shape, orientation, colour, and texture are spontaneously perceived as classes of elements within a variation. While the selective variables luminance, texture, shape, colour, and orientation are perceived as distinct items of the same class without the need for visually scanning each symbol. The variable size is suggested to be the only quantitative variable that is able to exactly visualise numerical proportions.



Bertin (1974)

MacEachren (1995)

Figure 4. Graphical variables that might be appropriate to code ordinal data.

In the following years, several researchers have proposed extensions of Bertin's system (e.g. Mackinlay 1986, MacEachren 1995) and developed taxonomies of visualisation techniques (e.g. Shneidermann 1996, Ware, 2000). Others investigated design principles for statistic visualisations that were based on findings of processing graphics, colour and motion (e.g. Cleveland 1985, Bartram & Ware 2002). In this work the additional graphical variables colour saturation, crispness, resolution, and transparency (Figure 4) that were proposed by MacEachren (1995) are of interest due to their possible potential to effectively code ordinal data like the order of relevance (see 2.8). In 1995, the conception of communication began to adopt MacEachrens presumption that maps 'stimulate inferences' rather than 'transmit knowledge' from maps (MacEachren 1995). The advent of GIS and the manifold array of geovisualisation products that encode geographic information with visual variables have substantially reinforced efforts of cognitive map design.

Map use. MacEachren integrated the goal of exploration in his perspective on map use and distinguished communication and exploration oriented cartography (Figure 5). Following DiBiase (1990) who investigated the role of maps in scientific visualisation, MacEachren considered target audience (from private to public), presentation intentionality (from revealing unknowns to presenting knowns), and the degree of human-map interactivity (from high to low) as relevant dimensions of his cartographic visualisation model (MacEachren 1994, MacEachren & Kraak 1997). The so-called map use cube offers different goals of map use in dependency of intentions of use, user categories and degrees of human computer interaction. While some users explore geographic information by revealing unknowns in a private realm with high interactivity, the opposition needs the presentation of knowns through low interactivity in a more public realm.

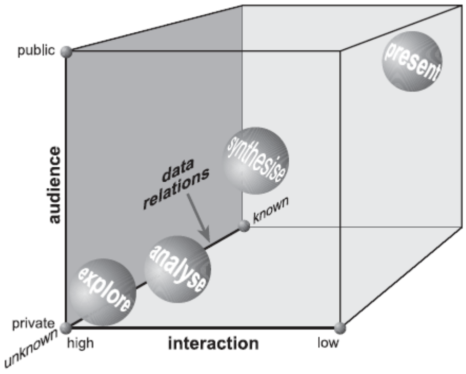


Figure 5. The map-use cube (adapted from MacEachren & Kraak 1997).

Although the degree of required attentional capacities during the visual processing of geographic information is not itemised as an integral part of one of the well-known map use cubes (MacEachren 1994, Kraak & Ormeling 1996, MacEachren & Kraak 1997), it is the determining factor to position this work within geovisualisation. Whenever users process geographic information, they have to invest a certain capacity of their attentional resources to perform a task, regardless of user categories, their intention of map use and degree of interaction. Such a capacity can be regarded as a multidimensional construct representing the load imposed by tasks on the cognitive system (Paas & van Merriënboer 1994). Figure 6 depicts the relation between relevant parameters influencing the efficiency of visual information processing.

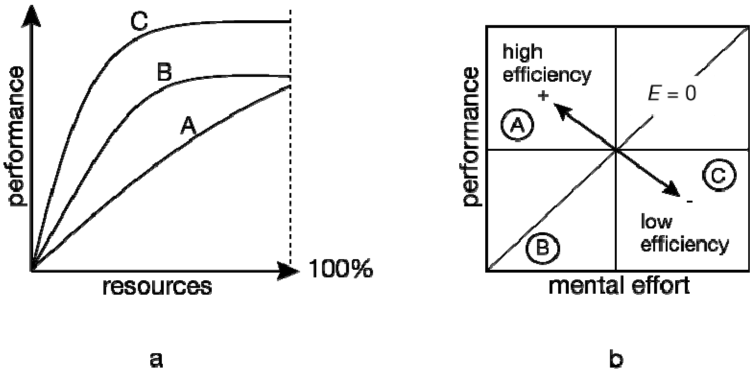


Figure 6. a) The performance-resource function (adapted from Norman & Bobrow (1975).
b) Instructional efficiency (modified from Paas et al. 2003).

Norman and Bobrow's (1975) performance-resource function in Figure 6a illustrates the performance as a function of resources required to accomplish a specific resource-limited task. The performance of a task varies, depending on the increase or decrease of deployed resources. The task complexity decreases from task A to C. Task B and C are data-limited, i.e. at a certain stage the supplemental employment of available resources does not lead to an improvement of performance. Task B represents task A after successful learning. The maximum performance is achieved by employing approximately 60% of available resources. Figure 6b shows the perspective from Paas et al. (2003) on the mental efficiency of instructional conditions. They consider the combination of low mental effort and strong task performance as highly efficient (A) and high mental effort related to low performance as less efficient (C). The position of B represents the neutral efficiency condition. The instructional condition efficiency score (*E*) is equated with zero, when mental effort and performance are in balance.

Based on these models, Figure 7 depicts a third axis of information complexity as a determinant dimension relating basic parameters involved in the efficiency of visual geographic information processing. Note that information complexity can be determined either by complex visualisations (e.g. information rich geovisualisations) or complex visual scenes (e.g. stimulus-rich environments), or by the combination of these. The focus is rather on the detection of relevant information embedded in a high density of sensory input than on decoding specific information from symbols.

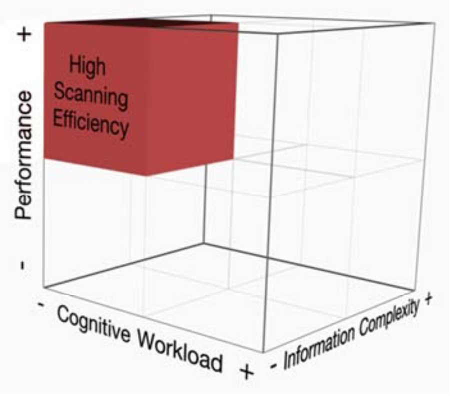


Figure 7. Visual scanning efficiency.

A geovisualisation can effectively visualise the location of information relevance classes by adapting the design methodology to the user's capability of visual scanning. This does not necessarily implicate that underlying semantics of these relevance classes can be easily decoded. In other words, someone is probably able to promptly locate the most important information, to decode its degree of relevance (in relation to less or more relevant information), and to relate this information to spatial dimensions. However, if symbols are not appropriate to successfully encode information significance, users have to employ more mental efforts, thus, the efficiency of visual geographic information processing will decrease.

The proposed axis of information complexity originates from measuring differences in visual search tasks. If the slope of a RT (reaction time required to affirm or negate the presence of an item) multiplicated with the set size function (number of items in the display) is near zero, the efficiency of the task can be labeled as high and vice versa. With respect to geovisualisation design, the basic goal is to keep the reaction time (time needed to visually detect the most relevant information) as short as possible and to reduce the amount of information to the minimum without neglecting geographic information that is needed to accomplish specific tasks. The parameter of set size is borrowed from cognitive testings in visual search tasks where items can be easily added or deleted from simple slides. Unquestionably, this approach is not transferable to the more complex content of geovisualisations. In other words, if a test person is asked to visually scan (search) for one red, big or tilted 'X' that is embedded in multiple black, small or untilted 'O's', it becomes obvious that the quantity of 'O's' as distracting stimuli does not significantly affect visual scanning efficiency. Hence, in visual scanning experiments, a test person's visual attention can be guided toward a target stimulus among distracting stimuli within a limited set of major features.

Due to the diversity of representing geographic information, users rather visually scan for various conjunctions of graphical variables embedded in diverse visual backgrounds. Although geovisualisations might consist of graphical variables that are appropriate to attract visual attention, users face an increasing difficulty that can lead to the 'needle in a haystack' phenomenon. In contrast to laboratory visual scan tasks, this difficulty is characterised by an augmented information complexity and an increased deployment of top-down processing like relating relevant geographic information to spatial dimensions. In other words, a user might quickly visually detect a favoured cinema but to see the movie one has to relate the cinema's location to the spatial context information. In this work, information complexity is not objectively calculated like face, vertex and edge complexity measures. It is rather referred to as visual complexity that in turn can be regarded as the proportion of visually salient and visually alleviated geographic information.

This work concentrates on adapting the design of geovisualisation to the human ability of visual attention. Visual attention serves as an effective filter mechanism protecting users from being overwhelmed by complex visual information. By balancing important and unimportant sensory input, and directing the gazes rapidly towards objects of interest (Nobre et al. 2000), this skill of shifting visual attention to particular regions or locations in visual environments is often referred to as 'visual scanning' (Reicher et al. 1976), 'visual search' (Treisman & Gelade 1980, 'selective looking' (Atkinson 1996), or 'visual exploration' (Niemeier et al. 2002).

To avoid the risk of automatically relating the cognition-oriented term 'visual exploration' to the function-based map-cubes corner of geographic 'information exploration', the ability of detecting and analysing relevant visual information is here referred to as 'visual scanning'. Visual scanning describes current sequences of gaze shifts during visual information processing and involves shifting of attention (accomplished by gaze shifts) as well as information processing (only during gaze fixations). This cognitive skill occurs whenever humans process visual information. Therefore, visual scanning is not solely assigned to information exploration as a main goal of map use.

Figure 8 illustrates the position of the proposed model of efficient visual scanning within MacEachrens map use cube. The map-cube's volume represents diverse levels of attentional capacities that users have to employ to process different representations of geographic information. Both, communication-oriented maps and explorative maps that represent the lower left and right corner of the map use cube can afford users to employ their visual scanning ability to a high degree (indicated by the shadily distribution).

Besides geographic data exploration, users apply their skill of visual scanning to a high degree even if they need the presentation of knowns for decision making in geographic tasks. For instance, mobile devices may communicate known geographic information on small displays with a low degree of human-computer interaction. Although explorative and mobile systems represent two different kinds of cartographic visualisation, they require similar cognitive scope. Explorative and mobile users have to cope with the complex visual environment. While visual attention of mobile users is strongly affected by distractive visual, auditory and tactile stimuli (Reichenbacher & Swienty 2006), gazes of exploring users can be deviated by numbers of displayed irrelevant geospatial objects (Swienty et al. 2006).

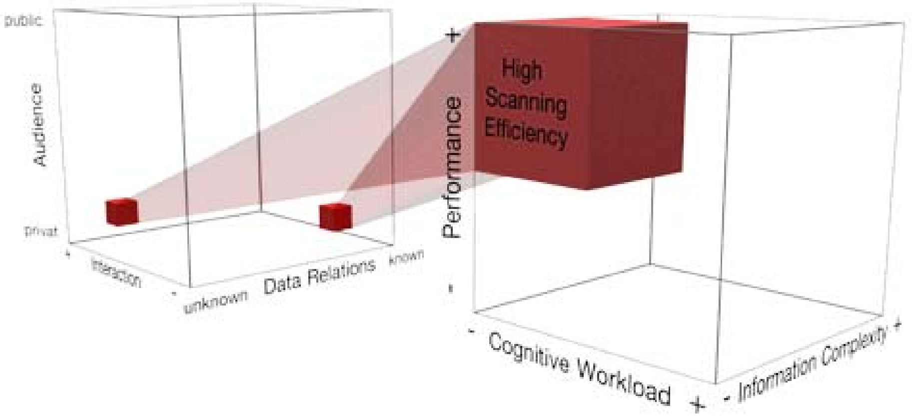


Figure 8. Visual scanning efficiency and the map-use cube.

Although the characteristics of explorative map use differ from those of communication-oriented map use, the way in which users visually process these different purpose-driven visualisations is characterised by the same cognitive process. In both cases, users have to visually process more or less complex geographic information by employing more or less attentional resources. Success in both cases of map use depends on the cognitive skill of selective visual attention, i.e. to visually pick up relevant information and to simultaneously omit irrelevant visual sensory input.

In this work, differences between the map-cube corner of geographic information exploration and communication is predominantly characterised by the orthogonal axis of map-use intention. Exploring users differ from non-exploring users by their intention to reveal so far unknown geographic information through explorative systems. However, by assigning visual exploration as a special context of use to data exploration, it can be misleadingly suggested that differences between *exploring unknowns* and *presenting knowns* are manifested in the absence or presence of visual exploration as a particular form of visual information processing. In other words, the biological skill of visual scanning (or visual exploration) cannot solely be related to a computer's capability of algorithmic data exploration.

To keep the cognitive load as low as possible by means of effective geographic information design is a basic challenge of this work. Users visually scan geovisualisations regardless of their intention such as data exploration, analysis, synthesis as well as presentation; the four goals of map-use identified by MacEachren and Kraak (1997).

2.8 Relevance of geographic information

Relevance of information is a fundamental concept in information processing and represents the criterion for filtering and reducing the amount of visualised information. The relevance of information always expresses a relation to another entity. According to Sperber and Wilson (1995), relevance can be divided into objective and subjective relevance. Objective relevance is applied in information retrieval (IR) and reflects the algorithmic determination of relevant information (Saracevic 1996) with regard to a user's query to a system. As van Rijsbergen (1979,6) stated, the objective of information retrieval is to " *… retrieve all the relevant documents (and) at the same retrieving as few of the non-relevant documents as possible*".

The traditional information retrieval focuses on algorithmic and objective relevance. In GI science, this objectivity is inadequate, because the relation to space is lacking. Therefore, an extension of the information retrieval with a spatial component evolved and introduced the field of geographic information retrieval (GIR). It is proposed to integrate temporal and semantic relevance by visualising these dimensions of geographic information, a notion that veers toward the field of geographic relevance (Raper et al. 2002). Several methods for determining geographic relevance that concentrated on spatial and temporal proximity were proposed by Reichenbacher (2004) and by Mountain and MacFarlane (2007). Others focused on the integration of individual relevance factors into a combined relevance value (Jones et al. 2001, Hobona et al. 2006, Reichenbacher 2007) as well as speed-ahead prediction surface and viewshed analysis (Mountain & MacFarlane 2007).

Geographic relevance of information can be measured at different levels. The binary relevance (relevant or irrelevant) is assessed at a nominal measurement level. Classes, degrees or grades of relevance are measured at an ordinal measurement level or are generalised from quantitative values of relevance measured at a numerical or quantitative measurement level. The importance for a model of information needs that is based on geographic relevance is emphasized by Raper et al. (2002). They name the sense-making methodology as a potential framework for this purpose.

"*To see an object in space means to see it in context*" (Arnheim 1997,54). Within the scope of geographic relevance, the underlying simplicity of this citation quickly led to highly complex research questions concerning the filtering and design of relevant objects because GI scientists dealt with a so far unidentified number of contextual parameters. Figure 9 illustrates a typical example of geographic relevance that was presented by Reichenbacher (2005) within his conceptual framework of mobile cartography (Reichenbacher 2004).

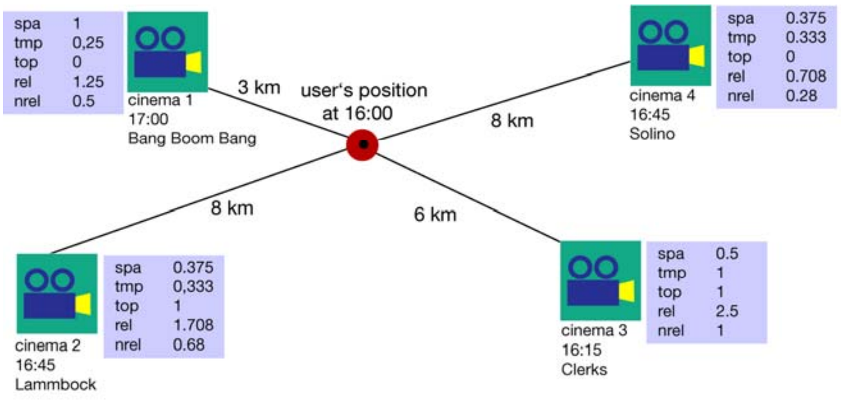


Figure 9. Relevance of geographic objects (modified from Reichenbacher 2005).

The assessment of relevance of geospatial objects is determined by the user's request. This assessment is a dynamic process involving a lot of overlapping relevance types, such as spatial relevance (spa), temporal relevance (tmp) or topical relevance (top). Accordingly, the overall relevance is a combination of spatial, temporal and topical relevance (rel) that allows calculating the most relevant information (nrel). Such an assessment combining different relevance types can be achieved with a fuzzy set approach implementing spatial, temporal and semantic distance functions.

For instance, a mobile user who is looking for a cinema (topical relevance) does not necessarily choose the nearest cinema. The user might probably choose a late beginning of the movie (temporal relevance), because she has first a rendez-vous in a restaurant (activity relevance) that has to be close to the underground station (spatial relevance). Hence, it is not necessarily the closest cinema that is the most relevant, but rather the cinema that combines all relevance types. Although cinema 3 is not the nearest (spatial relevance) to the user's position, it is the most relevant. The determining factors in this example are the relevance degrees of temporal relevance (beginning of the movie) and topical relevance (preferred movie). Note that, in comparison to geographic information retrieval mobile cartography depends on further dimensions (e.g. location, time, user, activity, information, and system) that determine the overall user's contextual information needs. Reichenbacher (2005,3) pointed out, that " *... in a mobile usage context the presented geographic information must be relevant to the context of use, i.e. to the current location at the current time, to the user, to the activity or task at hand, to the question/topic or request, and to the infrastructure available and co-located geospatial objects*".

The main goal of this work is to design geovisualisations that represent the largest relevance to the user by focusing on the subjective relevance as opposed to objective relevance. The notion of objective relevance indicates that it is inapplicable in communication and pragmatics where the relevance of geographic information is subjectively determined by the user. Following Sperber and Wilson (1995), factors like situation, topic, motivation, and cognition affect the relevance of geographic information. In this work, the influence of cognition is of prime importance. The attention-guiding design of geovisualisation as a mediating artefact between the computational filtered information and the users' skill of visual scanning is based on the theory of cognitive relevance (Sperber and Wilson 1995). The cognitive relevance serves as an assessment criterion for the processing of information that is influenced by interfering factors, e.g. by non-filtered irrelevant information or distractive stimuli. Figure 10 illustrates the theory of cognitive relevance in conjunction with the basic information processing pathways.

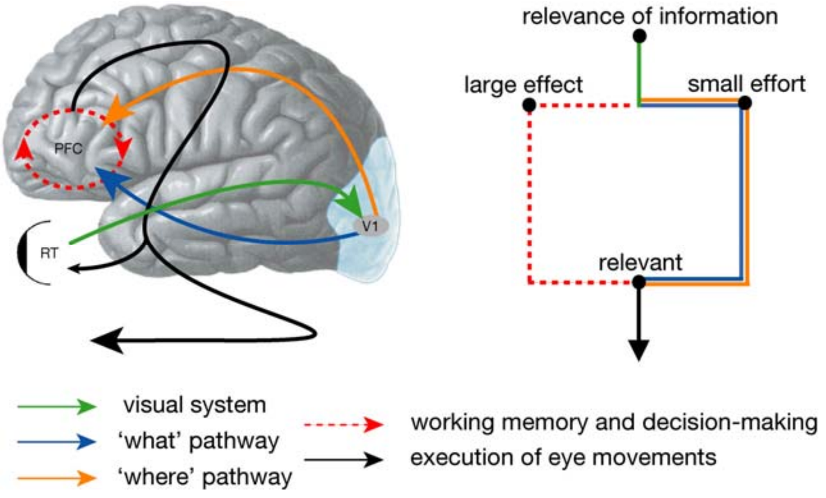


Figure 10. Visual information processing and cognitive relevance (based on Saracevic 1996, Sperber & Wilson 1995).

Only geographic information that unifies small effort and large effect is considered as relevant and is further processed by the user (Swienty et al. 2006, Reichenbacher & Swienty 2007). Hence, only stimuli that allow users a fast localisation (via the 'where' path) and an effective decoding (via the 'what' path) are visually detected with small effort. At the same time, these stimuli need to provoke large effect (e.g. decision-making) in brain areas involved in the working memory system. The combination of small effort and high effect in visual geographic information processing identifies which geographic information is regarded as relevant enough to be further processed by brain areas involved in motor-output and motor-control, i.e. for instance activating eye muscles to direct gazes to relevant information or triggering finger muscles to move the mouse towards information of interest. For the visual representation of spatial relevance, relevance classes that can be encoded with ordinal graphical variables are of particular interest in this work, where the ranking order of geographic information contains merely three classes (highly relevant, relevant, and less relevant).

2.9 Acceptability of geovisualisation

According to Nielsen (1993) (Figure 11), the acceptability of a system results from the combination of practical and social acceptability. A further category is the usefulness of a system as "*... the issue of whether the system can be used to achieve some desired goal* " (Nielsen 1993,24).

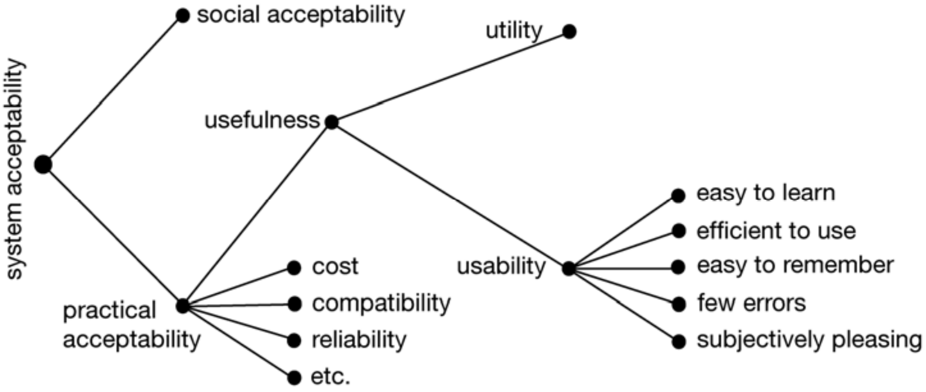


Figure 11. The attributes of system acceptability (redrawn from Nielsen 1993,25).

A basic challenge of this work is to optimise the usefulness of geographic information systems by considering the relevance-based filtering of geographic information as an element of utility and the cognitively adequate design of geovisualisations as an element of usability (Figure 12).

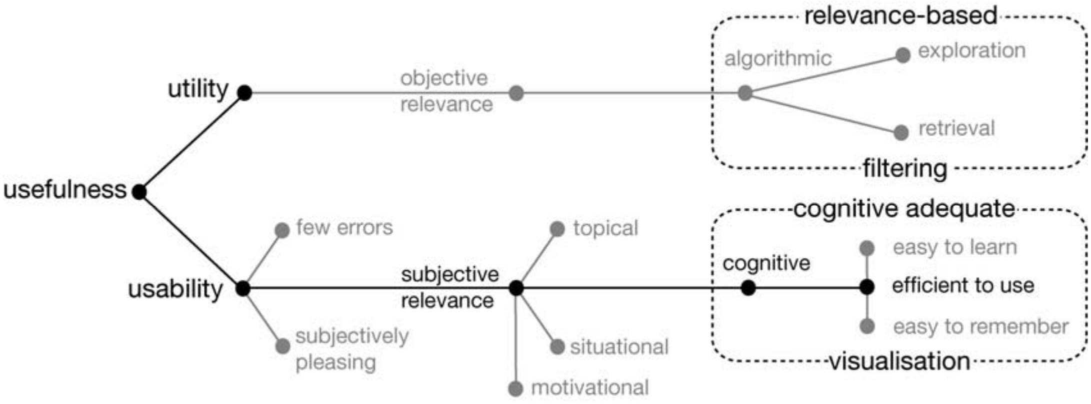


Figure 12. Relevance-based filtering, cognitive adequate visualisation, and system acceptability (modified from Nielsen 1993,25).

Both categories utility and usability have a strong influence on the usefulness of systems and are underdeveloped in geographic information systems. However, they are not sufficiently investigated in geovisualisation systems, taking mobile maps and exploratory maps that are located in the opposite corners of the aforementioned map use cube.

On one hand, in mobile cartography, a lack of relevance-based filtering might interfere with the context-awareness of a mobile user and can lead to a visualisation of irrelevant geographic information. The design of map services for small displays of mobile devices relies on the relevance-based filtering and cognitively adequate visualisation to antagonise an attentional competition between displayed information (information space) and distractive sensory input in the visual environment (geographic space) (Reichenbacher & Swienty 2006). On the other hand, in exploratory systems, the visualisation of non-filtered spatio-temporal objects might cause overcrowded displays with highly detailed information as well as complex relationships. Geovisualisations of exploratory systems often consist of a high information complexity in multiple dimensions that are visualised in distributed windows to operate brushing and linking techniques. In comparison to mobile devices, the design of exploratory visualisations relies on the relevance-based filtering and cognitively adequate visualisation to avoid distractive effects from displayed information rather than from influencing environmental stimuli.

In this work the relevance-based filtering will be taken for granted. Therefore, the main emphasis is on the cognitive adequate visualisation in order to support users in their subjective visual processing of geographic information. Within this category of subjective relevance, the attention-guiding design methodology aims at enhancing a user‘s visual scanning efficiency. The subcategories ’easy to learn’ and ’easy to remember’ are considered as indispensable consequences of a user’s high visual scanning efficiency. Both components are depicted in grey because they are beyond the scope of this work.

One basic principle of raising user‘s visual scanning efficiency is to visualise the relevance feedback. The relevance values of geographic objects are embodied and visualised as attributes to support users in keeping their visual focus on the task with minimal distraction in operating the display. It is suggested, that the combination of a cognitively adequate visualisation and the separation of irrelevant from relevant information increases the overall usefulness and hence the acceptability of geovisualisation systems.

Summary. This chapter presents the interdisciplinary theoretical background and the state of the art of external geographic information visualisation. GI science, cartography, and geovisualisation are the research areas that are intimately connected with the cognitive aspects of geographic information processing. Due to fuzzy overlaps of these aspects, the opposed psychological perspectives of the behaviouristic and cognitive perspective are discussed to point out the cognitive approach of this thesis. It is argued that the technology-driven development needs to be accompanied by profound empirical research on user’s cognitive skills. An approach to user-centred research is proposed by implementing the parameter of visual scanning efficiency into the concept of cartographic communication and visualisation. By following the recommendations of prominent research agendas it is illustrated that this thesis tends to fulfil cognitive and usability issues of geovisualisation by considering the relevance-based filtering as a utility criterion and the cognitively-adequate geovisualisation as a utility criterion within the the framework of a systems acceptability.

3. Internal visual information processing

While the proceeding chapter is dedicated to the external geovisualisation this chapter deals with the task of designing cognitively adequate geovisualisations that allow users an efficient visual processing of the depicted geographic information. The term ‘cognitively adequate’ implicates that the design of geovisualisations needs to be adapted to the human ability of internal visual information processing. ‘Internal’ as the cerebral visual processing of geographic information is opposed to ‘external’ as the visual representation of geographic information. In other words, ‘internal’ means ‘inside the brain’ whereas ‘external’ is related to ‘outside the brain’. The cognitive activity of processing geovisualisations results from complex functional interactions between and within specific brain areas. It is therefore a fundamental challenge to understand the underlying functions of visual brain areas by retracing the sophisticated information processing pathways in the brain (Swienty 2005). By answering how and why a visual representation works the cognitive approach tries to formulate appropriate design principles and to develop a design methodology. It benefits from a high level of analytic strength that provides an insight into the functional segregation of processing, storage and retrieval of represented geographic information.

The following sections give an overview of involved relations between main visual information processing units especially involved in visual scanning of geovisualisations.

3.1 Visual attention in cognitive psychology

Humans’ everyday life is largely driven by an individual dynamic behaviour concerned with visual information processing. Due to the agility of psychological science, a rich terminological vocabulary is used to study this behaviour and is available for the study of this behaviour, although there exists inevitably some inconsistency and inadequacy in a number of terms when they are used in other disciplines (Newcombe & Ratcliffe 1989, Lishman 1997). This work does not intend for transferring psychological terms verbatim to GI science. It rather derives and borrows the relevant terms, conclusions and findings from psychological science so as to lay down a theoretical foundation for attention-guiding geovisualisation. Visual attention is intimately involved in visual information processing. Figure 13 illustrates the relations between relevant psychological terminologies derived from the basic concepts of Lezak’s ‘Neuropsychological Assessment’ (Lezak 2004).

Visual information processing is the functional system of behaviour that ranges from cognition to selective visual attention. Three sets of functions characterise the dimensions of behaviour. While ‘emotionality’ deals with feelings and motivation, and ‘executive functions’ represent the expression of behaviour, ‘cognition’ is the functional system that handles information. These systems prove to be when studying brain lesions. Regardless of the location of brain lesions, all dimensions of behaviour are affected by an impairment of one visual brain area. ‘Cognitive functions’ reflect cognitive abilities that are individual functional properties and that can not be directly observed but inferred from behaviour (Sivan & Benton 1999, in Lezak 2004). The cognitive functions fall into four categories.

The main components of ‘receptive functions’ are sensory reception (processes that trigger registration for analysis, encoding, and integrative activities) and perceptual functions (activities such as awareness, recognition, discrimination, patterning, and orientation). Thus, receptive functions are involved in the processes of sensory stimulation and integration of sensory impressions into memory. While ‘memory’ refers to storage and retrieval of information, ‘thinking’ deals with the mental organisation and reorganisation of information. The considered ‘expressive functions’ are the means through which information is communicated or acted upon. Observable behaviour like speaking, manipulating, or any physical gesture provides information about a distinct specific behaviour.

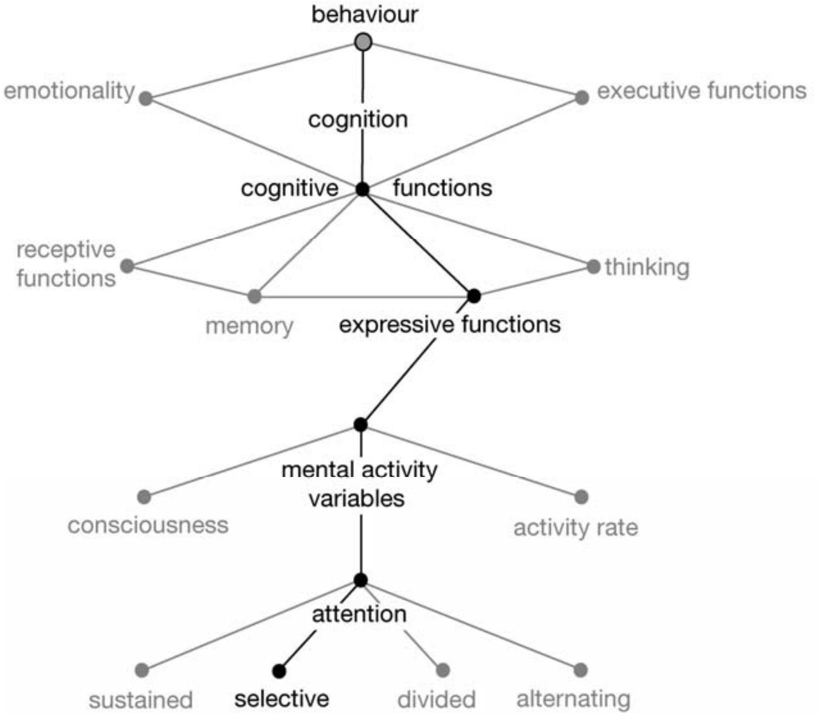


Figure 13. A brief survey of relations between relevant psychological terminologies (based on Lezak 2004).

Being infered from the expressive functions, 'mental activity variables' represent the behaviour characteristics that are intimately involved in cognitive operations. Three categories indicate the efficiency of mental processes. (1) 'Consciousness' is the level at which someone is receptive to a stimulus and (2) 'Activity rate' is the speed at which mental activities can be performed and motor responses occur. (3) 'Attention' corresponds to diverse capacities or processes that are related aspects of how the organism becomes receptive to stimuli and how it may begin to process incoming or attend to excitation.

One important characteristic of attention is its capacity limitation (Ullman 2000) that can vary individually under different conditions. To handle a large amount of sensory input humans make use of four interrelated mechanisms with distinct functional characteristics. (1) 'Sustained attention' also known as vigilance ensures that an attentional activity can be maintained over a period of time. (2) 'Divided attention' is the ability to respond to more than one task in a time or to multiple operations within a task. (3) 'Alternating attention' allows for shifts in focus and tasks. Finally, (4) 'Selective attention' also known as focused attention is the ability to highlight important stimuli while suppressing competing distractions. The vast number of environmental sensory inputs exceeds the processing capacity of the human brain. Selective attention serves as an appropriate filter mechanism, thus protects humans from being overwhelmed by complex information.

As discussed in section 2.5, attention is guided by both, bottom-up and top-down factors. The interaction of these factors controls where, how and to what humans pay attention to initiate the cognitive control, i.e. the organised and wilful behaviour to execute further operations. This interaction is involved in attention shifts that are intimately connected with eye movements in overt attention, i.e. humans activate corresponding eye muscles to control the gaze direction. Early in life, humans acquire the capability of covert attention by moving attention to the opposite direction of eye movements (e.g. Posner et al. 1982). However, it is concluded that freely moving eyes do not comprise covert attentional scanning and that tasks in visual search are solved more efficiently when humans employ overt visual attention (e.g. Findlay & Gilchrist 1997, Maioli et al. 2001). These processes control selective visual attention which is the ability to extract and recognise salient information in complex visual environments with high efficiency. The complexity of information is estimated to be in the range of 10^8 - 10^9 bits per second (e.g. Deco & Zihl 2001, Deco et al. 2002). Selective visual attention monitors executive functions (e.g. judging and decision making) by minimising responses to distractive information and maximising responses to relevant information (Shipp 2004).

Following Mirsky (1989), attention is embedded in the broad area of information processing. Similarly Marrocco and Davidson (2000) regard attention as a major and integral part of mnemonic processes. Thus, attention allows users to select appropriate information, facilitates the retrieval of remembered locations, and minimises responses to incorrect features by focusing on particular features. These mental functions enable humans to coordinate their behaviour with respect to environmental circumstances. In this thesis the term ‘attention’ is explicitly related to the functional system that processes visual information (Lezak et al. 2004). Selective visual attention is treated as a basic and decisive factor concerned with the detection of salient parts in a scene.

The theoretical background of the cognitive approach is characterised by putting emphasis on the multifaceted internal processes of visual information processing. There is a complex and rapid activity of visual neurons between the entering of a flashed stimulus into the retina (20-40 ms) and the execution of goal-oriented movements (180-260 ms) (Thorpe & Fabre-Thorpe 2001). Although the organisation of visual attention, its functional role in visual information processing, and corresponding mechanisms are far from being entirely understood, knowledge has been accumulated through the intensive research in the field of cognitive psychology such as single cell recording, measuring of Event-Related brain Potentials (ERPs), neuropsychological studies of brain lesions, as well as modern image technologies like functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET). Cognitive findings of visual attention mechanisms that result from testing non-human and human primates can be considered as valid for most primates. A detailed description of comparing non-human with human neuropsychological findings and its possibilities or limits can be found in Van Essen (2003) and Orban et al. (2004).

3.2 Centre-surround mechanism and fields of visual information processing

During the interaction with geovisualisations, users make use of a serial processing strategy to manage the plethora of sensory input. In visual information processing users therefore filter out irrelevant information and let selected information pass through with the goal to attain visual awareness (Crick & Koch 1990).

In order to respond to the location of a depicted stimulus and fixate the gaze on relevant information humans implement what Kosslyn (1994) calls a ‘stimulus-based attention-shifting sub-system’. This secondary component in his architecture of ‘visual mental imagery’ is responsible for the visual detection of focal information that is silhouetted against the surrounded context information because of its salient stimulus. The visual dissociation of objects from the background is regarded as the fundamental perceptual act of identifying objects (Ware 2004,196).

Amongst the large number of stimuli to be processed in geovisualisations, some are reflexively extracted from the visual environment in a mode of ‘bottom-up guidance’. Relevant geographic information is extracted due to local differences from surrounding. In contrast to the mode of ‘top-down guidance’, where observers employ prior knowledge to extract relevant information, in bottom-up guidance people don’t need any information about the target in advance (Wolfe 2005). This filtering capability is anatomically initiated by the retina and leads to the development of centre-surround receptive fields which allow users to focus on visual stimuli.

The retina depicts a thin layer of cells at the back of the eyeball that consists of photoreceptors capturing light rays and converting them into electrical impulses. About 120 million rod cells that are used to see at low levels of light are found in the periphery of the retina, being sensitive to light and dark changes. Approximately 7 million cone cells are required to distinguish colour. They are responsible to see fine details and are located in the fovea, the centre of the retina. In the peripheral part, the concentration of cones decreases in relation to the eccentricity. Because of this arrangement, high resolution visual information is available only within a reduced part of the visual field (Sekuler & Blake 1990). This retinal signal processing is involved in the centre-surround relationship of geographic information that is determined by the receptive field of visual neurons. The receptive field is the region of visual space in which a stimulus will elicit a response from a neuron (Kuffler 1952). This stimulus is then processed by appropriate pathways, whereby the size of receptive fields increases in higher visual brain areas. This mechanism allows users the visual detection of local information that is silhouetted against the surrounding context based on its salience.

In visual information processing, humans scan their environment like a moving spotlight until the information of interest located in the visual field is kept by the field of view and falls on the most sensitive region of the retina (fovea) (e.g. Treisman 1982, Crick 1984). However, neurons in visual brain areas do not respond to every location in the visual field. The field of view is processed by employing head and body movements (Arditi and Zihl 2000) and represents the largest region of simultaneous (parallel) visual detection. The total extent of the field of view covers about 280 degrees of the visual angle.

In contrast, the visual field "*... is the view seen by the two eyes without movement of the head*" (Mason & Kandel 1991,421). The visual field, also referred to as macular region (Henderson 2003), is smaller than the field of view and has a total binocular extent about 180 degrees. Because of the inhomogeneous distribution of spatial resolution and visual acuity in the visual field, its extent for processing visual details (e.g. form) is much smaller, and covers merely 9 degrees. Hence, the visual field corresponds to the extent of visual space over which visual processing is possible with the gaze held in a fixed position, typically in straight ahead direction. Accordingly, receptive fields allow users to focus on salient locations or regions in geovisualisations. To transmit visual information to visual brain areas, retinal (ganglion) cells encode the information from the receptive field which assesses local temporal contrast by combining excitatory and inhibitory signals over both, a narrow region 'the centre' and a wider region the antagonistic 'surround' in the visual field.

Due to the empirical significance of the visual field in evaluations with the eye-movement recording method and the more natural character of the field of view it is necessary to have a closer analysis of their basic characters. Users simultaneously make use of three major options to position the centre of the visual field (Zihl & von Cramon 1986) (Figure 14):

Case 1. Head fixation with eye movements.
Case 2. Head fixation without eye movements.
Case 3. Body fixation with head and eye movements.

In their perimetric study, Zihl and von Cramon (1986) measured the capability of older and younger subjects to detect light, colour, form and flickering stimuli to determine the area of the visual field under the above-mentioned circumstances. They found out that when detecting light, colour and flickering, the extension of the visual field is much broader than for shapes. They equated the broadest limit of light detection with the extension of case 2 and stated that the extent of the area of the visual field in case 1 is bounded by the area of moving eyes. It is therefore smaller than in case 2. Furthermore, they discovered different extensions of the visual field when detecting colours and forms. The colour red has a more limited visual field than green and blue. Moreover, different forms were visualised in the display to measure the visual acuity of subjects. At the horizontal extension of nearly 8°, subjects barely perceived shapes with 25% visual acuity and the visual acuity of the shapes drops further to 6% at the extension of 30°. However, the extension of the visual field for colour is broader than for forms. Finally, by detecting flickering stimuli with a frequency of nearly 22 Hz at a horizontal extension of 60° (40 Hz at 0°), young and old subjects proved to be highly sensitive for flickering stimuli within a broad extension of the visual field.

Due to the fact that humans often additionally employ body movements to perceive relevant objects, the visual field in case 3 is much larger than in case 1 and 2. Its angle of horizontal extension (115° to each side) results from the sum of the angle of horizontal extension of case 1 (45°) and case 2 (70°).

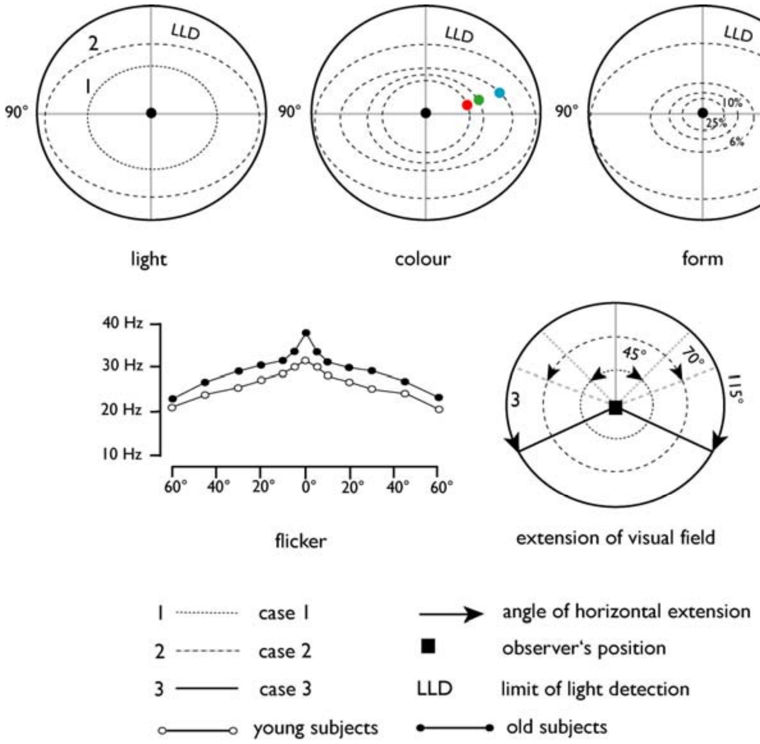


Figure 14. The visual field (modified from Zihl & von Cramon 1986).

The dimensions of the visual field (head fixed) and the field of view (head not fixed) are of particular interest insofar as they represent potential spheres of distractive influence that is initialised by irrelevant visual sensory input. Figure 15 illustrates the dimensions of the visual field of users when processing geographic information in different typical geovisualisations at a distance of 40 cm.

a
printed map
80 x 100 cm

b
map displayed on a desktop
27 x 34 cm

c
map displayed on a PDA
6 x 8 cm

© Landesamt für Vermessung und Geoinformation Bayern

Figure 15. Dimensions of the visual field when processing geovisualisations.

Figure 15a shows the dimension of the visual field of users when processing a typical printed map. It is obvious that the map size exceeds the dimension of the visual field. In Figure 15b the visual field is bigger than the desktop size and users have to visually scan the map to a higher degree by employing eye and head movements. Accordingly, the extension of the visual field when processing printed maps is much smaller than the extension of the visual field during processing desktop maps because eye movements delimit the dimension of the visual field. Processing sizable maps or wall-size screens at the same distance as dealing with normal desktop displays does not necessarily ease visual geographic information processing. Due to the decreased visual field, users have to intensify their visual scanning activity. Wall-size displays are potential means for visualising geographic information to a group of users who are positioned at an appropriate distance. The dimensions of the visual field of mobile users (Figure 15c) will be later discussed in detail.

Visual information processing is in a first step scene-based and not detail-based. Users process geographic information in a fast and global context-dependent manner before slowing down the scan path to a local mode of information processing. This mechanism allows users to maintain a crude representation of geographic context information in the visual background for visual spatial orientation that guides scan paths during detailed local information processing (Torralba et al. 2006). For both global and local processing of geographic information, the user need to employ a visual scan path that is adapted to the global and local design of the visualisation as well as to the his intentions.

Figure 16 demonstrates the dimension of the focus of attention (foA) and the surrounded field of attention (FoA) during a single gaze fixation when processing geographic information on a desktop display. According to the above mentioned extensions and degrees of visual acuity, the geovisualisation is configured with corresponding degrees of a soft-focus tool to show what and how users see when focusing the centre or shifting their gazes to the corner of a display. The field of attention is the region of vision where attention is particularly focused on to improve visual information processing. While it can vary in its extent, the field of attention is mainly restricted to the macula (a small region near the centre of the retina). The centre of the field of attention is the fovea, a spot in the middle of the macula which represents the focus of attention.

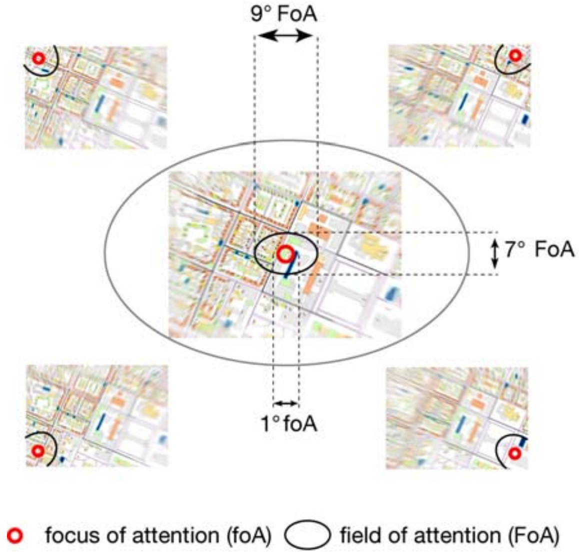


Figure 16. The focus and the field of visual attention.

It coincides with a given position of gaze fixation, whereby spatial resolution and visual scanning efficiency is highest around this position and lower for the surrounding. Only in the fovea, the most sensitive region of about 1° in the field of attention, visual acuity and spatial contrast sensitivity amount to 100%. Both visual functions then decrease rapidly towards the periphery.

The field of attention is modulated in a bottom-up (e.g. by colour) and top-down guidance (e.g. by intention). This interplay allows users to adapt the field of optimal visual information processing to the task on demand like a window with flexible space and time boundaries (Hochstein & Ahissar 2002). In comparison to printed maps or desktop displays, users have to process geographic information within a smaller space of high visual acuity when dealing with smaller displays like those of a Personal Digital Assistant (PDA) or a mobile phone.

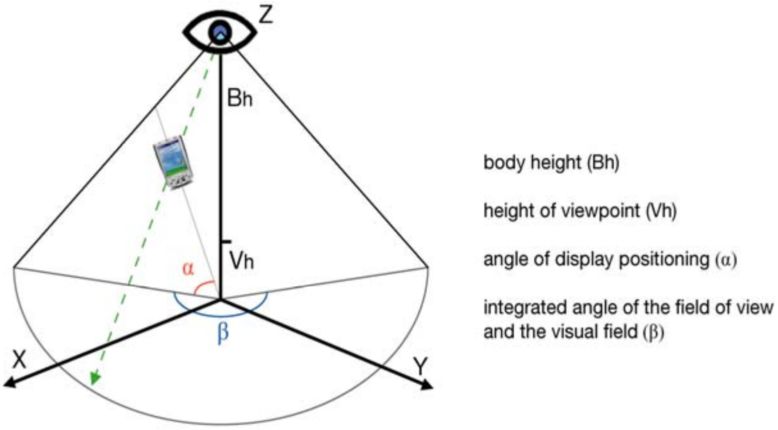


Figure 17. Dimensions of the egocentric space of a mobile user (adapted from Reichenbacher & Swienty, 2006a,b).

Figure 17 illustrates the egocentric space of mobile users when processing mobile devices. As a result of the decreased information space (small displays), the dimension of the geographic space (physical visual environment) increases. Therefore, various visual distractors (e.g. walking people, driving cars, etc.) can affect a user's scanning strategy by deviating gazes from the display. Additionally, mobile users can be influenced by auditory (e.g. talks, sirens, etc.) and tactile sensory input (e.g. rain, wind, etc.). Mobile users individually employ eye-, head-, and body movements, and have to visually process the spatial depth of their visual environment. Thereby, the space of distractive sensory input is enlarged to the egocentric space. Further influencing parameters are body height (Bh), height of viewpoint (Vh), angle of the display relative to the horizontal plane (α), and the integrated angle of the field of view (90°) plus the visual field (140°) (β). For example, the egocentric space of a keeling truck driver (Bh =1,80m, Vh =1,50m, α=75°, β=230°) is larger than a pedestrian's egocentric space (Bh =1,80m, Vh =0m, α=45°, β=230°).

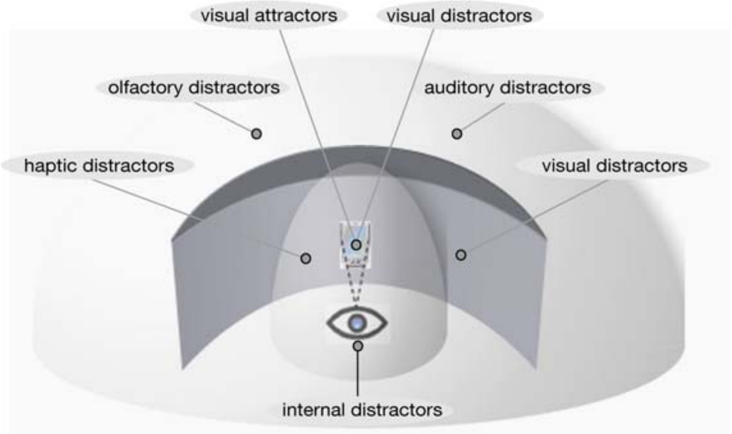


Figure 18. Internal and external distractors in the egocentric space.

Accordingly, the egocentric space contains of individual distractive environments that influences users in visual geographic information processing (Figure 18). The environment of visual attractors (geovisualisation) is in competition with the environments of haptic (e.g. rain and wind), olfactory (odours), auditory (e.g. car noise and conversations), and visual distractors (e.g. walking pedestrians and traffic signs). These external distractive environments are more or less extended in dependence of the usage context. While explorative users in offices predominantly have to visually detect relevant information that is embedded in visual distractors on the display, attentional capacities of mobile users in urban areas can be exceeded in the environments of distractive influences. Additionally, users can be influenced by internal distractors like stress. For instance, fire men, soldiers, and air traffic controllers are often involved in time-critical decision-making tasks. For this reason, in mobile environments it is more difficult to guide the user's attention to information on the display and to keep gazes on the relevant geographic information than in other usage contexts.

3.3 Visual scanning: saccades and fixations

The users' skill of attending to regions or locations of interest in geovisualisations involves the visual detection and analysis of salient stimuli as well as intentionally searching for relevant information. For reasons that have been discussed in section 2.7, this cognitive capability is termed as 'visual scanning'. It is characterised by two essential actions: shifting of attention (i.e. of gaze) as well as visual information processing (fixation). The sequences of gaze shifts and fixations that occur whenever users visually process geographic information form the scan path. Users visually scan geovisualisations until the information of interest is processed by the focus of attention in detail. For visual scanning, users employ distinct types of eye movements to shift their focus of attention from one area or location to another. While pursuit eye movements shift in a slow conjunction, saccadic eye movements allow rapid transportation of the gazes to a particular location in space to place the focus of attention in depth relative to the user's viewpoint. Saccadic eye movements are probably the most favourable technique to rapidly shift the focus of attention to relevant geographic information. Figure 19 exemplifies the scan paths of a user that was recorded during an ongoing study with an eye-movement recording system at the eye-movement recording laboratory of the Department of Geography, University of Zürich.

Figure 19. Saccades and fixations form the visual scan paths.

The radius size of the circles indicates the length of time that fixations have been spent on geographic information. The red line provides information about the length and direction of saccades. Saccades occur three to four times per second and can reach velocities of about 500° per second. About 90% of saccadic eye movements are smaller than 15° when humans spontaneously scan everyday environments. Different types of saccades are involved in specific tasks of visual information processing that require particular cognitive demands. While voluntary saccades (to a location without a visual transient) and memory-guided saccades (to a cued location after delay) are top-down guided reflexive saccades are visually triggered by salient signals, thus mainly bottom-up controlled. However, they do not show the characteristics of a motor reflex because they can be modified or suppressed by top-down factors such as the user's expectation or current goals.

Figure 20 illustrates the durations of gaze fixations as a heat map. The yellow to red colours represent higher degrees of visual attention that was guided to the relevant geographic information. The lemon to green colours indicates lower degrees of visual attention guided to less relevant regions or locations of geographic information.

Saccades are interrupted by fixations, where the focus of attention remains on locations or in regions of interest for at least 200 ms. Users who scan geographic information process relevant information only during stable fixations at attended locations. Interestingly, a gaze fixation indicates the location of the focus of attention but a non-fixation does not necessarily signify the neglect of relevant information. While the eyes can fixate gazes at one particular location or cartographic symbol, users are able to focus their attention on an interesting stimulus outside the fixation area but within the field of attention. This phenomenon results from the interplay of overt (with eye movements) and covert (without eye movements) attention (Deco et al. 2002). However, while attention can shift without eye movements, users are not able to shift eye movements without a concomitant shift of attention.

Figure 20. The heat map illustrates the durations of gaze fixations.

3.4 Visual extraction of features

While MacEachren's (2001) definition of geovisualisation involves 'exploring data', 'generating hypotheses', 'developing solutions', and 'constructing knowledge', the goal of a recommendation in the research agenda on visual analytics involves to facilitate " *... the reasoning process* *to enable action*" (Chinchor et al. 2005,98). These terms approximately trace the neuroanatomical interrelations of detecting and analysing relevant information, i.e. the neuronal activity of visual neurons between interconnected visual brain areas when selectively processing visual information. Pathways and functions of involved visual brain areas play a dominant role in formulating appropriate design principles, developing the design methodology, and conducting the cognitive evaluation of attention-guiding geovisualisation.

Visual geographic information processing relies on complex interrelations between bottom-up and top-down driven information processing pathways. To adapt the design of attention-guiding geovisualisation to the modes of visual information processing, the cognitive approach surveys the connectivity between guidance of attention and fixation in geovisualisations, global and local visual information processing, and visual working memory. The human brain consists of many areas that are specialised in processing and storing various dimensions of visual information. Evidence for this functional fragmentation is the anatomical organisation and connectivity of the brain as well as the selectivity and specificity of neuronal activity of visual neurons regarding visual sensory input.

The cognitive approach is grounded on major correlates between visual brain areas that are responsible for visual monitoring and scanning capabilities of users. Both bottom-up and top-down factors are treated in equal shares to provide the basis of relating one process to the other and to understand interdependencies of these factors. In other words, graphical variables like colour or motion can be more or less effectively extracted from geovisualisations but this does not automatically indicate high visual scanning efficiency. The cognitive approach rather aims at stimulating specific visual brain areas or information processing pathways to release brain areas that are involved in the working memory system or decision-making process. One information processing pathway that is predominantly bottom-up guided is the retino-striate pathway (from the retina to the striate cortex, also known as primary visual cortex) often referred to as the visual system. Figure 21 illustrates the basic anatomic correlates along the retino-striate pathway that are involved in visual information processing.

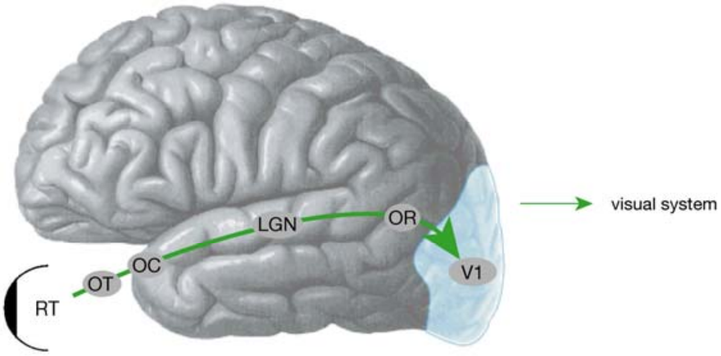


Figure 21. The retino-striate pathway. Abbreviations: retina (RT), optic tract (OT), optic chiasma (OC), lateral geniculate nucleus (LGN), optic radiation (OR), primary visual cortex (V1).

Geographic information that is located in a user's field of attention enters the eye in form of visible light and is inverted by the lens of the eye to project an image on the retina. The retina as the part of the visual system is concerned with the extraction of early visual features (e.g. colour, size, orientation, spatial frequency, direction of motion, binocular disparity) that users need for binding geographic information representation into a unitary concept (e.g. Treisman & Gelade 1980). Each part of this retinal surface is mapped in a clear point-to-point topography in the primary visual cortex (V1) along the entire visual system.

Electrical impulses fire then from the retina to the lateral geniculate nucleus (LGN) on the so called retino-geniculate pathway and cross at the optic chiasm (OC). Here, visual information is separated corresponding to the field of view. Information perceived in the left part of the field of view is conducted to the right hemisphere of the brain and the other way around. The optic tract (OT) is a continuation of the optic nerve and runs from the optic chiasm to the lateral geniculate nucleus.

The visual information processing via the lateral geniculate nucleus runs in a parallel way that is reflected in two major classes of retinal cells - the small parvocellular cells and large magnocellular cells. As shown in Figure 22, the lateral geniculate nucleus consists of six layers corresponding to the similarly-named retinal (ganglion) cells. Each alternating layer receives input from the left and right eye, so that visual information from each eye is triply stored.

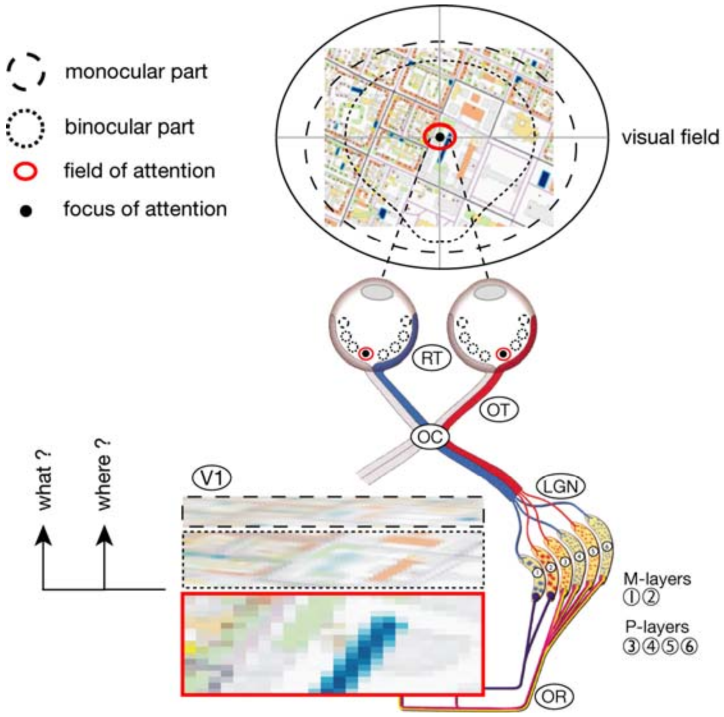


Figure 22. Basic processing steps on the retino-striate pathway. Abbreviations: retina (RT), optic tract (OT), optic chiasma (OC), lateral geniculate nucleus (LGN), parvocellular layers (P-layers), magnocellular layers (M-layers), optic radiation (OR), primary visual cortex (V1) (modified from Penzlin 2004).

Layer 1 and 2 are linked to large retinal cells (magnocellular) and referred to as the magnocellular layers (M-layers). M-layers receive sensory input from the peripheral retina and are highly sensitive to information about motion and binocular disparity. They have monochromatic responses and mediate responses to stationary and dynamic light and dark distributions. As part of the visual system that tells the brain ‘where’ something is, they operate fast with low spatial resolution. Layer 3 to 6 are linked with small retinal cells (parvocellular) and referred to as parvocellular layers (P-layers). P-layers receive sensory input from the field of attention and respond to chromatic signals. They operate slowly with high resolution to process details of geographic information (e.g. cartographic symbols). Accordingly, they are the part of the visual ‘what’ network that tells the brain ‘what’ something is.

From the lateral geniculate nucleus, features of geographical information are separately transmitted through a collection of axons called the optic radiation (OR) to the primary visual cortex. Each part of the retinal surface is mapped in a clear point-to-point topography in the primary visual cortex. The left visual hemifields of both eyes are represented in the right part of the primary visual cortex and the other way around. Only the field of attention is represented bilaterally (Arditi & Zihl 2000). While spatial coding is highly accurate in the primary visual cortex, feature contour processing is mainly restricted to the central part of the visual field representation. Approximately 50% of neurons in the primary visual cortex are allocated to visual signals kept by just 2% of the retina, which corresponds to the focus of attention (fovea) and the field of attention (macula). The primary visual cortex acts as a distribution centre by transferring extracted features of geographic information to higher visual brain areas according to their spatial (where?) and object (what?) properties.

3.5 Visual processing of semantics

The complexity of geovisualisations can be reduced if the recognition of an object (what) can be dissociated from its localisation (where). Such a functional division allows users to effectively scan geographic spatial and object information. Furthermore, the location of a stimulus can vary within geovisualisations (e.g. in animations) while a given location or region of geographic information can contain diverse stimuli (e.g. various colours or shapes). To effectively deal with this visual problem, users possess of a dual route visual network that can be divided into a ‘what’ and ‘where’ information processing pathway. Evidence for the existence of these specialised pathways is given amongst others by neuropsychological research with patients having various brain lesions. While lesions of visual areas along the ‘where’ pathway interfere with visuospatial abilities, they mostly do not affect the performance of object discrimination. On the other hand, lesions of visual areas along the ‘what’ pathway predominantly impair the capability of object form or pattern differentiation, but they do not compromise visuospatial judgements. The functional segregation and appropriate interconnections were confirmed by using multidimensional scaling of anatomical data (Young 1992).

Similar to bottom-up and top-down factors the two visual pathways are hereafter separately presented. However, it is important to note that these pathways are strongly interconnected (Niebur & Koch 2000). The discovery of the visual functional differences are documented in e.g. Dubner and Zeki (1971), Zeki (1978) or Ungerleider and Mishkin (1982). A detailed illustration of interrelated visual processing areas derived from anatomical tract tracing methods is given by Ungerleider (1995) and Webster and Ungerleider (2000). In the following, major visual information processing pathways, functionalities and interdependencies between brain areas that are involved in processing geovisualisations are presented.

The ‘what’ pathway, also known as ‘ventral pathway’ (running through ventral areas) or ‘occipitotemporal pathway’ (running from occipital to temporal brain areas) participates involved in processing semantics of geographic information. It is specialised in processing local visual attributes (colour, form, shape and texture) and in identifying, categorising and recognising visual objects (Grill-Spector and Malach 2004). It passes from the visual areas V1, V2, and V4 in the human visual cortex and via inferotemporal cortex (ITC) to the prefrontal cortex (PFC) (Figure 23). Neurons that fire from the primary visual cortex (V1) to the inferotemporal cortex (ITC) consist of large receptive fields that span wide regions over the retina (RT) and are sensitive to the position of features within an object (Olson & Gettner 1995).

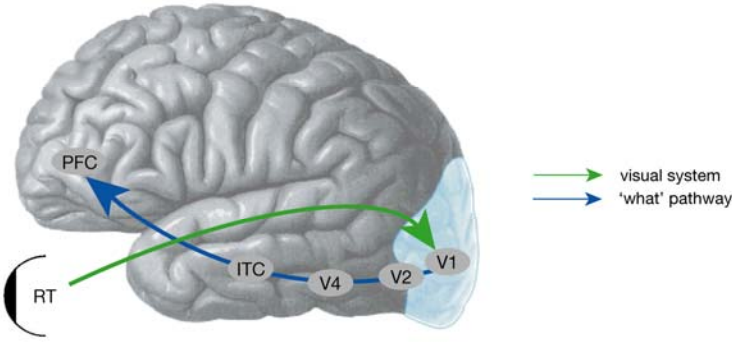


Figure 23. The ‘what’ pathway. Abbreviations: retina (RT), primary visual cortex (V1), secondary visual cortex (V2) visual cortex V4 (V4), inferotemporal cortex (ITC), prefrontal cortex (PFC).

The primary (V1) and secondary (V2) visual cortex form the foundation of the cortical visual system. The primary visual cortex encodes spatial geographic information with high accuracy, because neurons in this brain area have small receptive field size. They are immediately altered by the penetration of light signals into the retina. The secondary visual cortex possesses larger receptive fields and processes contour, colour, and form of geographic information with special reference to depth signals.

The visual area V4 receives signals from the secondary visual cortex, and processes colour, orientation, and disparity of visual information. This area has an orderly retinotopic map, and receptive fields of neurons are about thirty times larger than those in the primary visual cortex (Van Essen & Zeki 1978). Furthermore, V4 is involved in complex shape and object recognition (Kobatake & Tanaka 1994), especially in the systematic tuning of contour features by responding to contour orientation of varying angles and curves as well as in figure-ground segregation. Desimone and Schein (1987) reported that some neurons are specifically activated when a stimulus pops out of the background because of differences in colour or form. These findings underline the important role of area V4 as an intermediate processing stage between bottom-up and top-down processing.

The inferotemporal cortex (ITC) is specialised in visual object processing and recognition. Neurons in the inferotemporal cortex have large receptive fields that cover wide retinal regions of the visual field, and respond to particular locations of a feature within relevant objects or regions when visual attention is directed towards them. About 50-66% of neurons respond selectively when complex stimuli (e.g. patterns) are visualised (Tanaka et al. 1991). Gibson and Maunsell (1997) found that in addition to visual attention, expectation and motivation can influence stimulus processing in the inferotemporal cortex. Similar to the visual brain area V4, the inferotemporal cortex is influenced by bottom-up and top-down factors and allows users to separate behaviourally relevant from irrelevant information (Jagadeesh et al. 2001). Finally, neurons in the inferotemporal cortex fire to the association area prefrontal cortex (PFC).

3.6 Visual processing of locations

The ‘where’ pathway, also known as ‘dorsal pathway’ (running through dorsal areas) or ‘occipitoparietal pathway’ (running from occipital to parietal brain areas) processes the location of geographic information and is the determinant pathway for target-oriented visuomotor tasks. Hence, the ‘where’ pathway is involved in the deployment of visual attention (e.g. extracting spatial properties like location and size of geographic information and their spatial relationships), directing gazes to relevant geographic information, and moving the mouse to identified geographic information (Zihl 2000, Corbetta 2000). It passes the visual areas V1, V2, and V3 in the human visual cortex to the middle temporal area (MT), the medial superior temporal area (MST), and via the posterior parietal cortex (PPC) to the (PFC) (Figure 24). Neurons that fire along the visual ‘where’ pathway are highly sensitive to locations and spatial properties of geographic information.

While V1 and V2 have the same functions as in the ‘what’ pathway little is known about the neuronal properties of the visual brain area V3. Its intermediate role is reflected in connections with the primary visual cortex for visual responsiveness, with the brain area V4 for higher-order form analysis, and with the middle temporal area for tuning movement direction (Felleman and Van Essen 1987). Most V3 neurons are selective for movement direction and many are selective for colour. Gegenfurtner et al. (1997) reported that similar to the secondary visual cortex (V2), 80% of neurons in V3 are selective for orientation, 54% for colour, and 30% for size. About 40% of V3 neurons exhibit strong directional selectivity (20% in the secondary visual cortex) and respond stronger to contrasts than neurons in the secondary visual cortex.

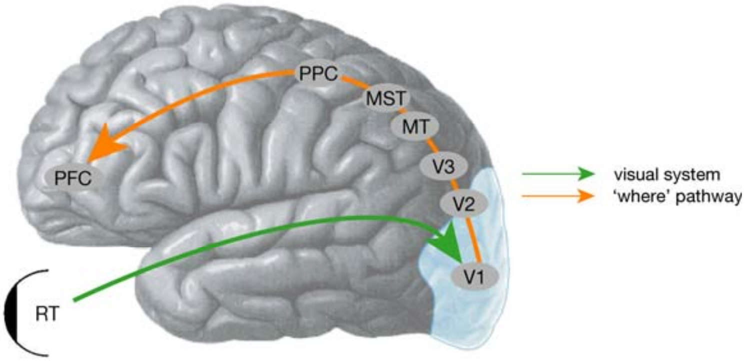


Figure 24. The 'where' pathway. Abbreviations: retina (RT), primary visual cortex (V1), secondary visual cortex (V2) visual cortex V3 (V3), middle temporal area (MT), medial superior temporal area (MST), posterior parietal cortex (PPC), prefrontal cortex (PFC).

The middle temporal area and the medial superior temporal area are involved in processing movements. Neurons in the middle temporal area respond as strongly as V3 neurons to achromatic contrasts but possess larger receptive fields. Approximately 90% of neurons are selective for motion direction and velocity, 70% for disparity (spatial depth), and 50% for stimulus orientation (Zeki 1974). It is suggested that the middle temporal area represents the three-dimensional structure of the visual environment, particularly with respect to visual motion (Duffy & Wurtz 1997). In the medial superior temporal area, 15% of neurons are selective for higher order motion stimuli like clockwise and counter clockwise rotation, contraction and radial flows (Tanaka et al. 1986, Saito et al. 1986). Furthermore, cells in the middle temporal area and the medial superior temporal area respond to dynamic patterns, such as radial and concentric sequences of glass patterns with the same directional selectivity as for real motion (Krekelberg et al. 2005). These patterns are processed as forms that move coherently but in an ambiguous direction, i.e. in accordance with the global structure of a form. This phenomenon of implied motion (form implies motion) probably results from interactions between brain areas that process motion (e.g. MT, MST in the 'where' path) and form (e.g. V4, ITC in the 'what' path). This combined processing may enable users to interpret semantic motion signals evoked for instance by speed lines that are employed in cartoons to suggest the speed of items (e.g. Burr & Ross 2002).

The posterior parietal cortex plays an important role in representing visual dimensions of geovisualisations, particularly in configuring the visual surrounding. Moreover, it is involved in orienting and shifting visual attention, in filtering distractive stimuli, and in coding specific motor intentions. The posterior parietal cortex also possesses a coarse topographic representation of the visual field for salient objects (Koch & Ullman 1985). Koch and Ullman's model is derived from the 'feature integration theory' (Treisman & Gelade 1980) illustrating visual search strategies and results in a 'saliency map' which topographically codes for local 'purely bottom-up guided' conspicuity over the entire visual scene (Itti et al. 1998).

The posterior parietal cortex is selectively activated when either voluntary allocation of attention is required via 'top-down' orienting of attention or during target detection without knowing the spatial location of targets depending on 'bottom-up' processes (e.g. Corbetta et al. 1995). Corbetta et al. (2000) suggested that the posterior parietal cortex is engaged in both of these processes. This brain area is concerned to be highly selective for salient stimuli, even when covert attention occurs (attention without eye movements) (e.g. Bowman et al., 1993). Constanidis and Steinmetz (2005) reported that the posterior parietal cortex might detect and encode the location of a salient stimulus although the stimulus itself was irrelevant to the behaviour. Hence, neurons in the posterior parietal cortex represent the location of a salient stimulus and are involved in directing the attention to that stimulus embedded in a complex scene. Moreover, the posterior parietal cortex seems to be involved in filtering distractors, i.e. filtering irrelevant stimuli that can deviate gazes from the target (Friedman-Hill et al. 2003). Visual information is finally transmitted to the prefrontal cortex, a brain area that is suggested to be involved in working memory processes (Owen 1996).

3.7 Working memory and decision making

When processing geovisualisations, users need to (1) retain local features (e.g. single cartographic symbols) and global representations (e.g. spatial dimensions) based on differences and similarities among the complex geovisualisations, and (2) apply rules for taking into account these similarities and differences. Both memory-guided aspects allows the detection of relevant geographic information to initiate further motor activities (e.g. directing gazes to less relevant information). To perform and complete this complex task, users use their working memory system that is fractionated with respect to visual 'where' and 'what' information (Finke et al. 2005). Hence, the working memory system is involved in guiding and transiently allocating visual attention to relevant information (e.g. Awh & Jonides 2001). The functions of the prefrontal cortex (PFC) and the corresponding sub-regions dorsolateral prefrontal cortex (DLPC), and ventrolateral prefrontal cortex (VLPC) are considered to illustrate internal processes of working memory and decision-making (Figure 25).

The inferotemporal cortex on the 'where' path and the posterior parietal cortex on the 'what' path are directly linked to the prefrontal cortex (Webster et al. 1994). Hence, both information processing pathways converge into the prefrontal cortex that plays the major role in behaviour and cognitive control (Petrides 1994, Baddeley 1998, Miller & Cohen, 2001). It is crucially involved in the acquisition and flexible use of rules and routines that users need for successful coping with varying demands of geographic relevant tasks (e.g. problem solving, decision making). Studies have shown that the prefrontal cortex is involved in the monitoring, manipulation, and evaluation of representations (Petrides 1991) and this area can be referred to as the centre of executive functions, planning, and suppression of irrelevant stimuli (Prosiegel et al. 2002). Moreover, investigations observed task-specific neuronal activity in the prefrontal cortex, i.e. neurons can encode rules between concrete stimuli and behavioural responses (e.g. White & Wise 1999), like for instance 'red' means 'stop'. Due to this association capability, the prefrontal cortex can be considered as the centre of 'visual analytics'.

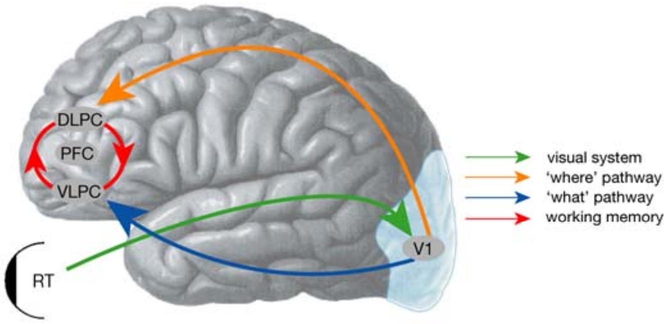


Figure 25. Brain areas involved in processes of the working memory system. Abbreviations: retina (RT), primary visual cortex (V1), dorsolateral prefrontal cortex (DLPC), ventrolateral prefrontal cortex (VLPC), prefrontal cortex (PFC).

Several complex task studies tried to specify the role of the prefrontal cortex in different memory processes and proposed a hierarchical two-stage model that describes major functions of the ventrolateral and dorsolateral prefrontal cortex. For a discussion see e.g. Owen (1997), Petridis (1994), and Rypma and D'Esposito (1999). The findings of neurocognitive researched suggest that both areas represent anatomically and functionally separable sub-regions within the prefrontal cortex that have distinct contributions to a user's memory. While the ventrolateral prefrontal cortex is primarily involved in updating and maintenance of contents in a user's memory system, the dorsolateral prefrontal cortex selects information that is already active in the memory (Fletcher & Henson, 2001). With regard to the theory of memory, three main stages of memory were differentiated by Melton (1963) as shown in Figure 26.

Figure 26. Basic components of memory (after Melton 1963).

'Encoding' refers to the physical input to memory, i.e. users transform the wavelengths of visual geographic information into memory. 'Storage' refers to the maintenance of this information in memory. 'Retrieval', where the information is recovered from memory, represents the final component and is effective whenever users need to remember geographic information that they have already seen before. On the other hand, the memory can fail at any of these stages.
In the context of the time interval of information storage, users activate their short-term (for few seconds) or long-term memory (for minutes to years). Both memory mechanisms differ in three main relevant aspects. (1) While the long-term memory is structural, the short-term memory is rather dynamic (Hebb 1961). (2) The long-term memory is non-decaying and the short-term memory is automatically decaying (Hebb, 1949, Brown 1958). (3) While the capacity of the long-term memory is infinitely expansible, the capacity of the short-term memory is fixed and limited (Broadbent 1963, Atkinson & Shiffrin 1968).

The working memory consists of several separated processes. Some are required for the retention of information and some are needed for the allocation of attention while others coordinate information that is being temporarily maintained (Baddeley 1986). Correspondingly, the working memory is suggested to support users along the entire visual geographic information processing by acting as an interface between the process of perception, the storage in long-term memory and appropriate executive functions. Recent studies have confirmed that working memory is strongly involved in guiding attention to relevant visual information (Oh & Kim 2004, Woodman & Luck 2004).

Atkinson and Shiffrin (1968) developed one of the most influential working memory models that is based on the mechanism of a limited capacity bottleneck. They hypothesised that before reaching short-term memory, information is filtered by passing various sensory memories that are part of bottom-up driven perception processes. Another famous working memory model from Baddeley and Hitch is based on short-term memory models (e.g. Broadbent 1958). Baddeley (1996, 2000, 2003) pointed out that short-term memory differs from working memory in two major aspects: (1) working memory is a multicomponent system and short-term memory is based on the concept of a unitary module, and (2) working memory has a stronger emphasis on involved functions in complex cognitive tasks.

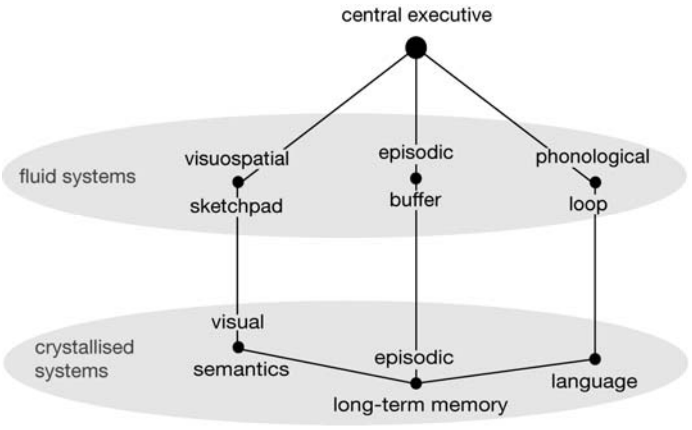


Figure 27. 'Multicomponent Working Memory Revision' (modified from Baddeley 2003).

Based on the multicomponent character of working memory, Baddeley and Hitch (1974) introduced a ‘three component model of working memory’ and the more advanced ‘Multicomponent Working Memory Revision’ (Baddeley 2003) that is illustrated in Figure 27. The model comprises a ‘central executive’ as a control system, a ‘visuospatial sketchpad’ and a ‘phonological loop‘ as transient storage systems as well as an ‘episodic buffer’ as a feature binding component.

The role of the central executive could probably be related to the functions of the dorsolateral prefrontal cortex (Baddeley 2003) that is suggested to play an important role in controlling performances of the working memory (Prosiegel et. al 2002). The central executive represents an attentional control system of limited capacity that supervises information integration. It is based on the theory of the ‘Supervisory Attentional System’ introduced by Norman and Shallice (1986) and operates as “*... an attentionally limited controller*” (Baddeley 2003,835), i.e. the central executive intervenes whenever humans are not capable to process automatic routine behaviour. The central executive is appropriate to control resources of attention and to regulate the information flow from and to connected storage systems. Moreover, it is responsible for directing attention to relevant information while neglecting irrelevant information, integrating ‘what’ and ‘where’ object information as well as coordinating visual information processing in multi-tasking. To realise this supervision, it is linked to two sub-ordered fluid and crystallised systems.

The fluid systems consist of a ‘phonological loop‘, a ‘visuospatial sketchpad‘, and an ‘episodic buffer‘ that activate local or regional focusing, selection, coordination and switching of attention. The capacity of these components is fluid because they do not solely depend on learning processes. The phonological loop stores phonological information (e.g. sound, language, scripts) and prevents memory traces from fading away. These traces can be refreshed when retrieved in a ’rehearsal loop’. In other words, the memory’s limited capacity can be updated when retrieved through e.g. re-articulation. The visuospatial sketchpad stores visual and spatial information (e.g. colour, location or speed of information). In analogue to the rehearsal loop, a ‘backtracking process’ stores the spatial properties of visual information. In doing so, it supports users to keep the spatial position of information in mind for a short term.

By relating several performances of the working memory and the long term memory to brain areas involved in memory processes, Fletcher and Henson (2001) assumed that the dorsolateral prefrontal cortex is involved in the updating and maintenance of contents in the working memory which corresponds to the ‘rehearsal’ and ‘back-tracking’ process. They suggested that the dorsolateral prefrontal cortex selects information that is already active in the working memory and it manipulates and monitors contents of the working memory. Hence, in contrast to the posterior parietial cortex (PPC on the ‘where’ pathway) that is associated with allocating attention in general; the activation of the dorsolateral prefrontal cortex is more related to the difficulty of task.

Based on the concept of episodic memory (Tulving 1998), Baddeley (2000) added the episodic buffer as a third component that differs from Tulving’s approach in the fact that the buffer represents a temporary store. The episodic buffer plays a major role in binding single features into larger units, depending on attentional resources supplied by the central executive (Allen et al. 2006). These ‘chunks’ (Miller 1956) result from processes of organising or grouping sensory input and they are closely related to the process of learning. It is suggested that the capacity of this temporary store is limited in terms of the number of chunks that can be stored simultaneously (Baddeley 2000). Additionally, the episodic buffer is related to the long-term memory for long-term episodic learning (e.g. the acquirement of visual semantics and language). Accordingly, these components are regarded as crystallised systems because of their capability to accumulate knowledge over a long period of time.

As a centre of visual analytics, the prefrontal cortex and its contribution to working memory plays a major role in converting sensory input to the execution of target-oriented visuomotor activities (e.g. directing gazes to relevant information) by sending signals to motor areas of the brain.

3.8 Execution of target-oriented visual activities

To simplify the complex process of visual scanning, it is appropriate to assume that afore mentioned internal correlations of visual brain area functions took place before any eye-movement towards relevant geographic information is conducted by the user. To finally execute eye movements, signals are sent from a user‘s prefrontal association areas to the frontal eye field (FEF) or through the premotor cortex (PMC), via the motor cortex (MC), to the spinal cord (SPC) for innervating skeletal muscles to execute motor responses (activating finger muscles (FM) to click or move a mouse button) (Figure 28).

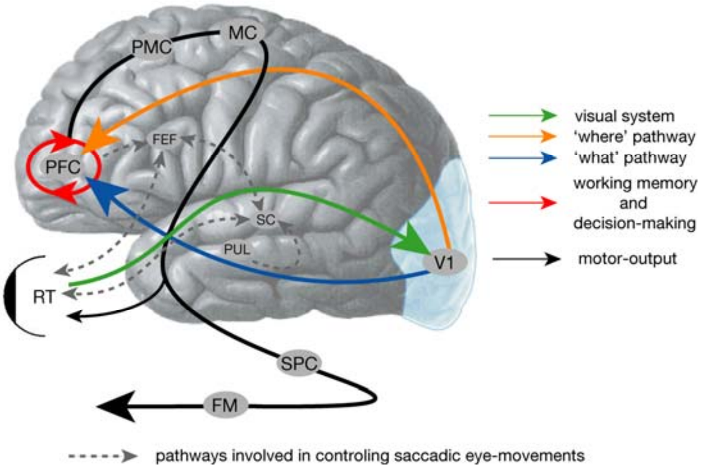


Figure 28. Execution of target-oriented visuomotor activities. Abbreviations: retina (RT), primary visual cortex (V1), prefrontal cortex (PFC), premotor cortex (PMC), motor cortex (MC), spinal cord (SPC), finger muscles (FM), frontal eye-field (FEF), superior colliculus (SC), pulvinar (PUL).

The premotor cortex and the motor cortex have been recognised as areas in which learned activity sequences and the integration of motor skills (execution of relevant movements) occur in two- and three-dimensional environments (e.g. Schwartz et al. 1988, Nilsson et al. 2000, Lezak 2004). Hence, both areas seem to play a major role in sensorimotor transformation. While the premotor cortex shows neural response in context-dependent selections of targets and planning of movements (e.g. Kalaska & Crammond 1992, Wise et al. 1997), the motor cortex is highly involved in reaching visually guided target locations. The prominent role of the motor cortex in preparing movement executions is well reflected in four major co-varying aspects of a behavioural paradigm (Shen & Alexander 1997).

(1) Direct reaching the position of a target , (2) the physical properties of this target (e.g. spatial location), (3) the instructed location of the target (the goal of the movement) and (4) the trajectory of reaching this target. To execute relevant movements, signals are sent from the motor areas to the spinal cord where spinal neuronal systems transfer motor control that was prepared by appropriate brain areas to executions (by innervating e.g. corresponding finger muscles). A user’s brain consists of visual brain areas that are highly involved in bottom-up and top-down processes of controlling saccadic eye-movements. These visual areas are somewhat apart from the before mentioned simplified and well-structured information processing pathways.

The major functions of the frontal eye field and the superior colliculus were elucidated in the context of high- and low-level tasks in cartography (as discussed in section 2.5). With respect to the focus on visual information processing, the pulvinar is a brain area that is deeply involved in visual scanning by integrating sensory information into spatial control of attention. This function is amongst others characterised by being afferent to the frontal eye field, i.e. the pulvinar sends signals to the frontal eye-field (Kandel et al. 1996). The pulvinar can be regarded as a relay station that distributes sensory input to various visual brain areas that control visual orientation and visual attention (Prosiegel et al. 2002). Moreover, the pulvinar promotes and directs shifts in visual attention by routing information to and from involved areas (Olshausen et al. 1993, Michael et al. 2001), and it participates in the modulation of activity in visual areas to enable filtering of irrelevant distractors and in directing covert attention (Pashler 1996, Deco et al. 2002).

Several studies revealed that the pulvinar is linked to the primary visual cortex, V3, V4, and the middle temporal area on the ‘where’ pathway to mediate the identification of objects when selective attention is needed (e.g. Bender 1981, Shipp 2001). In their neurodynamical model of visual attention, Deco and Zihl (2001) pointed out that the pulvinar takes part in allocating attention to location. They suggested that the pulvinar is connected to areas of the ‘what’ pathway and to the superior colliculus that is involved in moving the focus of attention. Hence, the pulvinar can probably control the information processing flow from the primary visual cortex to the inferotemporal cortex on the ‘what’ pathway. Due to the afferent connection to the posterior parietal cortex on the ‘where’ pathway (having a saliency representation of a visual information), Deco and Zihl hypothesised that the pulvinar receives a feedback mechanism of the ‘where’ pathway. This extensive connectivity to multiple visual areas can lead to the suggestion that the pulvinar regulates the enhancement and the location in directing visual attention.

3.9 Visual attention-guiding attributes

The preceding sections have explained how users search for interesting information. The complex processes have been related to the centre-surround mechanism of receptive fields that occurs whenever users deploy visual attention to process geographic information in specific dimensions of the visual space. This section deals with cognitive aspects of visual scanning efficiency.

Users are skilful in visually scanning for interesting information. They search the sideboard for books, the office desk for pencils, the wardrobe for T-shirts. With regard to geovisualisation design, an important aspect is to know which stimuli exist or can be designed to guide a user’s attention to relevant information. Wolfe (2005) suggested that there are more than dozen attention-guiding features (and no more than two dozen) but only a limited number of attributes are able to efficiently guide attention to visual information. Wolfe and Horowitz (2004) ranked such attention-guiding attributes (e.g. colour) and corresponding values (e.g. red) based on their efficiency to attract attention in experimental visual search tasks (Table 1).

They identified colour, motion, orientation, and size as candidates for undoubted attributes that are processed pre-attentively. In contrast to attentive processes where humans direct visual attention to specific features of objects, and select and highlight these targets, pre-attentive processing operates as a more rapid scanning system. It is solely concerned with the detection of objects by rapidly scanning the overall features of objects. Hence, pre-attentive processing encodes the ‘useful elementary properties’ of a scene and observers can rapidly and automatically detect these properties without particular demands on attentional resources. These attributes are detected although test persons don’t know anything about these items in advance. As probable attributes, Wolfe and Horowitz (2004) classified amongst others luminance (onset / polarity) and shape. The attribute ‘semantic category‘ is a fundamental category in geovisualisations and is highlighted to illustrate its status as a candidate for probable non-attribute. As described in section 2.5 and 3.5, semantics of information are predominantly processed via the ‘what’ pathway and the working memory-system that are both more or less involved in top-down processes. Thus, humans need to retrieve stored information to decode underlying semantics, which might slow down the reaction time required to say that a target is present. According to the RT x set size function (reaction time multiplicated with the set size), reaction time decreases and the slope will fade away from zero indicating that the semantic category can be labeled as inefficient in visual scanning tasks. To illustrate, users might pre-attentively locate a red or big cartographic symbol but referring this symbol to a particular underground station requires further cognitive activities to accurately identify and compare this feature with existing semantic knowledge.

undoubted attributes (1)	**probable attributes** (2)	**possible attributes** (3)	**doubtful attributes** (4)	**probable non-attributes** (5)
colour	**luminance onset**	lighting direction	novelty	intersection
orientation	**luminance polarity**	glossiness	letter identity	optic flow
size	vernier offset	expansion	alphanumeric category	colour change
motion	stereoscopic depth and tilt	number		3 D volumes (geons)
	shape	aspect ratio		faces
	line termination			names
	closure			**semantic category**
	topological status			
	cervature			

Table 1. Visual attention-guiding attributes (modified from Wolfe & Horowitz 2004).

In addition to the classification from Wolfe and Horowitz, further attributes and corresponding subdivisions are considered as possible candidates to guide attention to relevant information (Figure 29). According to the description of the visual areas functions on the ‘where‘ pathway (see section 3.6).

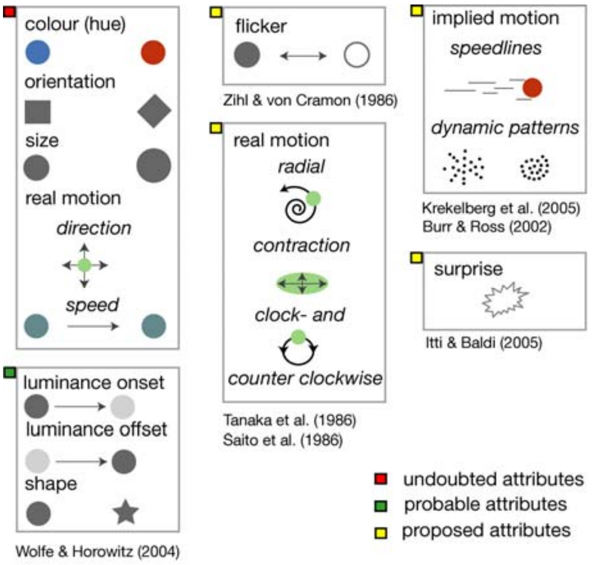


Figure 29. Some representative attention-guiding attributes.

For example the attribute ‘motion‘ is added to the list due to high neural responses that this attribute provokes in the middle temporal area and medial superior temporal area. In general, motion is faster detected compared to static attributes (Peterson & Dugas 1972), and can play a decisive role in attracting attention in geovisualisations, particularly in the corner of displays (Bartram et al. 2003). This includes direction, speed, and acceleration of motion that are captured by large receptive fields in the motion processing middle temporal area on the ‘where’ pathway. According to the functions of the medial superior temporal area, direction of real motion implies clockwise rotation, counter clockwise rotation, contraction, radial flows, and modes of implied motion such as speed lines and dynamic patterns. Although Wolfe and Horowitz related the attribute flicker in brackets to the attribute luminance onset, flicker is added to the list as an independent attribute. In this work, flicker is considered as multiple frequencies of luminance onset and offset, while luminance onset and offset are considered as a unique (dis-) appearance of a light stimulus.

Finally, the attribute ‘surprise‘ can be added to the list according to Itti and Baldi (2006) who developed a Bayesian surprise model. Surprise is somewhat apart from the before mentioned attributes because it is rather related to an unexpected event that can be seen as a ‘wow factor‘ than to a specific physical stimulus. Itti and Baldi (2006) defined surprise *“… as the distance between the posterior and prior distributions of beliefs over models*“. As the authors stated, evidence to consider surprise as one of the “*strongest attractors of human attention*“ is given by neuropsychological studies and results of their experiment with the eye-movement recording method. Itti and Baldi postulated that electrophysiological studies have revealed that surprising stimuli provoke high neural responses in visual brain areas, the lateral geniculate nucleus, as well as in retinal cells.

By hypothesising that surprise attracts gazes they recorded eye movements from visually scanned scenes (daytime and night time scenes of crowded environments, video games, television news, sports, and commercials) and found out that surprise-driven gaze fixations occurred more efficiently than e.g. motion- or saliency-driven gaze fixations. However, surprise is highly top-down driven because it relies on acquired beliefs and the question of how surprise differs from novelty (ranked as a doubtful attribute) is probably a matter of debate. Nevertheless, surprise is added to the list due to its strength in attracting gazes in comparison to motion. Itti and Baldi suggested that computable surprise could guide the development of data mining.

Summary. This chapter gives an overview of cognitive foundations characterised by the term ‘internal visual information processing’. Emphasis has been put on simplifying the analytical strength of the sophisticated functionalism of involved information processing pathways and corresponding visual brain areas. Within visual attention, a user’s capability of highlighting important stimuli while suppressing competing distractions was related to the skill of selective visual attention. It has been argued that the contents of geovisualisation research agendas can be related to internal processes of detecting and analysing relevant geographic information and that internal processing pathways and visual brain area functions play a dominant role in formulating appropriate design principles, developing the design methodology, and conducting cognitive evaluations of geovisualisation design. The biological centre-surround mechanism and the characteristics of the fields of visual information processing have been presented to illustrate the skill of visual information filtering and to determine the visual space of visual geographic information processing. Then, a more local perspective on visual scanning has been presented. In a next step, these characteristics of visual cognition have been related to internal processes of visual information processing and have been considered to be relevant for formulating design-principles and developing a design methodology for geovisualisations. Finally, attention-guiding attributes have been presented and considered to be appropriate for facilitating high neural responses in visual brain areas and consequently for stimulating information processing pathways involved in visual geographic information processing with the goal to release the limited capacity of the cognitive workload.

4. The development of attention-guiding geovisualisation

While users are able to visually process geographic information faster and more accurate than computational systems, the latter is superior in terms of processing a large quantity of geographic data. The cognitive design approach of 'attention-guiding geovisualisation' aims at minimising this large capability discrepancy between users and geographic information systems. The basic challenge is therefore to unite a system's capability with a user's cognitive skill by adapting the external design of geovisualisation to user's internal foundations of visual information processing. Attention-guiding geovisualisation is any kind of geographic data representation that aims at promptly directing a user's attention to relevant geographic information for rapid and accurate visual analytical tasks.

The attention-guiding approach is rooted on three interrelated fundamental characteristics of GI science research.

First, the technology-driven aspect of geographic information system engineering is not in accordance with the development of attention-guiding geovisualisation. Due to the large amount of geographic data and the technological advances in system engineering, much attention has been paid to the technology-driven development of geographic information systems since the 1980s. Although cognitive research of geovisualisation design rises again since the 1990s (Montello 2002) the technological focus on system engineering dominates the perspective on geographic information processing. GI scientists still code a huge amount of geographic information into complex visualisations and assume that users have sufficient cognitive skills for visual geographic information processing. Such an approach is questionable because it neglects usability issues as the basic attributes of system acceptability (Nielsen 1993). It forces users to adapt their powerful capability of visual information processing to the limited possibilities of computational geographic information design. Ideally, GI scientists should rather first investigate a user's potential cognitive skills and then adapt the visualisation design to the user's need in a second step. This user-centred approach raises among GI scientists the awareness of the necessity to undertake the interdisciplinary research.

Second, the cognition-driven aspect reflects the importance of investigating user's visual skills. With regard to internal processes, the black-box metaphor (MacEachren 1995, Slocum et al. 2005) expresses the need to find out how and why users visually process geovisualisations rather than identifying which visualisation works best. This need can hardly be fulfilled without opening the black-box. The knowledge about internal correlations of visual information processing represents the scientific base to formulate design principles and to develop and evaluate a design methodology for attention-guiding geovisualisation. 'Opening the black-box' means the placement of the internal capabilities of visual information processing in the centre of the user (including the external observable behaviour).

Third, the cognition-driven aspect requires also more attention to the interaction between the internal visual information processing and the external geovisualisations. Two suggestions were formulated by MacEachren (1995) with respect to his conceptualisation of communicating geographic information through the use of maps. These formulations can be extended to consider the fundamental characteristics of visual information. With respect to his conceptualisation of communicating geographic information through the use of maps, MacEachren supposed that (1) maps neither contain nor transmit geographic messages and that (2) maps do stimulate inferences of users by interacting with their prior beliefs. In this work geovisualisations (1) represent a complexity of external visual stimuli in terms of graphical variables that are combined to geographic information by internal processes of users. Furthermore it is suggested, that (2) geovisualisations stimulate decision-making of users by activating visual brain area functions along visual information processing pathways to combine knowledge with an actual task on demand.

This work is based on the hypothesis that a function-driven relation of graphical variables, design principles, and methodology to internal processes offers the opportunity to adapt the design of geovisualisation to user's capability of visual information processing more precisely thus to facilitate inference making in geographic tasks. Reasoning processes in geographic tasks result from stimulating specific visual brain areas along visual processing pathways. Accordingly, the cognitive approach predominantly studies the underlying internal cognitive processes of the functional partition of visual information processing. In addition to the cognitive approach, the development of attention-guiding geovisualisation is also strongly driven by usability concerns in accordance with the research agendas (MacEachren & Kraak 2001, Slocum et al. 2001, Chinchor et al. 2005, Montello & Freundschuh 2005). They call for studies of cognitive and usability issues for the purpose of optimising geovisualisation design.

Five major challenges are involved in the following conceptual framework for designing attention-guiding geovisualisation (Figure 30).

4.1 Integration of cognitive and usability issues

Integration of cognitive and usability issues as the first challenge aims at improving a system's acceptability. This can be realised by relating relevance of geographic information to the utility criterion and the cognitively adequate visualisation to the usability criterion (see section 2.9). Both components are based on relevance theory (Sperber & Wilson 1995, Saracevic 1996) that distinguishes between cognitive relevance as a category of subjective relevance and algorithmic relevance as a category of objective relevance (see section 2.8).

The main focus is on the theory of cognitive relevance that determines the relevance of an item by the degree of employed effort and attended effect. Only information that is processed with small effort and large effect is relevant. This aspect of information filtering can be related to the biological filter mechanism involved in visual scanning and leads to the conclusion that only promptly located and easily decoded information that stimulates effective decision-making is considered as most efficient to use.

The categories ‘easy to remember‘ and ‘easy to learn‘ that Nielsen (1993) has directly linked to the usability criterion (see section 2.9), are considered as subcategories of ‘efficient to use‘ in terms of ‘efficient visual scanning‘. Learning and memorisation processes are highly affected by interrelations of the fluid and crystallised components of the working memory system. Efficient visual scanning releases the central executive as the attentional control system of limited capacity that supervises the acquisition of information and retrieving of knowledge (see section 3.7). The cognitively adequate visualisation on one hand leads to the challenge of reducing information complexity.

4.2 Formulation of cognitive design principles and development of a cognitive design methodology

To cope with the basic challenge of reducing information complexity, it is desirable to formulate cognitive design principles and develop a cognitive design methodology that reduces the cognitive workload of users. Based on the theories of external geovisualisation and internal visual information processing, a cognitive design approach for attention-guiding geovisualisation is presented in the following.

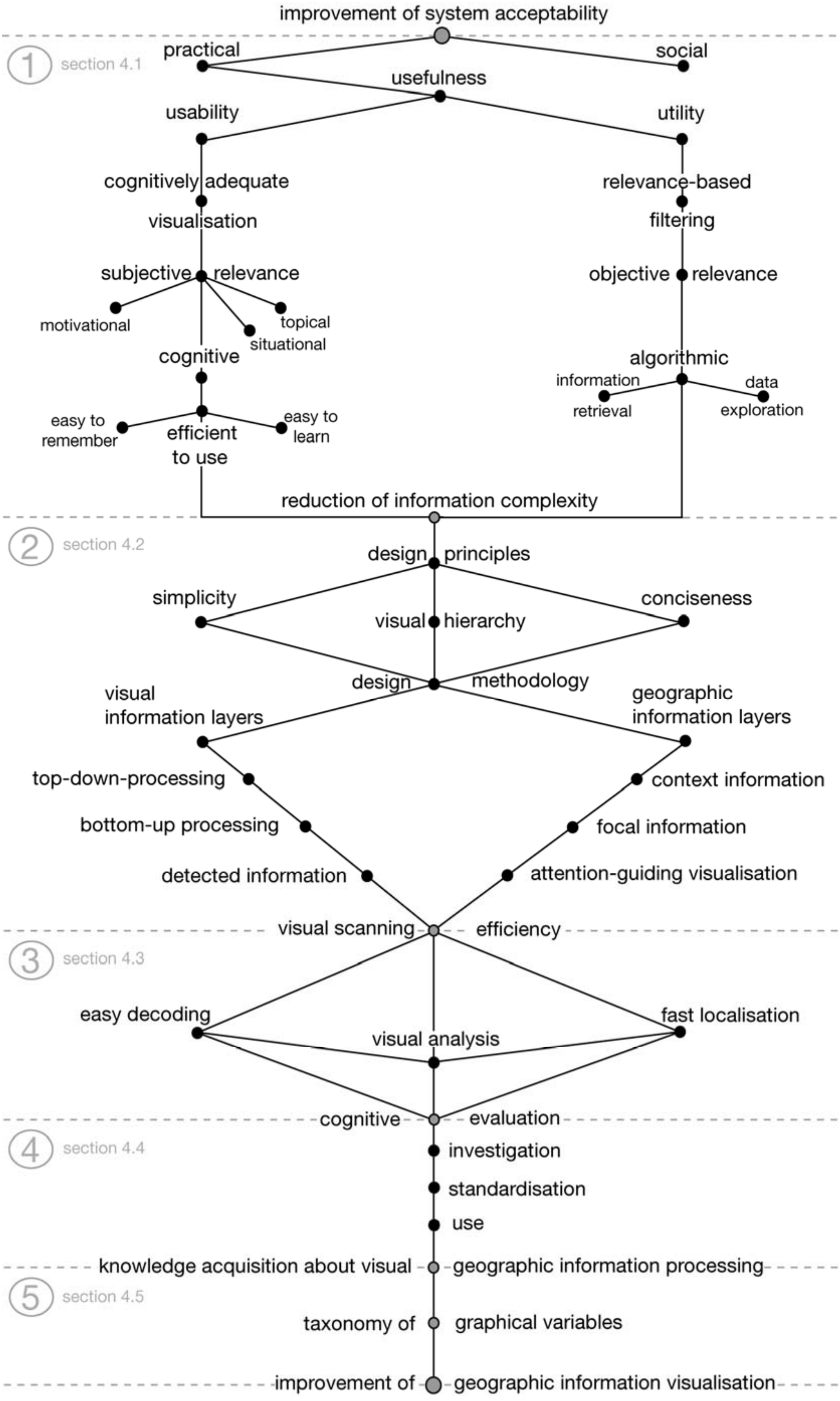


Figure 30. A conceptual framework for designing attention-guiding geovisualisation.

The design process includes the following steps:

(1) The relevance of the geographic information is assessed and represented based on the information usage context (e.g. query parameters, spatiotemporal setting etc.).

(2) Relevant geographic objects are selected based on their relevance for the usage context (e.g. information retrieval on mobile displays or data exploration on static displays).

(3) The relevance hierarchy of the selected objects (rankings) is saliently visualised with attention-guiding attributes.

The attention-guiding design faces the visual information complexity as well as the user's capacity limitation of visual scanning. Consequently, two crucial questions arise:

(1) How can we reduce the complexity of geovisualisations without omitting spatial context information that is required for navigation?

(2) How can we promptly guide the user's attention to the location or region of relevant information to enable the decoding of the ranking order of geospatial objects that is supervised by a limited attentional control system?

The solution should allow the the effective processing of geovisualisations without exceeding the cognitive workload. The overall objective is to present maximum information that can be retrieved with minimum effort. This overlaps with the main task of map design which is to select relevant objects and visualise them as salient features in a map (Dent 1999).

Design principles. The design principles are reflected in three classical rules of thematic map design:

• simplicity:	reducing the visual complexity.
• visual hierarchy:	organising and structuring the information into visual layers.
• conciseness:	visualising the important information in a salient way that requires little visual processing resources.

Simplicity deals with the visual complexity of a visualisation. When processing geographic information, users apply their visual scanning capability to filter away irrelevant geographic information based on global (overview) and local (feature-based) contrast which is constrained in space and time by limited attentional resources. To improve processing performance, it is important to reduce the visual complexity on the display. Accordingly, a first step is the selection of relevant geographic information. By reducing the number of visual elements, the problem scope will be reduced.

Visual hierarchy is realised by organising the geographic objects in vertical visual layers that form a clear hierarchy and consequently support the visual scanning process. This structure enables to keep relevant information as less as possible in the background and as much as possible in the visual foreground. In doing so, attention-guiding geovisualisation is adapted to the properties of the neurophysiological centre-surround mechanism that allows users to direct their focus of attention to the relevant information. The focus of attention reflects the actual centre of prominent processing activity (local attention), while the less attended background represents the surround (global attention). The application of figure-ground segregation stimulates this centre-surround mechanism, i.e. the visual dissociation of objects from the background. One of the elementary design principles to establish a visual hierarchy is that a figure has more salient features than the background (Krygier & Wood 2005), whereby the inhibition of the surrounding context information is comprised in figure-ground segregation (Born et al. 2000). By visually extracting the location or region of relevant geographic information from the background, users' visual scanning of complex visualisations is efficiently supported.

Conciseness is reached by applying visual attributes with strong attention-guiding properties. A main strategy is to attract user's visual attention as fast as possible by the salient representation of relevant geographic information. The saliency of relevant information is additionally improved by reducing the degree of visual appearance of the less relevant context information. This principle of displaying the important information in a salient way that claims little visual processing resources is in accordance with the model of visual scanning efficiency based on the performance-resource-function (Norman and Bobrow 1975), the model of instructional efficiency (Paas et al. 2003), and the RT x set size function (Wolfe & Horowitz 2004) (see section 2.7). The model of visual scanning efficiency illustrates the relation between information complexity, cognitive workload, and cognitive performance.

Design methodology. The attention-guiding design methodology aims at representing relevant geographic data through graphical variables that are able to guide visual attention (where) and to encode the meaning and variation (what) of geographic information at visual locations or regions of interest.

Figure 31 illustrates a collection of potential attention-guiding graphical variables as result of cognitive research on attention-guiding capabilities of visual attributes (see section 3.9) in combination with the set of well-established graphical variables in cartography (see section 2.7).

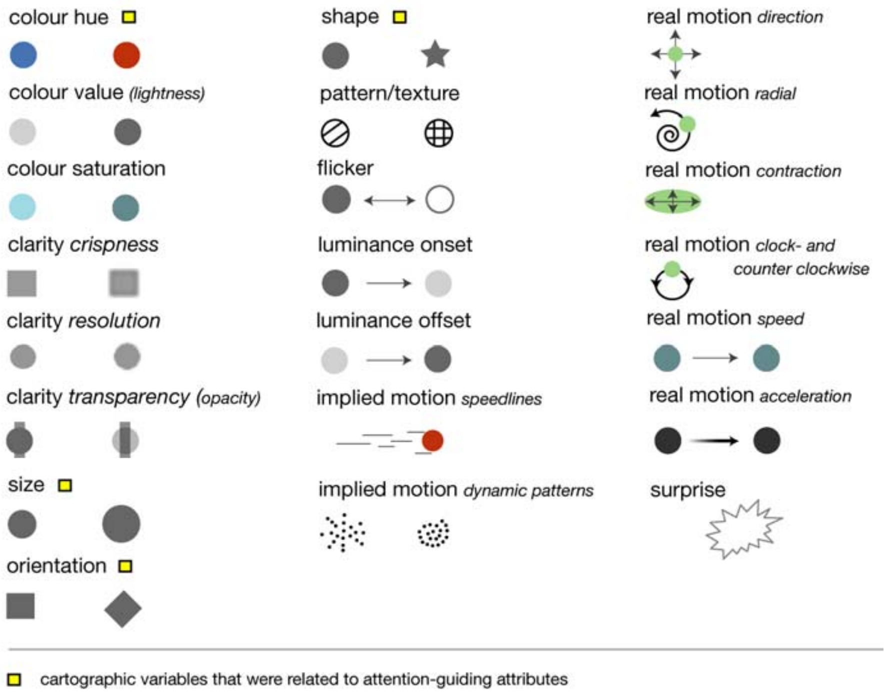
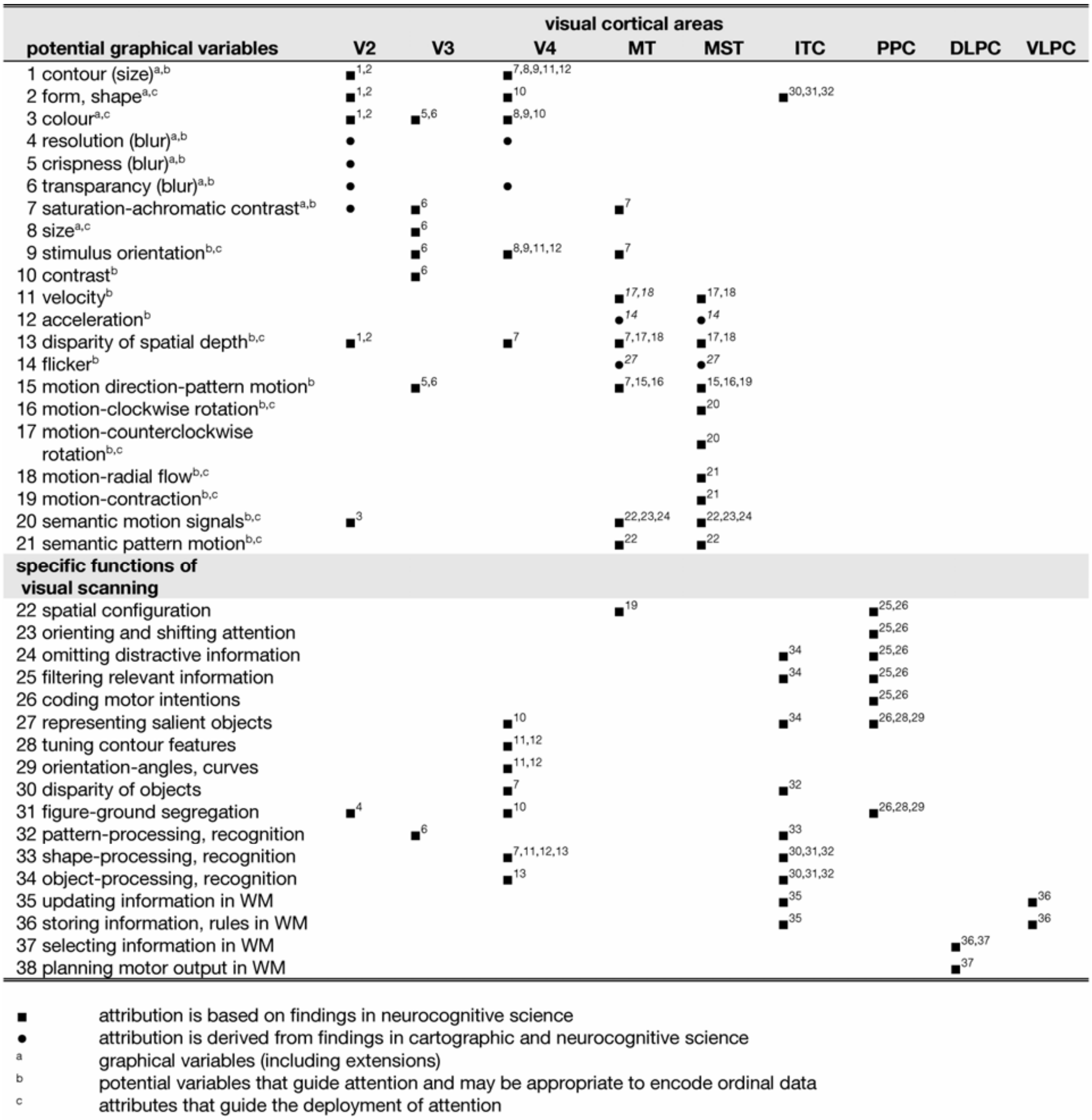


Figure 31. Potential attention-guiding graphical variables.

These graphical variables are first of all composed of Bertin's (1974) and MacEachren's (1995) graphical variables that prove to encode ordinal data (the order of relevance) more or less effectively. Some of them fit well in Bertin's theory of graphical variables (e.g. colour, orientation, size, value, and shape). MacEachren proposed the variable clarity, composed of transparency, crispness, and resolution to be favourable and the variable colour saturation to be marginally effective for visualising ordinal data. Note that these listed variables represent possible attention-guiding candidates due to the missing empirical evidence of their potential to support users in different geographical tasks. Although some variables proved to be highly appropriate to guide attention in psychological visual search tasks, the empirical evidence about their efficiency in visual scanning of geovisualisations is not yet available (see section 4.4).

To understand how and why these attention-guiding attributes support users in visual geographic information processing, it is necessary to relate them to functions of visual brain areas involved in visual scanning of geographic information (Table 2).



	visual cortical areas								
potential graphical variables	**V2**	**V3**	**V4**	**MT**	**MST**	**ITC**	**PPC**	**DLPC**	**VLPC**
1 contour (size)[a,b]	■[1,2]		■[7,8,9,11,12]						
2 form, shape[a,c]	■[1,2]		■[10]			■[30,31,32]			
3 colour[a,c]	■[1,2]	■[5,6]	■[8,9,10]						
4 resolution (blur)[a,b]	●		●						
5 crispness (blur)[a,b]	●								
6 transparancy (blur)[a,b]	●		●						
7 saturation-achromatic contrast[a,b]	●	■[6]		■[7]					
8 size[a,c]		■[6]							
9 stimulus orientation[b,c]		■[6]	■[8,9,11,12]	■[7]					
10 contrast[b]		■[6]							
11 velocity[b]				■*[17,18]*	■[17,18]				
12 acceleration[b]				●*[14]*	●*[14]*				
13 disparity of spatial depth[b,c]	■[1,2]		■[7]	■[7,17,18]	■[17,18]				
14 flicker[b]				●*[27]*	●*[27]*				
15 motion direction-pattern motion[b]		■[5,6]		■[7,15,16]	■[15,16,19]				
16 motion-clockwise rotation[b,c]					■[20]				
17 motion-counterclockwise rotation[b,c]					■[20]				
18 motion-radial flow[b,c]					■[21]				
19 motion-contraction[b,c]					■[21]				
20 semantic motion signals[b,c]	■[3]			■[22,23,24]	■[22,23,24]				
21 semantic pattern motion[b,c]				■[22]	■[22]				
specific functions of visual scanning									
22 spatial configuration				■[19]			■[25,26]		
23 orienting and shifting attention							■[25,26]		
24 omitting distractive information						■[34]	■[25,26]		
25 filtering relevant information						■[34]	■[25,26]		
26 coding motor intentions							■[25,26]		
27 representing salient objects			■[10]			■[34]	■[26,28,29]		
28 tuning contour features			■[11,12]						
29 orientation-angles, curves			■[11,12]						
30 disparity of objects			■[7]			■[32]			
31 figure-ground segregation	■[4]		■[10]				■[26,28,29]		
32 pattern-processing, recognition		■[6]				■[33]			
33 shape-processing, recognition			■[7,11,12,13]			■[30,31,32]			
34 object-processing, recognition			■[13]			■[30,31,32]			
35 updating information in WM						■[35]			■[36]
36 storing information, rules in WM						■[35]			■[36]
37 selecting information in WM								■[36,37]	
38 planning motor output in WM								■[37]	

■	attribution is based on findings in neurocognitive science
●	attribution is derived from findings in cartographic and neurocognitive science
a	graphical variables (including extensions)
b	potential variables that guide attention and may be appropriate to encode ordinal data
c	attributes that guide the deployment of attention

Table 2. Relating potential attention-guiding variables to functions of visual brain areas that are involved in visual geographic information processing. References can be found in part two of the Bibliography. References are representative but not exhaustive.

The main criterion to tabulate attributes and to consider them as appropriate for the guidance of attention and encoding of information depends on their efficiency to provide enhanced neural responses in visual brain areas along the ‘where’ and ‘what’ processing pathways. Due to enhanced neural responses in visual areas along the ‘where’ path, diverse dimensions of motion are considered as potential variables to guide attention to relevant locations or regions. A variety of these motion attractors may also be appropriate to encode variations in geographic data. The assignment of brain areas to the variables resolution, crispness, transparency (correlated with blur), and saturation as well as to disparity of spatial depth, flicker, and motion are derived from neurocognitive research.

Based on a literature review, twenty-one visual attributes were identified that might be appropriate to guide visual attention and to code ordinal rankings. References that are indicated with a circle (●) come from studies in GI science that do not relate their results to functions of visual brain areas. References indicated with a square (■) result from neurocognitive research. For a list of superscripted references see part two of the bibliography or Swienty et al. (2007).

In a second category, seventeen specific functions of cortical areas that are involved in high-level tasks are tabulated. Attributed areas show high neural response when analysing visual information and play an important role in visual geographic information processing. These brain areas show selectivity for high-level tasks ranging from filtering to updating visual information. Although the primary visual cortex and the prefrontal cortex represent elementary processing areas in visual scanning (see section 3.4 and 3.7), corresponding functions in the list are not explicitly listed because of their complex distribution character. However, neurons in both primary visual cortex and prefrontal cortex are responsive whenever task-oriented visual scanning occurs (e.g. looking for task-dependent relevant geographic information). By considering functions of the major cortical areas along the ‘where‘ path, the ‘what‘ path and functions involved in the working memory, this table aims to provide a basis for investigating bottom-up driven tasks (detecting relevant information), top-down driven tasks (decoding relevant information), and interdependencies of these factors (why and how users locate and decode information) when processing geographic information. Figure 32 illustrates the general design methodology of attention-guiding geovisualisation that is oriented toward the biological mechanism of flexible receptive fields. The information is structured in three major visual layers:

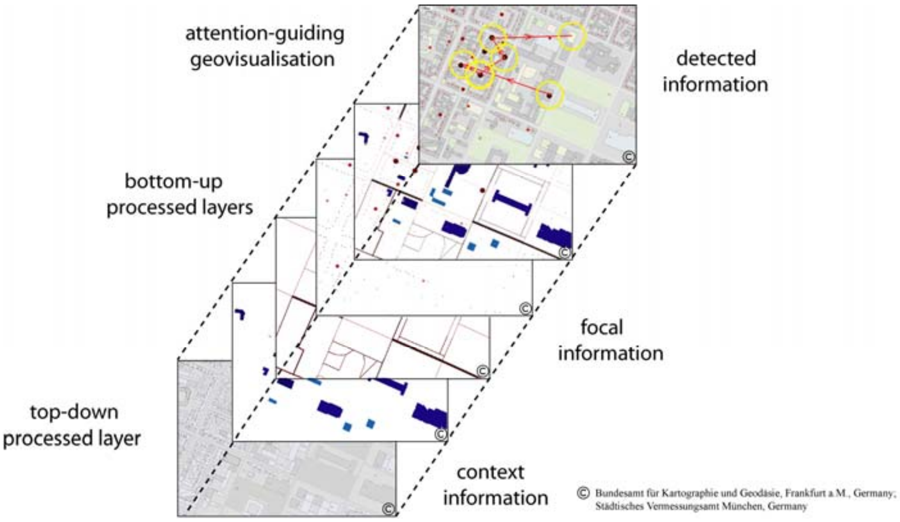


Figure 32. The design methodology of attention-guiding geovisualisation.

(1) *Top-down processed context information*. The spatial reference that offers the geographical context to relate the focal information to geographical dimensions is in the visual background.

(2) *Bottom-up processed focal information*. The relevance-based filtered information is in the visual foreground and is visualised with attention-guiding variables.

(3) *Detected attention-guiding information*. The relevance-based filtered information can be visually extracted from and related to the spatial context information.

To guide a user's gaze to the focal information, it is important that the background does not dominate the visualisation, because it could then act as a visual distractor by deviating gaze fixations from relevant information. Therefore, context information is coded in the least salient way. However, the adjustment of the degree of salience has to be adapted carefully in order to avoid the loss of more global geographic information (e.g. landmarks) required for the spatial reference and the successful orientation and navigation in the physical space.

Corresponding to the centre-surround mechanism, the context information in the visual background is processed in a global mode, while the relevant and focal information placed in the visual foreground is processed in a local mode (see section 3.2). Therefore, this interconnection of both context and focal information form the cognitively adequate design. Attention-guiding geovisualisation displays relevant information in a salient way without omitting important context information required for coarse spatial orientation. Consequently, attention-guiding geovisualisation allows users to direct their focus of attention to the relevance-based filtered information, which is visually detected only by the interplay of bottom-up processed focal information and top-down processed context information. The relevant focal information is coded with attention-guiding graphical variables that attract gaze fixations and allows users to decode relevance degrees.

4.3 Release of the cognitive workload and stimulating decision-making

Remembering MacEachren's (1995) suggestion that maps stimulate inferences of users by interacting with their prior beliefs, one can ask *How and why can attention-guiding geovisualisation stimulate inferences of users without exceeding the limited capacity of the cognitive workload ?*

The answer is *It stimulates decision-making and releases the cognitive workload by providing high neural responsiveness in brain areas involved in visual information processing, thus retains the maximum working memory capacity that is needed for knowledge acquisition and retrieval.*

Figure 33 illustrates the neurocognitive relationships of visual scanning and retraces the major information processing pathways engaged during visually scanning (see section 3.4 – 3.8). Obviously many different brain areas - each specialised in processing specific parts of a visual stimulus - are involved in visual information processing, which can be divided into three domains: sensory signals, signals processing and signals converting.

(1) *Sensory signals*. According to the attention-guiding design methodology, sensory signals are presented with graphical variables that are considered to be more or less appropriate to guide attention and to encode relevance classes of geographic information.

(2) *Signal processing*. This domain represents the main information processing pathways involved in visual scanning (see section 3.4 – 3.6). The P-pathway is sensitive to stimulus properties, while the M-pathway is sensitive to stimulus location. The retinal information is transferred to the primary visual cortex that acts as a distribution centre by sending signals to the dual visual network route. The 'where' path processes spatial properties of information and represents the determinant pathway for target-oriented visuomotor activities. The 'what' path processes high-resolution information and is involved in visual object identification and recognition. The functional segregation of these two pathways significantly reduces the complexity of geovisualisations by dissociating the recognition of information (what) from its location (where).

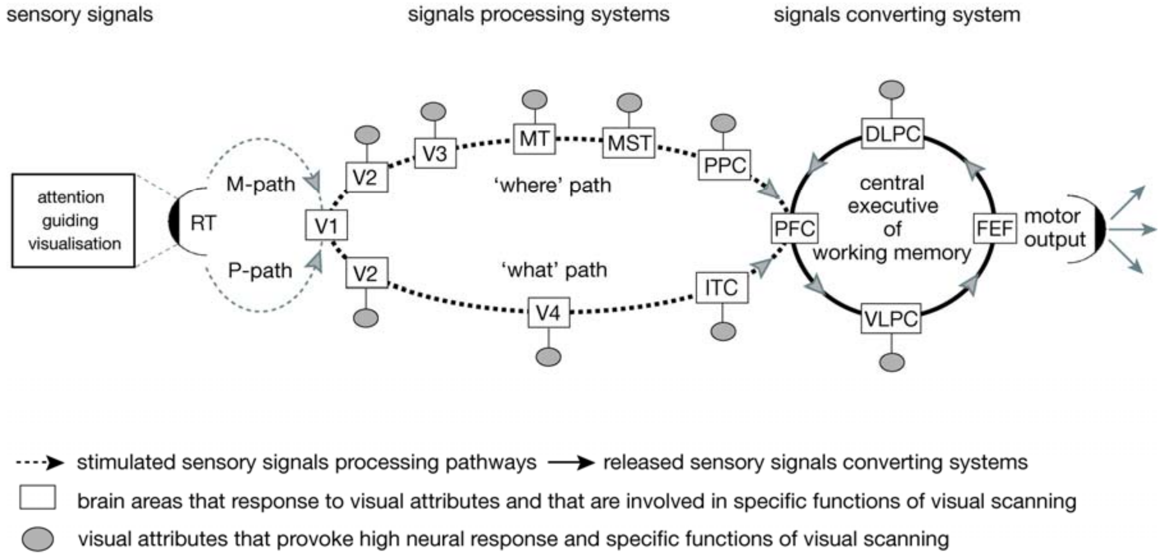


Figure 33. Attention-guiding visualisation stimulates decision making and releases the cognitive workload. Abbreviations: retina (RT), magnocellular path (M-path), parvocellular path (P-path), primary visual cortex (V1), visual cortices (V2, V3, V4), inferotemporal cortex (ITC), middle temporal area (MT), medial superior temporal area (MST), posterior parietal cortex (PPC), prefrontal cortex (PFC), dorsolateral prefrontal cortex (DLPC), ventrolateral prefrontal cortex (VLPC), frontal eye field (FEF).

(3) *Signal converting*. This domain represents the main information processing pathways involved in visual scanning (see section 3.7 and 3.8). In the sensory signals converting system, 'where' and 'what' information converges into the prefrontal cortex, which is activated whenever humans need sensory input to generate stimulus-driven motor output (e.g. directing gazes, clicking the mouse). For instance, the prefrontal cortex sends signals to the frontal eye field area for guiding gaze fixation to regions or locations of interest. This centre of visual analytics is crucially involved in the acquisition and flexible use of rules and routines that users need for successfully coping with varying demands of tasks (e.g. planning, problem solving and decision making). This transformation takes place in the working memory system that is supervised by the central executive. Because of the limited capacity of working memory, the central executive controls visual attention and supervises the cognitive workload, i.e. the amount and integration of 'what' and 'where' information. How well these functions work is very strongly dependent on the level of cognitive workload. An overstraining of its capacity reduces a user's capability to direct visual attention to important information in a stimulus-driven manner and to skilfully apply rules for selecting relevant information. A high workload makes it difficult and time consuming to complete a visual geographical task and associated learning processes.

For this reason the legibility of geovisualisation plays an important role. Especially professions that deal with 'overloaded' complex environments consisting of a large number of internal and external distractors (see section 3.2) would benefit from any effort of releasing cognitive workload (Chesneau 2006, 2007). The distractors take different forms. While explorative users in offices predominantly have to visually detect relevant information that is embedded in visual distractors on the display, attentional capacities of mobile users in urban areas are additionally challenged by environmental distractors and internal distractors such as time pressure and stress. Hence, in some environments it is more difficult to guide the user's attention to information on the display and to keep gazes on the relevant geographic information than in other usage contexts.

This research is based on the assumption that stimulating both sensory signal processing pathways supports the sensory signal converting system. Thus, precisely relating attention-guiding variables to relevant information in the design methodology enhances the visual scanning efficiency in term of reduction of the cognitive workload and faster and more accurate decision-making.

4.4 Investigation and standardisation of cognitive evaluation methods

Many evaluation methods have been conducted in GI science to access the quality of geovisualisation designs. They range from questionnaires through paper-and-pencil tests, keystrokes, eye movement recording to fMRI. However, due to missing cognitive theories and empirical evaluation methods, the test validity and reliability are underrepresented (see section 2.6). This problem has provoked a mismatch between technology-driven and user-centred research and hinders the progress of GI science research. Collaboration with cognitive psychologists offers the possibility to investigate their standardised evaluation methods elaborate them so as to establish corresponding scientific standards in GI science.

In contrast to the technology-driven evaluation of GIS products, the evaluation of the cognitive adequacy of a specific geographic information design has to bridge a larger gap between laboratory conditions and real use circumstances. For instance, visual stimuli in laboratory experiments are mostly isolated in time and space (Figure 34) while geovisualisations deals with spatiotemporal phenomena (Figure 35). In laboratories observers visually scan static displays, while mobile users watch a small mobile display, and collaborative users might tackle geographical problems in teamwork on wall-sized screens.

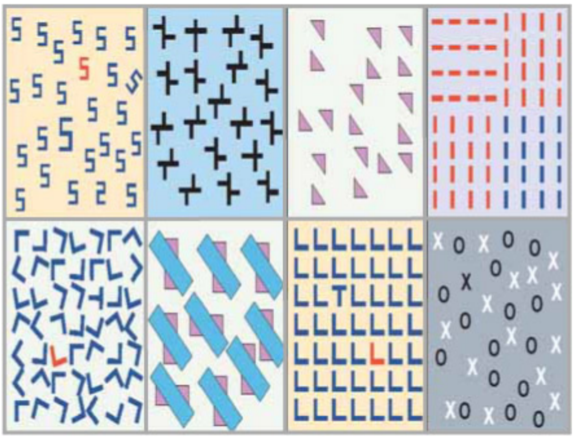


Figure 34. A set of visual search examples (modified from Wolfe & Horowitz 2004).

Moreover, during laboratory visual search tasks subjects visually scan for visual stimuli within a restrained visual field while users of geovisualisations process complex geographic information in their egocentric space that can be disturbed by numerous distractive stimuli (see section 2.2 and 3.2).

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Figure 35. Different usages of geovisualisation. Geographic information in a) ARC GIS 9.0, b) a PDA display, c) an ESAR scene.

Similarly, there are obvious differences in different circumstances of geovisualisation processing. Like laboratory observers, desktop users process information in rather static environments where distractors are predominantly embedded in the visualisation on the screen. Selective attention of mobile users is additionally affected by environmental (visual, tactile, auditory) non-targets (see section 3.2).

With respect to selective attention tasks, it is therefore beneficial to look into the empirical tradition of measuring and analysing valid visual scanning parameters in neurocognitive sciences. In turn, such collaboration offers cognitive scientists new insights into the characterisation of spatial information processing. Due to the differences between laboratory and field experiments, the main aspect of collaboration is to investigate standardised psychological cognitive evaluation methods to transfer fruitful knowledge into the domain of GI science. The overall goal is not only to get insight into the cognitive perspective of geographic information design but also to acquire knowledge from empirical test methods to adapt these standards to specific research questions of visual geographic information processing.

For evaluating geovisualisations, it is essential to define specific inclusion and exclusion criteria of performance. Without these methodological considerations, results may be misleading, falsified or non-transferable. For example, reduction of visual acuity, contrast sensitivity or colour hue discrimination as well as visual field defects can interfere with the performance in a visual task (Arditi & Zihl 2000). Therefore, subjects with impaired visual functions should be excluded by means of conventional routine measures. For instance, users who receive medication that reduces velocity and accuracy of saccadic eye movements, increases saccadic latency, or impairs visual scanning, can be excluded through e.g. simple interviews, colour blindness and visual acuity testing.

The common and widely used evaluation methods in GI science are questionnaires and the thinking-aloud method that requires users to articulate their behaviour during visual processing tasks. Despite some shortages, like the incompleteness of protocols due to synchronisation difficulties (subjects may slow down their activities for an easier verbalisation), the think-aloud method can reveal useful data for geographic processing tasks (Van Someren et al. 1994). Nevertheless, with regard to the information flow in the human working memory system (see section 3.7), the thinking-aloud method is inappropriate for evaluating human visual scanning strategies and capabilities while processing complex geovisualisations. The additional costs at the expense of the central executive‘s capacity caused by the supplementary use of the phonological loop may interfere with the user’s visual scanning performance and may falsify test results.

In this work, the design methodology undergoes a three-step evaluation. First, a pre-evaluation is conducted with a computational attention model. Second, based on these computerised outcomes, a second user-centred pre-evaluation in form of a paper-and-pencil test is performed to reveal differences between attentional capabilities of a computer and users. Third, the eye-movement recording method is used to evaluate the design methodology based on attention relevant parameters. The potentials of the eye movement recording method are described in section 2.6.

In the following, a computational attention model (Itti et al. 1998, Itti & Koch 2001) is presented as a potential pre-evaluation method, because it is able to roughly predict human visual scan paths. In contrast to attention models that contain both top-down and bottom-up mechanisms, this model is image-based (bottom-up guided), i.e. the focus of attention is solely directed by sensory input. Thus, the simulated user scans the visualisation in the order of decreasing saliency (Figure 36).

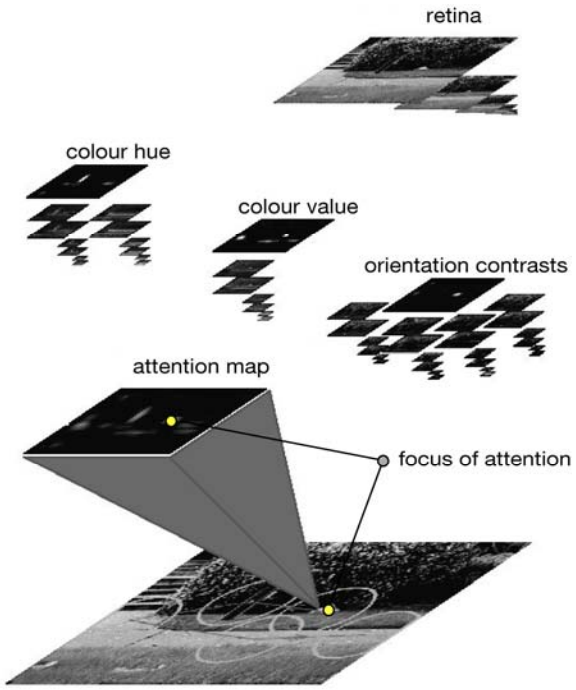

Figure 36. The computational attention model (modified from Itti et al. 1998).

This model follows the centre-surround mechanism (see 3.2), which is reflected in computed differences between fine and coarse scales allowing earlier detection of a salient stimulus than irrelevant information in more distant regions of the visual field. The model starts with computing early visual features by multi-scale feature extraction.

It implements the centre-surround mechanism and extracts three mainly pre-attentively processed features (colour, orientation, and intensity contrast) that are stored in three corresponding feature maps. Running the model in a Linux system allows the extraction of the additional features motion (right, left, up, and down) and flickering. The feature maps are then combined into three conspicuity maps. A saliency is derived from the three normalised and summed conspicuity maps. The maximal response within the saliency map indicates the most salient regions of the image. An inhibition of return mechanism hinders the visual system to return to a previously attended location. Therefore all previously scanned information will be assigned to the value zero. The next most salient locations are then successively selected. Finally, the focus of attention highlights salient regions on the attention map, thus generating the global maximum of the saliency map.

4.5 A knowledge base for the development of a contemporary taxonomy of graphical variables

As a result from the before mentioned section, GI scientists get the possibility to investigate potentials for developing and establishing an up-to-date taxonomy of graphical variables that takes account of three major challenging characteristics of nowadays geographic information design.

(1) The ever growing amount of geospatial data at various levels of detail.

(2) The diversified applications of geospatial data.
(ranging from data presentation to data exploration in multiple usage contexts)

(3) The continuously expanding range of display sizes.
(ranging from miniaturised displays to wall size displays)

The proposed cognitive design framework aims at developing a scientifically tested taxonomy of graphical variables to minimise the capability discrepancy between users and systems. The effort of establishing an up-to-date taxonomy of graphical variables does not necessarily have to result in ‘one fundamental’ taxonomy fitting for all applications. Instead, different taxonomies of graphical variables can be constructed for different usages. For instance, a taxonomy of graphical variables for data exploration on desktop displays should differ from a taxonomy for collaborative visualisation on wall size displays. Likewise, a taxonomy for mobile devices should consider different usage contexts and diverse visual environments.

To summarise, five major challenges of a framework for developing cognitively adequate geovisualisations were presented in this chapter. The proposed framework follows general recommendations of research agendas to consider (1) cognitive and usability issues, (2) interdisciplinary research, and (3) evaluation and standardisation as essential prerequisites to link a computer’s capability of geographic data processing to a user’s cognitive skill of visual geographic information processing. The gained insight will lead to an improvement of the usability (cognitively adequate visualisation) and the utility (separation of irrelevant from relevant information) of geographic information systems, thus, contribute to the overall acceptability of geographic information systems and appropriate visualisations that are needed for fast and accurate decision-making processes.

5. Application and computational pre-evaluation in pixel-based attention-guiding geovisualisations

The concept of attention-guiding geovisualisation can be applied to a variety of visualisations that depict geographic information (see section 2.2). This chapter describes the implementation of the concept in pixel-based remote sensing satellite images.

5.1 Remote sensing image information mining systems

Image Information Mining (IIM) systems are linked to large data bases that contain a large number of satellite images. Based on an interactive training, IIM systems allow users to define probabilities of pixels and to retrieve satellite images from the image data base (Schröder et al. 2000). By clicking on e.g. street pixels of a given satellite image, the user trains the system to systematically detect pixels with the same likelihood in the displayed image and in images that are stored in the data base. Figure 37 shows two examples of satellite images that a user retrieved from an IIM system by searching for streets. The most relevant information (streets) is depicted in red while three classes of less relevant information (e.g. forests and buildings) is coded by changing values ranging from dark grey to bright grey.

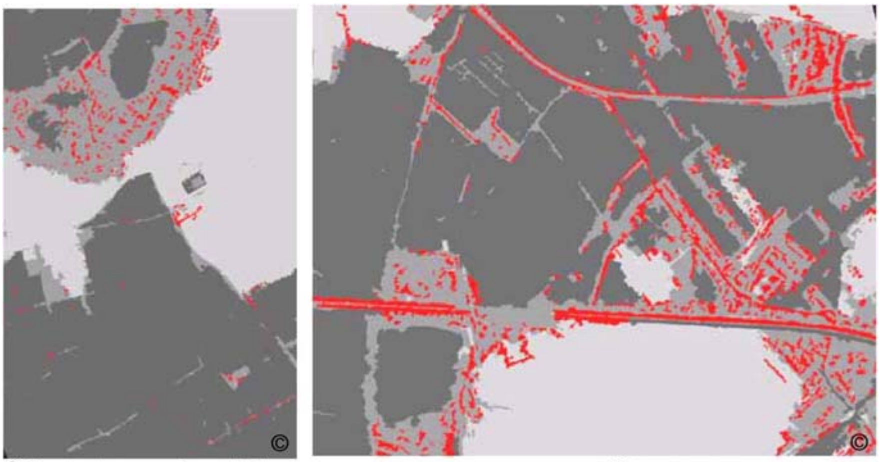

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Figure 37. Two examples of ESAR satellite images that were retrieved with an IIM system.

There is an increasing demand on IIM systems due to the rapid growth in the volume of remotely sensed imagery data. Using satellite images for land cover classification or managing ecosystems is no longer restricted to military or scientific experts. Missions like TerraSAR-X, coordinated by the German Aerospace Center (DLR), that are realised in public private partnerships allow the general public a spatiotemporal exploration of geographic phenomena on a very high level of detail of information.

In order to derive semantic information from images, researchers have made great efforts in developing semantic concepts for visual databases and providing various solutions for the retrieval of earth observation data (e.g. Burl et al. 1999, Bretschneider & Kao 2002, Aksoy et al. 2004). However, the technique of Content-Based Image Retrieval (CBIR) is characterised by the focus on the system's ability to retrieve semantic information rather than human ability to visually detect the location of relevant information. Assuming that CBIR *"... addresses the problem of finding images relevant to the users' information needs ..."* (Laaksonen et al. 2005,127) implies that users are searching for relevant information by visually scanning the display. The attention guiding design approach aims to support users in visually detecting relevant information and decoding the relevance values of retrieved information.

Due to the novelty of IIM and its experimental stage in research (Zhang et al. 2001, Li & Narayanan 2004), the attention-guiding design methodology is not bound to a specific remote sensing IIM prototype system. Rather it is positioned in both image mining frameworks presented by Zhang et al. (2001), i.e. the function-driven framework, and the information-driven framework. In the function-driven framework attention-guiding visualisation plays an important role as a component of the pre-processing system and image mining system, affording to explore image meaning and to detect relevant patterns. In the information-driven framework, the proposed methodology is an important element that aims to highlight the role of information at different levels of representation.

5.2 Relating attention-guiding attributes to pixel-based images

So far, the attention-guiding design framework has focused on variables and attributes that can be visualised by points, lines and polygons as elements of a vector model. In contrast, satellite imagery deals with pixels as elements of a raster model. Consequently, some of the variables are not applicable due to the intrinsic characteristics of the raster model.

To derive the applicability of visual attention-guiding attributes, Figure 38 illustrates the possible use of attention-guiding variables in image processing techniques.

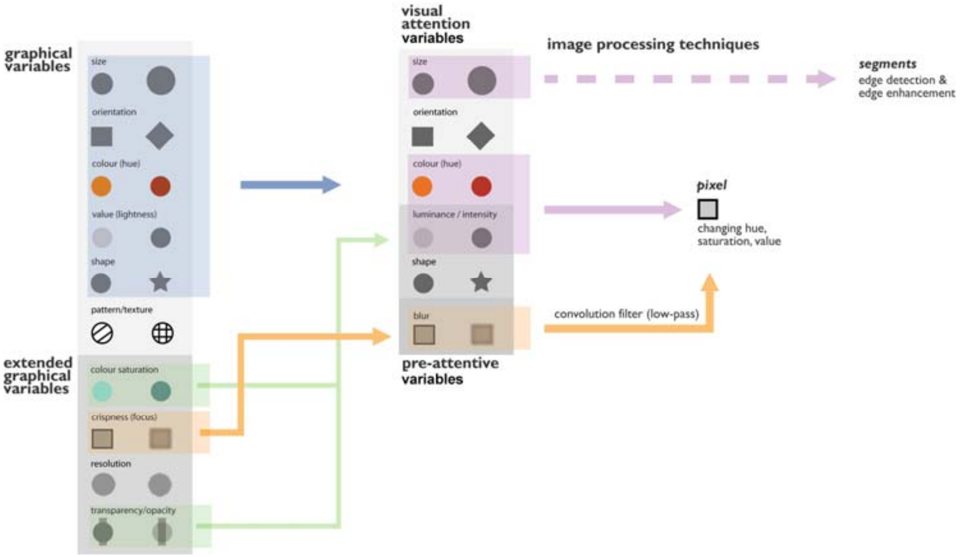


Figure 38. Applying attention-guiding variables to pixel-based images.

The variables 'orientation' and 'shape' do not make sense in this raster model. The attribute 'size' might be useful to highlight relevant objects in segment-based IIM systems. Thick edges make information to stand out against the thin edges of irrelevant information via figure-ground segregation. The variable blur is implemented to regulate the clarity of objects by using low-pass convolution filters. Objects that are in focus and sharp are extracted faster than smooth or blurred ones and the relevance order can be easily decoded (Kosara et al. 2002). The variables colour hue and luminance / intensity are used to configure the saliency of objects by regulating hue, saturation, and intensity values of pixels.

5.3 Implementation

The implementation of the proposed visualisation methods is demonstrated with two image information mining scenarios. The scenarios are based on an ESAR (German Aerospace Center

– X-SAR Sensor) scene from Mannheim, Germany. The pixel ground size is two meters. An unsupervised k-means clustering of the SAR scene is performed that leads to four spectral clusters C1…C4, described by the assignment of image pixels to clusters I→C.

Based on these clusters, an interactive (supervised) training is performed to estimate the conditional probabilities $p(L \mid C_i)$, and $p(\neg L \mid C_i)$ which define the probability for the label L given cluster C_i. Here, L defines the label, which the user wants to detect in the image and ¬L the alternative hypothesis, e.g. label L is street if the user wants to find streets and ¬L means “not street”. This is a restriction, as no other labels are allowed, which the user could detect. By giving positive or negative examples of the desired label L, the likelihood function can be estimated, which, according to the Bayes Theorem, is proportional to the a posteriori function $p(L \mid C_i)$ (Datcu et al. 1998, Datcu & Seidel 2005).

Table 3 shows the values for two simulated scenarios of image information mining. For all clusters, example values for the a posteriori function $p(L \mid C_i)$ are tabulated. Here, the classes street and forest are defined as label L, because the user wants to detect streets and forests in the image database. In practical applications, the a posteriori probabilities are estimated by giving positive or negative examples of the desired label as for example seen in the values 0.9 for cluster 1 and 0.2 for cluster 4.

class	$p(Street \mid Ci)$	$p(\neg Street \mid Ci)$	$p(Forest \mid Ci)$	$p(\neg Forest \mid Ci)$
cluster 1	0.9	0.1	0.2	0.8
cluster 2	0.6	0.4	0.4	0.6
cluster 3	0.4	0.6	0.9	0.1
cluster 4	0.2	0.8	0.6	0.4

Table 3. Simulated information mining example. A *posteriori* probabilities for streets and forests.

The attention-guiding method is implemented given the original image I, the clusters C, and the *a posteriori* probabilities $p(L \mid C_i)$. Attention-guiding variabels of interest are colour saturation, value, blur, and combinations of these. The variable blur is applied by using smoothing techniques. As suggested by MacEachren (1995), the variable ‘colour hue’ could be suitable to visualise ordered data, if colours form a sequence on the colour circle like from yellow over orange to red.

Colour. To design colour examples, the variable colour is assigned to probability values by using a colour lookup table (Table 4). The above mentioned probabilities are now classified into four relevance classes of variables.

Each class is coded by colour, i.e. relevance degrees are visualised through the regulation of colour hue (H), saturation (S), and value (V). The first row shows the parameters of the above mentioned common visualisation in IIM systems (see Figure 37). The following five examples tabulate variations of the hue, example 7 reflects the change of saturation values, and example 8 corresponds to the variation of value.

0<p≤0.3	**0.3<p≤0.5**	**0.5<p≤0.7**	**p>0.7**
(1) common visualisation			
(0-0-10)	(0-0-30)	(0-0-70)	(3-100-100)
(2) yellow-orange-red			
(17-100-100)	(12-100-100)	(6-100-100)	(3-100-100)
(3) orange-red-violet			
(12- 100-100)	(6-100-100)	(3-100-100)	(95-100-100)
(4) light blue-dark-blue-violet			
(50-100-100)	(60-100-100)	(67-100-100)	(75- 100-100)
(5) yellow-light green-dark green			
(17-100-100)	(24-100-100)	(31-100-100)	(39-100-100)
(6) light blue-mid blue-dark blue			
(50-100-100)	(55-100-100)	(60-100-100)	(65-100-100)
(7) saturation			
(3-30-100)	(3-50-100)	(3-75-100)	(3-100-100)
(8) brightness			
(0-0-20)	(0-0-40)	(0-0-60)	(0-0-80)

Table 4. Relevance classes and their recommended colour use (HSV).

Smoothing. In general, image smoothing is the convolution of a filter matrix F of size k with the original image I and usually involves a loss of information. Parameter k defines the magnitude of smoothing as a linear function depending on the a posteriori probabilities $k = a + b * p$, i.e. the original image I will be smoothed pixel-by-pixel with a varying mean filter depending on the a posteriori probability p. The linear equation implies that in pixels with low probability p the original image I will be more strongly smoothed. Due to a user's capacity of visually processing fine filter size differences, an indexing of filter sizes is applied that is oriented on the degrees of colour coding (Table 3), which corresponds to linear parameters $a=1.04e02$ and $b=-1.22e02$ from the above mentioned equation.

	0<p≤0.3	0.3<p≤0.5	0.5<p≤0.7	p>0.7
k	90	50	30	3

Table 5. Relevance classes and their recommended filter sizes *k*.

Combinations. The combination of colour and smoothing is suggested to unify the advantages of both methods. The visualisation of colour is superimposed with the smoothed original image. Eight overlays of colourisations are generated on the smoothed original image with transparencies of $t=0.33$ and $t=0.66$ each corresponding to a class. In general, the case of a visualisation V, which includes the transformation of the original image I by a function g (e.g.

smoothing) and the visualisation of probabilities by a function f (e.g. colouring) could be stated as follows

$$V = [1 - t(p)] \cdot g(I, p) + t(p) \cdot f(C, p)$$

This equation includes also a functional relationship between the probability p and the transparency t, i.e. the transparency changes with the probabilities. Applying such a function would show more details of the less smoothed original image in pixels with higher probabilities. Accordingly, the salience of colour coding would decrease with the reducing propability.

5.4 Computational pre-evaluation with the attention-model

The design methodology is pre-evaluated with the computational attention-model that only predicts possible scan paths in a bottom-up mode based on the centre-surround mechanism of receptive fields (see section 4.4). In this work this computerised evaluation is considered as a pre-evaluation due to the focus on investigating the user's visual information processing capability. The model has been successfully validated against experimental evidence for visual search tasks (e.g. Treisman & Gelade 1980) and has served as a promising pre-evaluation method for eye-tracking studies (e.g. Fabrikant & Goldsberry 2005, Swienty et al. 2006, 2007a; Fabrikant et al. 2006).

Figure 39-41 depict outcomes from the attention-model. The salient locations that might attract a user's gazes are indicated. The yellow circles represent single eye fixations and the black and red arrows code sequences and directions of predicted scan paths. The light areas in the three conspicuity maps at the bottom indicate salient image locations related to hue, intensity, and orientation contrasts. The most salient image locations of the image are indicated by the blue areas in the attention map.
Figure 39a illustrates the configuration with the variable 'colour hue'. The most relevant information (streets) appears in dark blue and was correctly located by the model except for the second fixation in the upper left corner of the image where colour hue and intensity deviated the gaze from the target. The street that horizontally crosses the image is located by the system within the first four fixations due to highly salient image locations of hue, intensity, and orientation contrast.

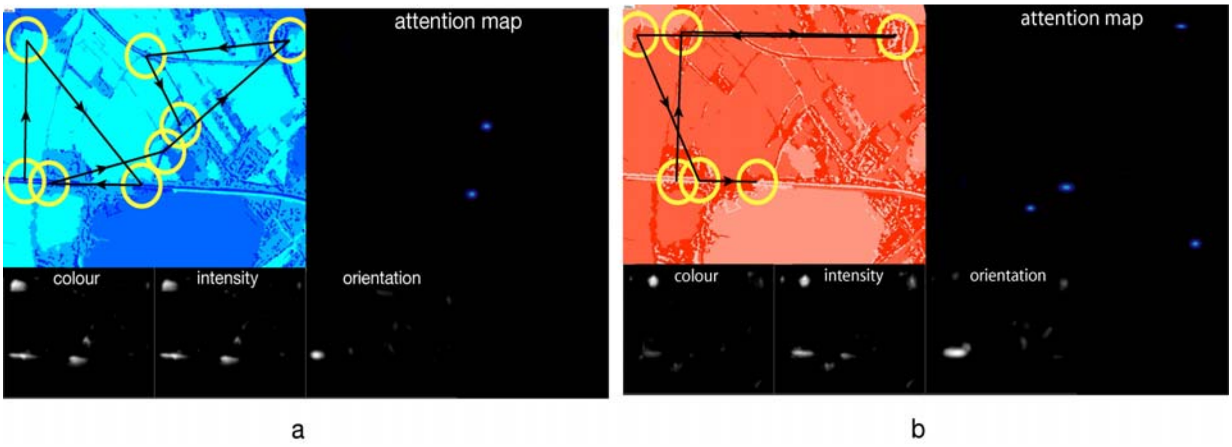


Figure 39. Satellite images configured with a) the variable 'colour hue' and b) the variable 'saturation'.

Figure 39b shows salient regions in the satellite image that are coded with the variable 'saturation'. Here, the information of interest (forest) appears in dark red and is fixated with the second and fourth eye fixation in the upper left corner due to high colour and intensity contrasts and the third fixation in the lower left corner due to high intensity and orientation contrast.

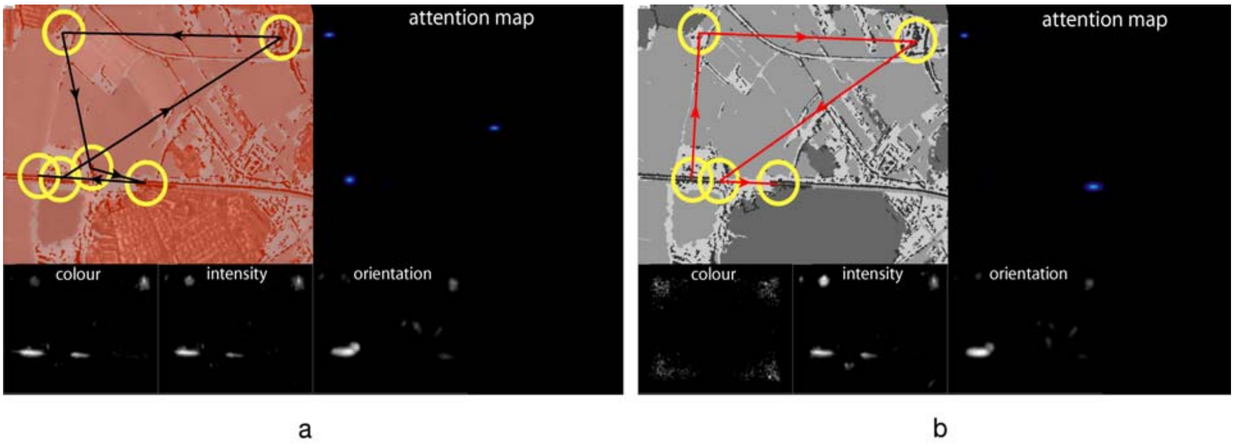


Figure 40. Satellite images configured with a) a combination of ‘colour intensity’ and ‘blur’, and b) with ‘colour value’.

The combined variables colour value and blur (constant transparency) were tested in Figure 40a. Due to high salient image locations of colour, intensity, and orientation the location of interest (streets) is rapidly detected. Salient regions in the upper left and right corner then deviate the gaze from the target. Finally, the last three fixations scan the street in short sequences. Figure 40b depicts the locations detected in the image where the relevant information is visualised with the variable ‘colour value’. The first fixation is guided to the relevant information (streets) due to high intensity and orientation contrast. The second scan path is deviated to the upper left and upper right corner attracted by high intensity contrasts. Finally, the scan path returns to the starting point.

The last two figures depict the fixations and scan paths during scanning for streets that are saliently visualised by the combination of transparency and blur (Figure 41a) and blur (Figure 41b). Only one location was correctly detected in Figure 41a. Gazes in Figure 41b completely fail to detect streets in the image.

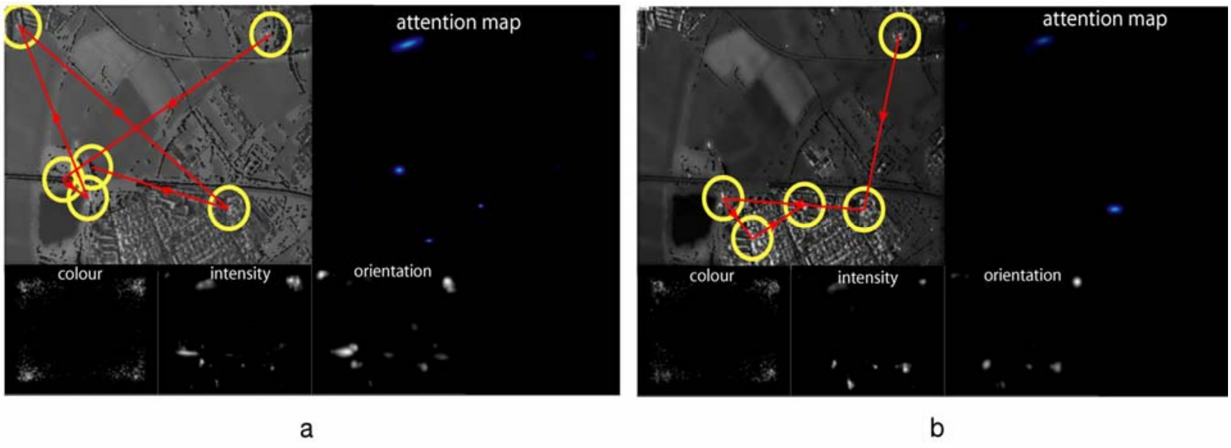


Figure 41. Satellite images configured with a) the combined variables ‘transparency’ and ‘blur’, and b) ‘blur’.

5.5 Discussions

A pre-evaluation of predicted scan paths of users in satellite images proves necessary and meaningful. Visualisations that were configured with the variables colour hue, colour saturation, colour value, and the combination of colour saturation and blur might be appropriate to support users in detecting structures depending on the adjacent cluster visualisation.

In Figure 39a,b and 40b the relevant information was detected due to high contrasts in colour hue, intensity, and orientation to neighbouring clusters in the image. For example dark red forests are rapidly detected by the system because of the co-location of bright red streets. Thus, changing hue, saturation, and colour values of pixels may be a useful technique to support the visual detection of salient information. The variable blur (Figure 41a,b) is not favourable for directing gazes to relevant information because both maps contain too many distractive salient locations with high intensity and orientation contrasts.
However, as shown in Figure 39a,b and 40a,b the pixel-based visualisation of relevant information is suitable only to a limited extent. While areas can easily be located, linear structures like streets are often interrupted by distractive information. Due to the bottom-up processing it is certainly quite difficult for the model to consider these interrupted structures as a whole street. Hence, in pixel-based IIM systems attention-guiding visualisation has limited capabilities for highlighting relevant linear information. On the other hand, it is an appropriate technique to make areal structures stand out and to rank the relevancies.

Aspects of sensors and IIM methods. The attention-guiding methodology can be considered as universal and independent of the sensor type, the viewing geometry, and the spectral and spatial resolution. However, results from active sensors like SAR may differ because they are noisy due to the speckle effect. Thus, isolated, very bright pixels that result from the speckle effect could act as distractors. Speckle denoising may reduce the distractive influence of these pixels. Besides, to get correct a posteriori probabilities and perfect clustering (i.e. all spectral clusters are directly related to information classes), it could be necessary to additionally pay attention to the visualisation of inaccurate probabilities and false clustering. Visualisation methods should avoid the suppressing of information in regions with low probabilities, since this information could be needed for the correct estimation of the a posteriori probabilities. Therefore, methods like masking or strong smoothing are rather inapplicable.

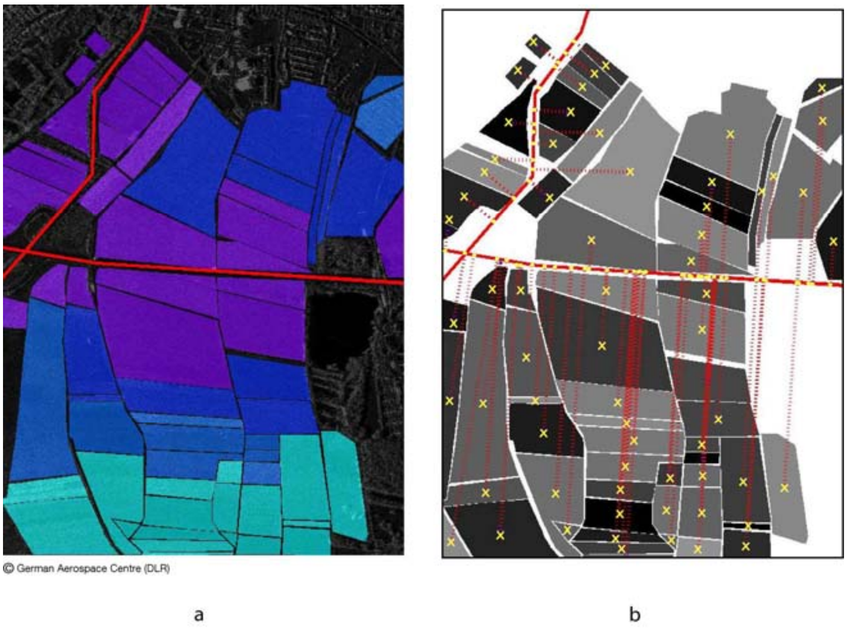


Figure 42. A possible attention-guiding visualisation in a) a segment-based IIM system and b) with graphics.

Aspects of segments and graphics. Here, solely the raster model with its intrinsic characteristics has served to test the design methodology. As discussed above, linear structures can be interrupted by distractive information or can provoke a failure of detection. This problem can be solved by implementing vector graphics in the design. As shown in Figure 42a, it is obvious that the design methodology is more effective in segment-based systems. Since segments provide homogeneity, segment-based images visualise less distractive stimuli and relevance values may be easily decoded by the user.

Furthermore, the variable size can be effectively implemented in segment-based systems. Differences in the width of segment contours might be appropriate to code the relevance values. Further it is recommendable to add vector graphics to the design for visualising spatial relations of geospatial objects. For example, if a user searches for fields located at intervals of x meters to a certain type of street, these spatial relations could be better visualised with vector graphics. Figure 42b shows a first approach that was realised in a prototype system at the German Aerospace Centre (DLR).

Aspects of top-down and dynamic attribute testing. The presented findings represent a first step towards supporting users in visual satellite image processing, because the selected attention variables exclusively serve to dissociate the location of relevant information from the context information. Additional studies that investigate the human gaze path of decoding semantic information from satellite images will provide further evidences to optimise information processing via the ‘what’ pathway.

6. Application and computational pre-evaluation in vectorised attention-guiding geovisualisation

As a well-known fact in cartography, it is quite problematic to display large number of geospatial objects simultaneously. The paper map approach of ‘one size fits all’ can lead to overcrowded visualisations that hinder the effective visual scanning. This chapter describes the implementation of the attention-guiding concept in a vector-based map.

6.1 Implementation of the attention-guiding design methodology in ArcGIS

To pre-evaluate the attention-guiding design methodology, the design principles are tested with geospatial objects stored in an ArcGIS database. Table 6 summarised the attention-guiding variables offered by ArcGIS 9.0 for visualising ordered data. The table additionally shows which variables are applicable to points, lines, and polygons. The variables that are not suitable for ordered data are omitted in the table. The variables such as transparency and focus are not considered either because they are not available in ArcGIS 9,0. The variable colour and its components ‘hue’, ‘saturation’, and ‘value’ are directly applicable to the HSV colour model implemented in ArcGIS. The variable size is either the point size or the width of a line or polygon outline.

variable	ordered	point	line	polygon
colour hue	to be confirmed	+	+	+(fill/outline)
colour saturation	to be confirmed	+	+	+
colour value	confirmed	+	+	+
size	confirmed	+	+ (width)	+(outline width)

Table 6. Ordered graphical variables implemented in ArcGIS 9.0.

6.2 Test cases

The general procedure of the attention-guiding design is composed of three steps.

(1) The relevance of information is assessed based on a user query.

(2) Relevant geospatial objects are selected.

(3) The selected objects are visualised in a salient way depending on their relevance values.

The relevance values are encoded as attributes of the geospatial objects. In analogy to the ‘relevance feedback’ of information retrieval systems, the visualisation represents a visual relevance feedback on the level of the geospatial objects. Figure 43 illustrates three comparative cases for the evaluation of the attention-guiding methodology.

Case 1: Unfiltered but cognitively adequate.

Case 2: Filtered but cognitively inadequate.

Case 3: Filtered and cognitively adequate.

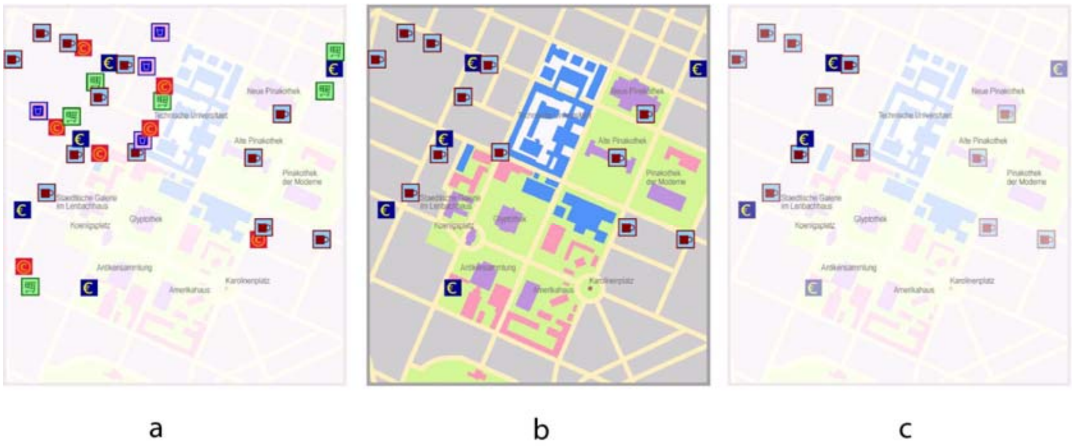


Figure 43. a) unfiltered but cognitively adequate, b) filtered but cognitively inadequate, and c) filtered and cognitively adequate.

In case 1 user's cognitive capacity has been considered but the foreground information does not show a distinction of relevance. In case 2 the relative relevance of foreground information has been considered but user's cognitive capacity is disregarded. Case 3 is the result of the attention-guiding methodology. Figure 44 shows the results of the attention model of geovisualisations that were configured with Scalable Vector Graphics (SVG) (Reichenbacher & Swienty 2007). The focal information on the bottom-up processed layer is saliently visualised and predicted gaze fixations are guided to the locations of relevant information due to high contrasts of colour hue, intensity and orientation. Gaze fixations are not deviated by distractive, irrelevant stimuli.

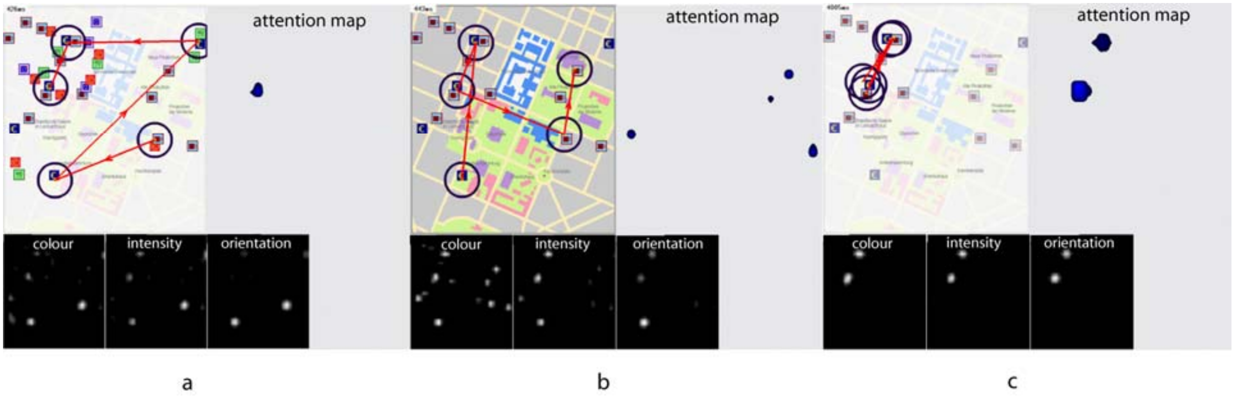


Figure 44. Predicted scan paths and fixation locations in a) case 1 b) case 2, and c) case 3.

6.3 Computational pre-evaluation with the attention model

In the following, the attention-guiding design is evaluated in a visualisation that depicts highly complex urban geographic information. The design methodology includes filtered and relevance-graded points, lines and polygons. Figure 45-49 illustrate the implementation of the proposed design principles as well as the output of the attention model. The visualisations are configured in ArcGis 9.0 and automatically adapted with a VBA Script. The four relevance classes are automatically ranked and visualised in a salient way while the irrelevant information in the background is simultaneously alleviated because of lower saturation and value reduction.

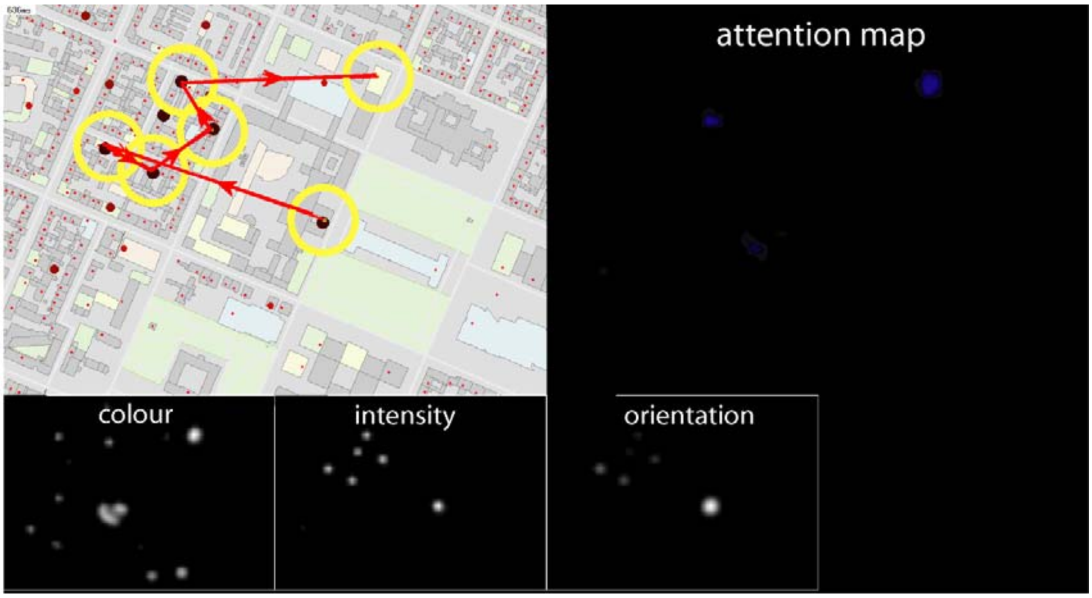


Figure 45. Model output for the combined variables 'value' and 'size' for point symbols.

Figure 45 illustrates the model outcome after applying the combined variables value and size to point symbols. The first five fixations moved to the most relevant information due to high intensity contrast. The last gaze path is then deviated from the target because the focus of attention is misguided by the polygon in the upper right corner of the map. This is due to the high colour contrasts of the polygon with its vicinity surrounding.

Figure 46 depicts the same relevant information. This time the model outcome shows the result of encoding the relevance of point symbols with the combined variables saturation and size. Again, the first five fixations moved to the most relevant information due to high saturation contrast. Even though the polygon in the upper right corner consists of unmodified colour hue, this time the gazes are not deviated from the relevant objects.

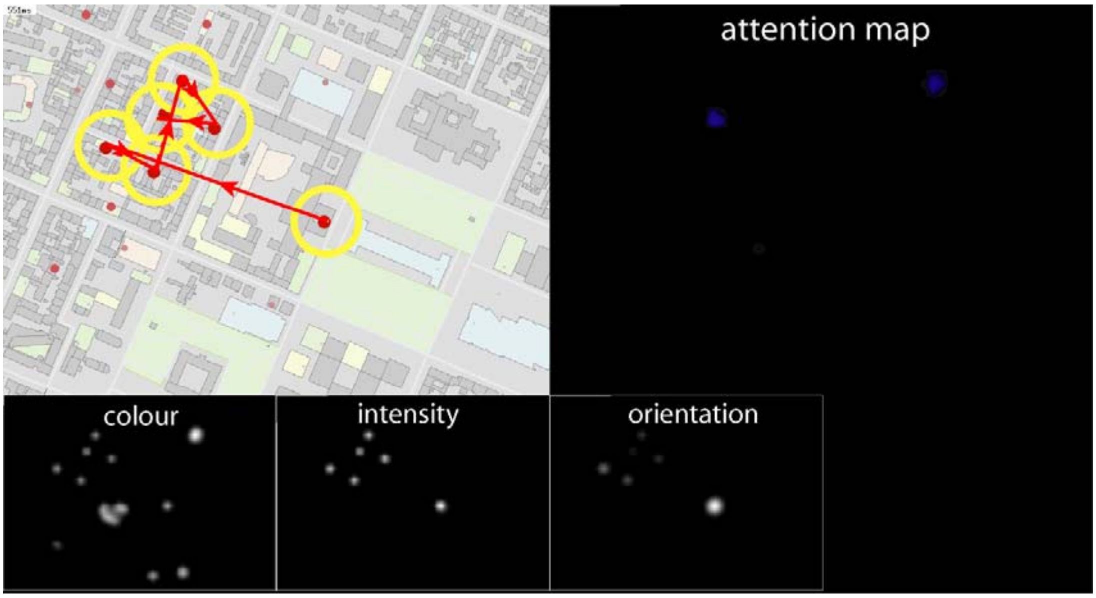


Figure 46. Model output for the combined variables 'saturation' and 'size' for point symbols.

Figure 47 shows the output of the attention model for the visualisation of relevant linear objects. Here, the information of interest is encoded with the variable colour value. The gazes are directly moved to the estimated target due to high contrast of intensity and orientation.

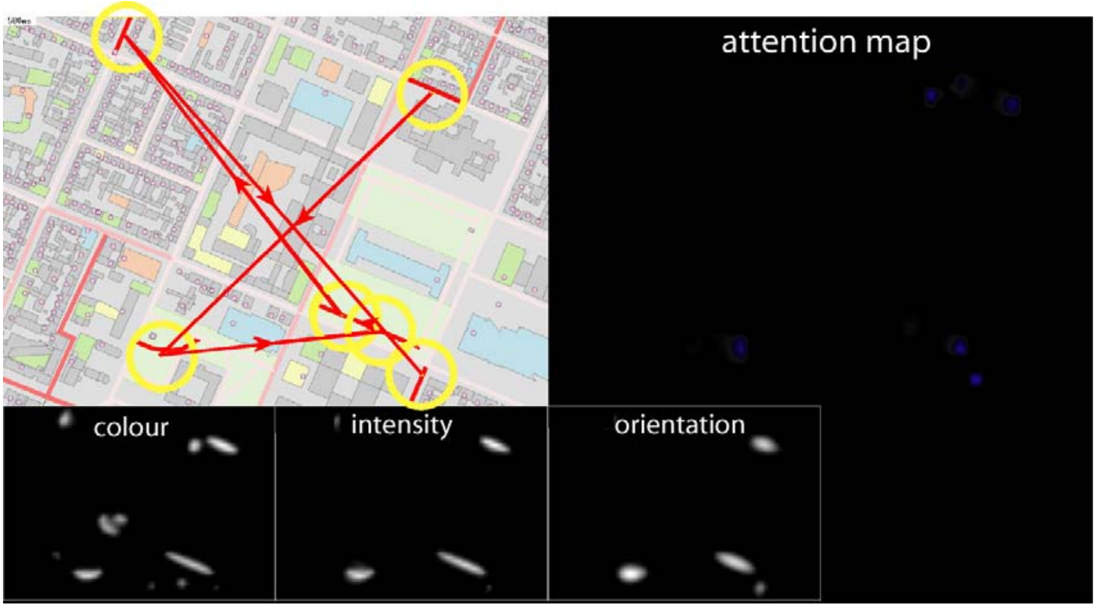


Figure 47. Model output for the variable ‘colour intensity’.

Figure 48 illustrates salient polygons where the relevance is encoded with the variable colour value. The first five gaze paths moved to the relevant objects due to high contrast in colour hue, value, and orientation in the map. It must be noted that the attention of the first, second, and fifth fixation are attracted by high orientation contrast of large-area polygons. Moreover, the last gaze path moved to the building in the lower left corner of the image because of high intensity contrast. The model due to insufficient sensory stimulation ignored two polygons of the first relevance class.

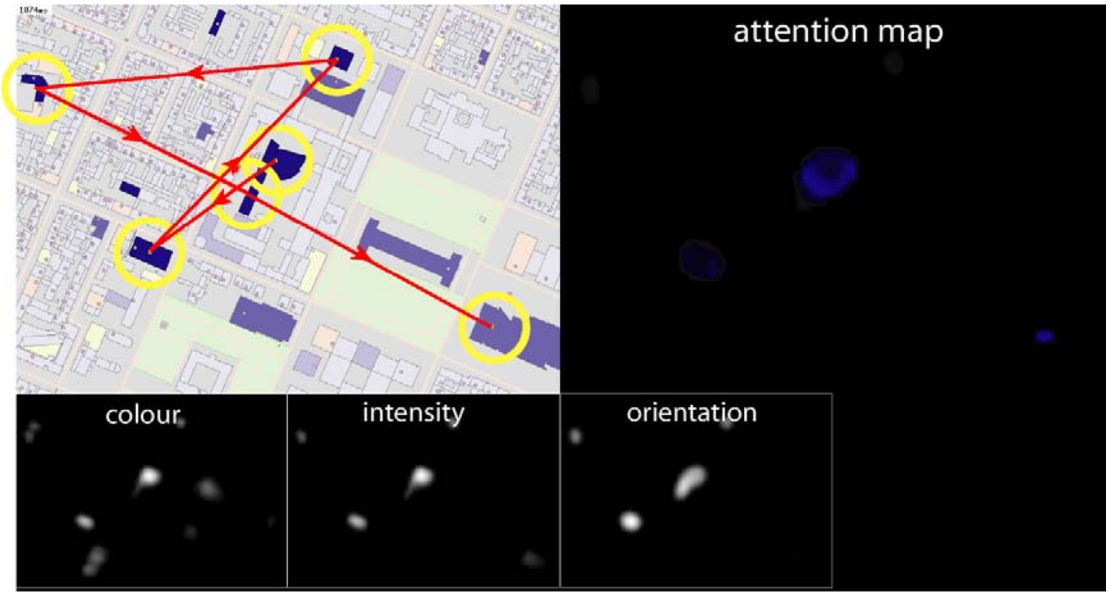


Figure 48. Model output for the variable ‘colour value’ for polygons.

Finally, Figure 49 depicts salient buildings where the relevance is expressed with the variable size for polygon contours. The first three foci of interest are successfully encoded. Then, the gaze is deviated by the polygon in the lower right corner. This building consists of high colour contrast and has a distractive effect on the gaze path. While the fifth fixation is attracted by high colour and intensity contrast, the sixth fixation is only attracted due to orientation contrast. Like in the previous example, the last gaze path moves to irrelevant information because of high colour intensity that is at the same time the most salient area in the map. The model ignores two polygons that are regarded as highly relevant information.

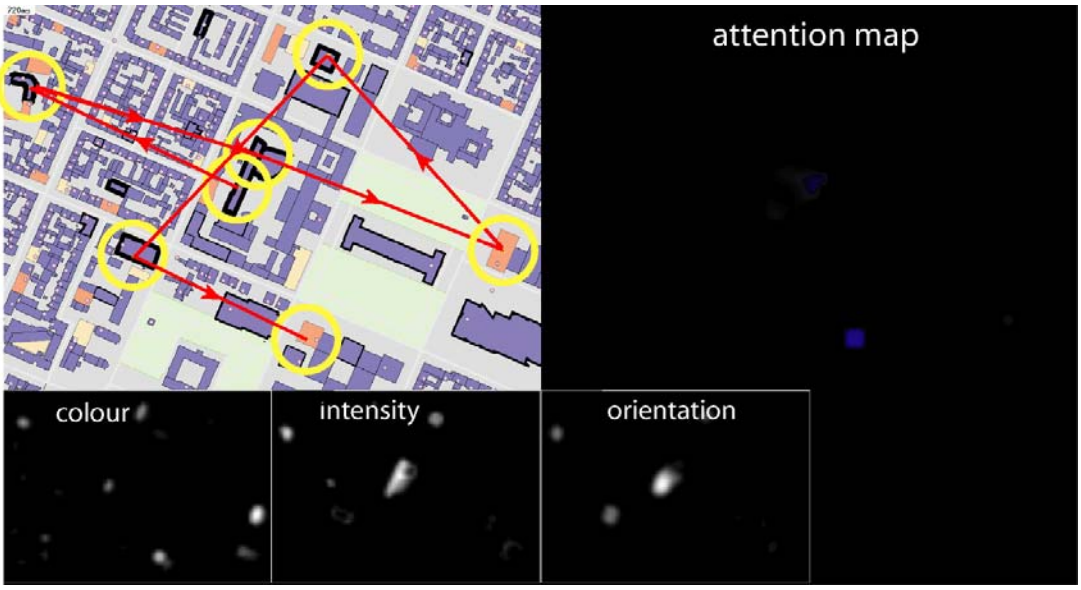


Figure 49. Model output for the variable 'size' for contours.

6.4 Conclusions

Visualising point symbols with the combination of the variables value-size and saturation-size is favourable for visually scanning locations of relevant information in the map. However, their application should be carefully handled in visually complex environments. Implementing these techniques requires the suppression of the colour hue regulation of the surrounded context information and the variable size should be precisely adjusted depending on the size of the adjacent objects. The oversize of relevant point symbols could implicate a loss of information because they might overlap with second-rate relevant objects.

The change of colour hues for reference objects must also be adapted with care to avoid the loss of geospatial information that is required for the successful navigation. The attributes 'colour value' and 'size' work well to locate relevant linear information. While both attributes are favourable to reinforce the orientation contrast, the variable size has a limited capability to encode several classes of relevance due to shortage of space. Implementing the attribute colour value to visualise more than two or three classes is advantageous.

Furthermore, due to limited space there is little scope left in varying line properties (size, colour) when using contoured symbols. As shown in Figure 46 and 48, the variables value and size are suitable to depict relevance-graded areal information. Both examples manifest that it is easier for the attention model to detect the location of big buildings than smaller ones due to the reinforced orientation contrast. Moreover, as shown in Figure 48 and 49, it is again crucial to carefully regulate the colour hue of irrelevant objects in order to avoid unnecessary gaze deviations.

Since colour hue, value, and saturation might cause conflicts with the background layer, the variable size should be combined in most cases with one of them. A solution to the possibly arising overlap problem might be the employment of displacement operators known from generalisation. It has to be stressed again that the significance of this evaluation results is restricted to the saliency of visual stimuli, i.e. where salient feature in the visualisation might attract the attention.

7. Evaluation with a paper-and-pencil test

Results have indicated that the attention-guiding methodology might be a potential method to support users in guiding their scan paths to relevant information. This chapter is devoted to a paper-and-pencil test developed in collaboration with psychologists of the Max-Planck Institute of Psychiatry in Munich to evaluate the attention-guiding design approach with users.

7.1 Research questions

Based on the hypotheses that (1) geovisualisations represent a complexity of external visual stimuli in terms of graphical variables that are internally combined to geographic information and (2) geovisualisations stimulate inferences of users by activating internal brain functions along visual information processing pathways, the attention-guiding design methodology tends to reduce the information complexity as well as to release user's capacity limitation of visual scanning.

The following attention-guiding variables are related to functions of visual brain areas that are involved in visually scanning attention-guiding geovisualisation (Table 7).

variables	**brain areas**				
	V2	V3	V4	MT	ITC
colour hue	●	●	●		
colour value	●	●	●		
colour saturation	●	●	●		
contour	●	●	●		
size	●	●	●		
contrast		●			
achromatic contrast	●	●		●	
form	●		●		●

Table 7. Evaluated variables and corresponding visual processing areas.

Since the design methodology aims to provoke figure-ground segregation (by decreasing the saliency of the context information and increasing the saliency of the focal information), different brain areas respond to the variables discussed in chapter 6 using their different functions of processing contrasting stimuli. Finally, the attention-guiding variable ‘form’ is also considered to be visually processed during the evaluation. The relevant information is coded as point symbols in the complex visualisation context. Due to their uniqueness and their attention-guiding properties, these point symbols pop out from the top-down processed context layer because they differ in their degree of saliency and their form properties.

specific functions	**brain areas**				
	V2	V3	V4	MT	ITC
figure-ground segregation	●		●		●
pattern processing		●			●
representing salient objects			●		●
tuning contour features			●		
orientation of angles, curves			●		
disparity of objects		●			●
shape processing			●		●
object processing			●		●
updating information in working memory					●
storing information					●

Table 8. Specific functions of brain areas that process attention-guiding variables.

Although the large number of motion variables and corresponding visual processing areas (ranging from velocity to semantic pattern motion) indicates that motion is highly appropriate to guide a user's attention (see Table 2) and probably suitable to code relevance classes, these variables are not evaluated in this work which focuses on static variables. The importance of stimulating involved areas is reflected in their specific functions of visual scanning. Table 8 relates stimulated areas to their visual scanning functions.

The following research questions are essential to validate the attention-guiding design approach.

(1) *Which design methodology allows users to promptly locate the most relevant information ?*

(2) *Do these design methodologies have an impact on the task difficulty ?*

(3) *Which potential attention-guiding variables are more appropriate than others to guide a user's scan paths to relevant information ?*

(4) *How do these variables vary in their property to guide attention in different complex geovisualisations ?*

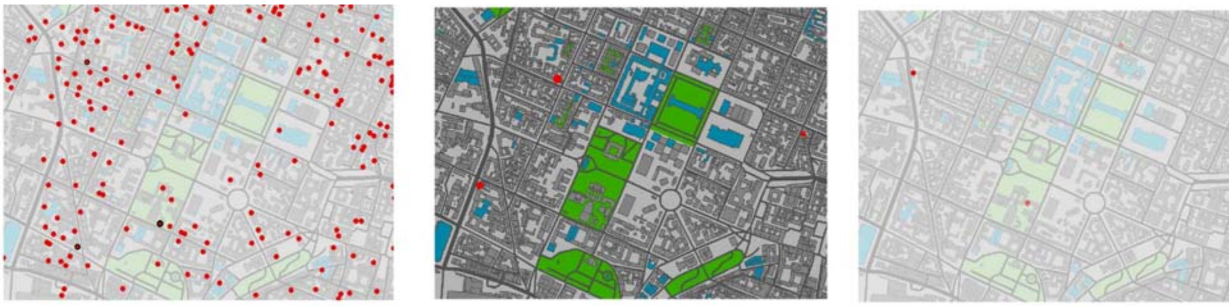
(5) *Do users agree in the ranking of specific variables depending on the design methodology ?*

(6) *Which variable is more appropriate to guide attention when it is directly compared to another variable ?*

7.2 Test methods

A two-part paper-and-pencil test was developed to evaluate the attention-guiding methodology. Figure 50 illustrates the chronology of part one. The paper-and-pencil test consists of fifteen randomised maps. Each map is indicated by an implemented variable and the design case.

For instance, the first three maps in the first row 'contour 1', 'size 2' and 'saturation 3' mean that they respectively implement the variable 'contour' in case 1 (filtered but cognitively inadequate), 'size' in case 2 (filtered but cognitively inadequate), and 'saturation' in case 3 (filtered and cognitively adequate, i.e. attention-guiding design). The relevant information is coded by simple dot symbols to avoid any decoding of the symbol's semantic content (e.g. house numbers) that would interfere with the task of evaluating the attention-guiding potential of proposed variables. The semantic content of visual information is considered as a probable- non attribute (see section 3.9). In other words, to code the relevant information with a lower degree of abstraction may hinder the evaluation of the capability of promptly locating the most relevant information. In accordance with the working memory model (see section 3.7) the basic focus is on releasing the visuospatial sketchpad that stores visual and spatial information by activating visual areas involved in processing the location of visual information, i.e. 'where' pathway. To code the relevant information with a lower degree of abstraction could increase the number of the working memory's backtracking processes that support users to keep the spatial position of the relevant information in mind.
However, this test inevitably involves a low degree of top-down processing. To process relevance classes of information, the visual information might stimulate the visual brain areas that are involved in processing the disparity of objects along the 'what' pathway. Especially the area ITC is involved in higher level tasks like updating and storing information in the working memory. A standardised cognitive evaluation should investigate how and why symbols can be designed to optimise the encoding of geographic semantics by stimulating visual areas along the 'what' pathway.



contour 1 size 2 saturation 3

hue 2 value 3 size 1

contour 3 value 1 saturation 2

saturation 1 contour 2 hue 1

hue 3 value 2 size 3

Figure 50. Part 1. Chronology of randomised visualisations applied in the paper-and-pencil test.

Four relevance classes were coded into point symbols. Class 1 corresponds to the most relevant symbol. To avoid a modification of the information complexity, the test cases were configured with the same context layer and the same quantity of point symbols. Due to memorisation of the relevant point's location, the first three relevance classes were randomised. The subjects were asked to turn the pages every 2 seconds. The time span of 2 seconds was defined after having conducted a prototype evaluation where the subjects needed about 2 seconds to complete the task and to turn to the next page.

The task on demand was: *Please sign the most relevant information that is coded in point symbols.* Each visualisation was followed by a ranking list (Figure 51), where subjects were asked to rank the degree of task difficulty within 2 seconds.

1	2	3	4	5

Figure 51. Ranking list. 1-excellent, 2-good, 3-satisfactory, 4-sufficient, 5-fail.

To get familiar with the procedure, the subjects were introduced to the test by signing and ranking three different visualisation examples in the required time.

Figure 52 illustrates the chronology of Part two that consists of twenty attention-guiding visualisations, each representing a possible combination of graphical variables. Each variable codes one relevance class and is directly opposed to another variable. To avoid a possible influence from the spatial context information in the base layer (e.g. converging streets can deviate scan paths to less relevant information through orientation processing), the locations of point symbols were exchanged in a second set. The visualisations were presented in a randomised order.

Again, the task of demand was: *Please sign the most relevant information that is coded in point symbols.* Subjects had 2 seconds to sign the most relevant information (the 'winning variable').

Subjects. 42 participants (21 male, 21 female) with a mean age of 28 years (range: 23-36) took part in the study. The test persons are untrained in the sense that they do not work in one of the GI science research discipline. However, this does not necessarily mean that they are less effective in visual scanning geographic information in comparison to GI scientists.

Inclusion and exclusion criteria. The test persons within the above mentioned age range are assumed to have optimal visual acuity and visual scanning performance within the visual field. The subjects were examined by means of conventional routine measures to exclude those with impaired visual functions. Test persons were allowed to wear glasses or contact lenses but had to pass a visual acuity test and a colour blindness test to be included in the evaluation. One subject was excluded through an interview concerning medications due to possible reduced velocity and accuracy of saccadic eye movements.

Experimental environment. The evaluation included two groups (2 x 21 subjects). The first test was carried out in collaboration with the Max-Planck Institute of Psychiatry in Munich, Germany. The second was conducted at the Technical University in Munich under the similar conditions of the first experimental environment. To avoid visual distractive influence as far as possible, each subject was asked to keep the places on their right and left side free and to place only the paper and a pencil on the desk.

hue vs contour
hue vs saturation
hue vs size
contour vs size
hue vs value
saturation vs contour
value vs size
value vs saturation
size vs saturation
contour vs hue
saturation vs hue
saturation vs value
size vs hue
value vs hue
contour vs saturation
size vs value
saturation vs size
size vs contour
value vs contour
contour vs size

Figure 52. Part 2. Chronology of randomised visualisations to evaluate concurrent variables.

7.3 Test results

The statistical analysis of the test results was conducted with SPSS 12.0. In design case 1, subjects were able to locate the most relevant information (Table 9). All variables have proven to be appropriate to encode the information of interest. The majority of the subjects believed that ‘size’ and ‘hue’ were the most potential variables. 16.7% of the subjects suggested that class four represents the most relevant information when it was encoded with the variable ‘contour’.

relevance	**variables**				
	contour	hue	saturation	size	value
class 1	35 (83.3%)	39 (92.9%)	36 (85.7%)	41 (97.6%)	38 (90.5%)
class 2	0	3 (7.1%)	6 (14.3%)	0	0
class 3	0	0	0	1 (2.4%)	1 (2.4%)
class 4	7 (16.7%)	0	0	0	3 (7.1%)

Table 9. Distribution of the number of subjects who attributed attention-guiding variables to classes of relevance in case 1 (unfiltered but cognitively adequate).

In design case 2, subjects were also able to locate the most relevant information (Table 10). All variables have proven to be appropriate to encode the information of interest. Again, 'size' was the most salient variable, followed by 'saturation'. Here, no subject suggested that class 4 represents the most relevant information. However, compared to design case 1, only 28.6% of the subjects attributed 'value' to the first relevance class. In turn, 66.7% of the subjects attributed 'value' to class 3. Moreover, 28.6% of the subjects signed relevance class 3 as the most relevant class when encoded with 'hue'.

relevance	**variables**				
	contour	hue	saturation	size	value
class 1	32 (76.2%)	27 (64.3%)	39 (92.9%)	40 (95.2%)	12 (28.6%)
class 2	9 (21.4%)	3 (7.1%)	2 (4.8%)	2 (4.8%)	2 (4.8%)
class 3	1 (2.4%)	12 (28.6%)	1 (2.4%)	0	28 (66.7%)
class 4	0	0	0	0	0

Table 10. Distribution of the number of subjects who attributed attention-guiding variables to classes of relevance in case 2 (filtered but cognitively inadequate).

When processing the attention-guiding design methodology (Table 11), 42.9% of the subjects considered relevance class 2 as the most relevant class when encoded with the variable 'saturation'. Again, 'size' was the most salient variable, followed by 'hue'. Like in design case 2, no subject suggested that class four represents the most relevant information. The variable 'size' was neither attributed to class three nor to class four. Every subject except one was guided to the most relevant information when it was encoded with the variable 'size'.

relevance	**variables**				
	contour	hue	saturation	size	value
class 1	32 (76.2%)	36 (85.7%)	22 (52.4%)	41 (97.6%)	31 (73.8%)
class 2	8 (19%)	2 (4.8%)	18 (42.9%)	1 (2.4%)	3 (7.1%)
class 3	2 (4.8%)	4 (9.5%)	2 (4.8%)	0	8 (19%)
class 4	0	0	0	0	0

Table 11. Distribution of the number of subjects who attributed attention-guiding variables to classes of relevance in case 3 (filtered and cognitively adequate).

Tables 12-17 illustrate the distribution of ranking values coding the task difficulty of processing relevant information in the three design cases. The values in Table 12 indicate that 59.9% of the subjects ranked the variable 'size' as excellent in its function as attention-guiding attribute.

The task difficulty seems to decrease when visually processing the variable ‘size’ in the unfiltered but cognitively adequate visualisation.

ranking	**variables**				
	contour	hue	saturation	size	value
excellent	4 (9.5%)	15 (35.7%)	9 (21.4%)	25 (59.5%)	7 (16.7%)
good	11 (26.2%)	11 (26.2%)	9 (21.4%)	11 (26.2%)	16 (38.1%)
satisfactory	15 (35.7%)	5 (11.9%)	11 (26.2%)	3 (7.1%)	11 (26.2%)
sufficient	10 (23.8%)	9 (21.4%)	9 (21.4%)	3 (7.1%)	6 (14.3%)
fail	2 (4.8%)	2 (4.8%)	4 (9.5%)	0 (0.0%)	2 (4.8%)

Table 12. Distribution of ranking values coding the task difficulty of processing relevant information in case 1 (unfiltered but cognitively adequate).

By applying the Friedman-Test, a mean rank was calculated to define the ‘winning’ variable in case 1. The variable ‘size’ was significantly ranked as the best attention-guiding attribute (p= <.001) while the variable ‘contour’ was considered as the least favourable one.

Case 1	Mean Rank
contour	3.51
hue	2.83
saturation	3.40
size	2.00
value	3.25

Table 13. Mean rank of the variables with regard to their contributions to guide attention in case 1 (unfiltered but cognitively adequate). The smaller the mean rank value, the more important its corresponding variable.

When visually processing the second design case (filtered but cognitively inadequate), in addition to ‘size’ and ‘hue’ most subjects ranked ‘value’ as being sufficient to solve the task and 14.3% decided that ‘value’ fail the task (Table 14).

ranking	**variables**				
	contour	hue	saturation	size	value
excellent	4 (9.5%)	5 (11.9%)	6 (14.3%)	14 (33.3%)	5 (11.9%)
good	12 (28.6%)	7 (16.7%)	14 (33.3%)	19 (45.2%)	7 (16.7%)
satisfactory	18 (42.9%)	19 (45.2%)	13 (31.0%)	6 (14.3%)	7 (16.7%)
sufficient	6 (14.3%)	7 (16.7%)	7 (16.7%)	2 (4.8%)	17 (40.5%)
fail	2 (4.8%)	4 (9.5%)	2 (4.8%)	1 (2.4%)	6 (14.3%)

Table 14. Distribution of the ranking values coding the task difficulty of processing relevant information in case 2 (filtered but cognitively inadequate).

Again, in the second design case, the Friedman-Test shows that the variable ‘size’ was significantly ranked as the best attention-guiding attribute (p= <.001) while the variable ‘value’ was considered as the least favourable one.

Case 2	Mean Rank
contour	3.12
hue	3.20
saturation	2.82
size	2.04
value	3.82

Table 15. Mean rank of the variables with regard to their contributions to guide attention in case 2 (filtered but cognitively inadequate).

The variables ‘contour’ and ‘size’ proved to be suitable as attention-guiding attributes in the attention-guiding design methodology (Table 16). Additionally, relatively high percentage of subjects considered ‘contour’ and ‘hue’ to be an excellent attribute. Ranking percentages of the variable ‘value’ were almost equally distributed from excellent to sufficient.

ranking	**variables**				
	contour	hue	saturation	size	value
excellent	18 (42.9%)	14 (33.3%)	10 (23.8%)	26 (61.9%)	9 (21.4%)
good	12 (28.6%)	11 (26.2%)	10 (23.8%)	13 (31.0%)	11 (26.2%)
satisfactory	7 (16.7%)	11 (26.2%)	6 (14.3%)	2 (4.8%)	10 (23.8%)
sufficient	4 (9.5%)	3 (7.1%)	11 (26.2%)	1 (2.4%)	10 (23.8%)
fail	1 (2.4%)	3 (7.1%)	5 (11.9%)	0 (0.0%)	2 (4.8%)

Table 16. Distribution of the number of ranking values coding the task difficulty of processing relevant information that is coded with attention-guiding attributes in case 3 (attention-guiding design methodology).

In the attention-guiding design methodology, the Friedman-Test shows that the variable ‘size’ was again significantly ranked as the best attention-guiding attribute (p= <.001). The variable ‘saturation’ was calculated as the least favourable attention-guiding variable.

Case 3	Mean Rank
contour	2.73
hue	3.02
saturation	3.69
size	2.02
value	3.54

Table 17. Mean rank of the variables with regard to their contribution to guide attention in the third attention-guiding design methodology (filtered and cognitively adequate).

Furthermore, the degree of agreement in the ranking of the variables was calculated by using the Kendalls W-Test.

The statistical analysis for the variable ‘contour’ revealed a significant result (W = .310; p = <.001), indicating a high level of agreement between the subjects.

Contour	Mean	Std. Deviation
Case 1	2.88	1.04
Case 2	2.76	.98
Case 3	2.00	1.10

Table 18. Means and standard deviations indicating the degree of agreement in the ranking of the variable ‘contour’.

The statistical analysis for the variable ‘hue’ revealed a significant result (W = .124; p = .005), indicating a high level of agreement between the subjects.

Hue	Mean	Std. Deviation
Case 1	2.33	1.30
Case 2	2.95	1.10
Case 3	2.29	1.21

Table 19. Means and standard deviations indicating the degree of agreement in the ranking of the variable ‘hue’.

The statistical analysis for the variable ‘saturation’ revealed a non-significant result (W = .007; p = .758), indicating a low level of agreement between the subjects.

Saturation	Mean	Std. Deviation
Case 1	2.76	1.28
Case 2	2.64	1.08
Case 3	2.79	1.39

Table 20. Means and standard deviations indicating the degree of agreement in the ranking of the variable ‘saturation’.

The statistical analysis for the variable ‘size’ revealed a significant result (W = .142; p = .003), indicating a high level of agreement between the subjects.

Size	Mean	Std. Deviation
Case 1	1.62	.90
Case 2	1.98	.95
Case 3	1.48	.71

Table 21. Means and standard deviations indicating the degree of agreement in the ranking of the variable ‘size’.

The statistical analysis for the variable ‘value’ revealed a significant result (W = .180; p = .001), indicating a high level of agreement between the subjects.

Value	Mean	Std. Deviation
Case 1	2.52	1.09
Case 2	3.29	1.25
Case 3	2.64	1.21

Table 22. Means and standard deviations indicating the degree of agreement in the ranking of the variable ‘value’.

Table 23 provides information about the distribution of the ‘winning‘ attention-guiding variables by comparing the two test sets in part 2. The second set visualised the same combination of variables but the position of the variables were exchanged. The variable ‘size’ is the ‘winning‘ variable as indicated in Table 24.

variables	1st set	2nd set
hue	24 (57.1%)	14 (33.3%)
contour	18 (42.9%)	28 (66.7%)
hue	7 (16.7%)	3 (7.1%)
saturation	35 (83.3%)	39 (92.9%)
hue	16 (38.1%)	20 (47.6%)
size	26 (61.9%)	22 (52.4%)
hue	12 (28.6%)	1 (2.4%)
value	30 (71.4%)	41 (97.6%)
saturation	9 (21.4%)	3 (7.1%)
contour	33 (78.6%)	39 (92.9%)
saturation	4 (9.5%)	3 (7.1%)
size	38 (90.5%)	39 (92.9%)
saturation	28 (66.7%)	35 (83.3%)
value	14 (33.3%)	7 (16,7%)
contour	12 (28.6%)	10 (23.8%)
size	30 (71.4%)	32 (76.2%)
contour	36 (85.7%)	41 (97.6%)
value	6 (14.3%)	1 (2.4%)
value	12 (28.6%)	16 (38.1%)
size	30 (71.4%)	26 (61.9%)

Table 23. Distribution of ‘winning’ attention-guiding variables in the proposed attention-guiding design methodology. The first and second sets indicate the opposite positions of the variables within the map.

Table 24 summarises the ‘winning‘ frequency of attention-guiding variables. The variable ‘size’ was four times the ’winning’ variable (of 4 possible winning cases) in both sets, followed by ‘contour’. The variables ‘hue’ and ‘value’ proved to be not strong enough to guide visual attention towards them when being opposed to the other variables.

Variables	1st set	2nd set
hue	1	0
contour	2	3
saturation	2	2
value	1	1
size	4	4

Table 24. ‘Winning’ frequency of variables in the two sets.

7.4 Discussions

It is believed that the reasoning processes of geographic tasks take place in specific brain areas along internal visual processing pathways. To stimulate these visual areas, it is proposed to apply attention-guiding attributes in the information design. In addition, the design methodology benefits from the biological centre-surround mechanism that arranges objects in a visual hierarchy, depending on their relative relevancies in appropriate visual hierarchies. For a proof of concept, three design methods were implemented that adopt proposed in accordance to the relevance-based filtering as an element of a system's utility and / or the cognitively adequate visualisation as a usability element.

In case 1, the information was unfiltered, but the geographic information was visualised in a cognitively adequate way. In case 2, the information was filtered, but the geographic visualisation was not adapted to user's capability of visual scanning. In case 3, information in the attention-guiding geovisualisation was filtered with regard to the user's query and the visualisation was adapted to user's visual scanning abilities. The challenge of the proposed attention-guiding design is to stimulate decision-making by guiding visual attention to relevant information and consequently to reduce the user's cognitive workload. Based on the statistical analysis of the paper-and-pencil test, the following insights have been gained into the conceptual framework for designing attention-guiding geovisualisations.

Cognitive adequacy of the attention-guiding design approach. The cognitively adequate design of geovisualisations seeks to be adapted to the skill of internal visual information processing. Hence, the cognitive adequacy of the attention-guiding design approach can be judged by evaluating the visual scanning efficiency of users when searching for geographic information. The main goal of attention-guiding geovisualisation is to achieve high visual scanning efficiency by reducing information complexity and the cognitive workload. Bearing in mind the functions of visual brain areas and major internal visual information processing pathways, one possibility to reduce a user's workload is to guide visual attention to relevant information. Accordingly, the research task is to determine the most favourable design methodology that supports users in promptly locating relevant information.

This can be realised by comparing the distributions of subjects who attributed attention-guiding variables to different classes of relevance. The statistical analyses of case 1 (unfiltered and cognitively adequate) revealed that visual attention was guided to the relevant information (relevance class one) by all variables ranging from the less appropriate variable 'contour' (83.3%) to the most appropriate variable 'size' (97.7%) (Table 9). However, 16.7% of the subjects attributed class four (points without contour) to the most relevant information when information was encoded with the variable 'contour' (Figure 53).

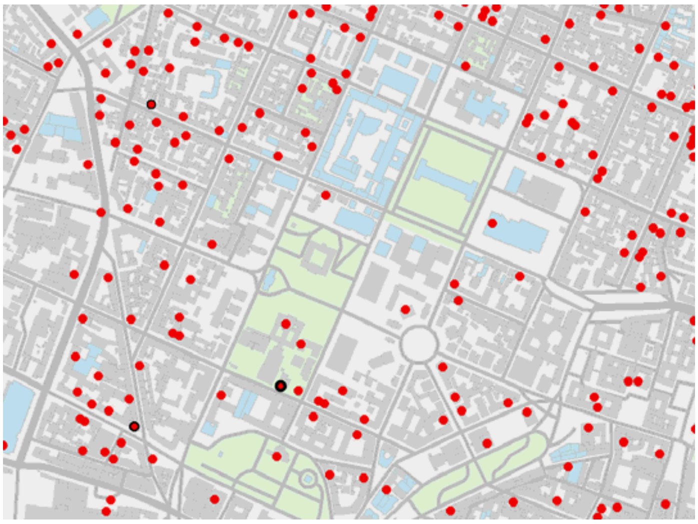


Figure 53. Visualising relevance classes with the variable 'contour' in case 1.

One possible reason for the false detection of the first relevance class can probably be related to the functions of ‘contour’ processing brain areas. Contours of objects are processed in the areas V2, V3, and V4. These visual areas are also involved in the specific functions of figure-ground segregation (V2, V4), processing disparities of objects (V3), and representing salient objects (V4).

Due to high colour contrasts between point symbols of class four and the decreased saliency of the context layer, the scan path of subjects could be distracted by the contoured point symbols due to high responses in area V2 and V4. Moreover, the distinction between the contoured and non-contoured point symbols might be too small. Subjects were not able to find the relevant information within two seconds. This probably results from low responsiveness of area V3, i.e. subjects were not able to distinguish class four from the other classes in the required time. This phenomenon leads to the conclusion that contoured symbols have to be visualised big enough for the sake of easy detection. Similar to the evaluation of ‘contour’ and ‘size’ with the attention model (see section 6.4), it is a question of interest to determine the width for contours in relation with the surrounded context information. An overlap with important spatial information (e.g. landmarks) or minor relevance classes can weaken spatial orientation and detection of less relevant information that is necessary for comparison. To support user’s centre-surround mechanism it would be recommendable to adjust the colour intensities of point symbols in class 4 in a way that they more fade into the background. However, due to missing contours and increased colour value, subjects might relate these symbols to another category of information that is not considered in the relevance classes.

In case 2 (filtered and cognitively inadequate) results show that visual attention was mostly guided to the most relevant information by four variables except ‘value’. ‘Size’ proved to be a favourable attention-guiding variable (95.2%) followed by ‘saturation’ (92.2%) (Table 10). However, compared to the first design methodology (38 subjects), only 12 subjects (28.6%) attributed ‘value’ to the first relevance class. Most of the subjects (66.7%) considered the third class as the first one. Figure 54 shows the geovisualisation where relevant information is coded with ‘value’. The third class is represented by the red point symbol in the upper left corner.

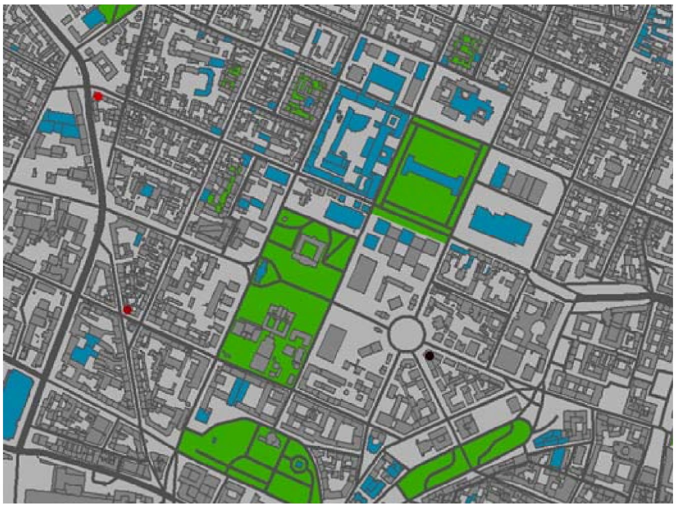


Figure 54. Visualising relevance classes with the variable ‘value’ in case 2.

The deviation of scan paths to the rather ‘irrelevant’ red point symbol can possibly be related to the functions of ‘value’ processing areas (V2, V3, V4). Especially area V4 is involved in higher processing tasks like tuning contour features and processing the orientation of angles and curves. It can be estimated that visual scan paths were guided to the third class because of the salient background. In comparison to case 1, here the spatial information is as saliently visualised as the focal information. The neglected design principles of ‘visual simplicity’ and ‘visual hierarchy’ has led to the failure of reducing information complexity and releasing the cognitive workload. High responsiveness in area V4 (tuning contour features and processing of angles and curves) may have deviated visual attention to the two saliently visualised streets (high intensity contrasts and thick contours) that converge right above the red point symbol. It seems that the distractive effect of these linear features is larger than the converging streets near the most relevant information (black point in the lower right part of the visualisation) because the latter reveals less contrast. Another possible reason might be the missing of a centred fixation point that is applied in eye-movement recordings to define the starting point of visual scan paths. If subjects start the visual scanning process in the centre of the visualisation, the distance from the centre to the most relevant information is much nearer than to the red point symbol. Therefore, subjects probably would have directed their gazes to the most relevant information.

In case 3 that represents the attention-guiding methodology, most subjects attributed the attention-guiding variables to the first class (Table 11). Beside the variable ‘size’ that again was the most potential variable (97.6%), all other variables except ‘saturation’ proved to be highly appropriate to code the most relevant information in the attention-guiding design ranging from 73.8% to 85.7%. However, the variable ‘saturation’ was often related to the second class (42.9%). Figure 55 depicts the proposed visualisation design for coding relevance classes with the variable ‘saturation’.

Figure 55. Visualising relevance classes with the variable ‘saturation’ in case 3.

A possible reason for guiding gaze fixations to the second class might be the degree of saliency and the dimensions (‘size’) of the underlying green area. Corresponding to the characteristics of scene- and local-based visual information processing (see section 3.2), the scan paths of subjects could have been guided to the green area in a global mode (scene-based) before fixating the point symbol in a local mode (detail-based). Hence, sensory input of the green area was first captured by the macula region before sensory signals of the point symbol entered the fovea on the retina. This misguided scan path might be related to the responsiveness of ‘saturation’ processing brain areas (V2, V3, V4) that also respond to the size (large green area) and saliency (contrast of dark red and light green) of information. Thus, the green area represents a rather distractive visual layer that is positioned between the focal layer and the context. To tackle this problem, it might be advantageous to reduce the saliency degree of the green area. This regulation is part of the adjustment question: *What degree of saliency decrease can be processed by the user without loosing spatial orientation?*

The attention-guiding visualisation design proved to be the most desirable to support users in visual scanning tasks. However, in case 1 user’s had no difficulties to detect the relevant information either. This indicates that the design principle of visual hierarchy is a fundamental to make important information stand out and reduce user's cognitive workload despite high information complexity.

Figure 56. Visualising relevance classes with the variable 'saturation' in case 1.

Figure 56 illustrates that the regulation of saliency also plays an important role in the design of geovisualisation. Like context visualisation, this adjustment task also applies to the focal information. When observing Figure 56 it seems to be difficult to locate the relevance class four due to overregulated 'saturation' values that interfere with the design principle of visual hierarchies. Thus, the high level of colour 'saturation' does not support the centre-surround mechanism to activate visual brain areas that are involved in figure-ground segregation (V2, V4, ITC) and representing salient objects (V4, ITC). A possible solution of this adjustment problem might be the changing of colour hues of the underlying rather top-down processed spatial information to achieve higher intensity contrasts between focal information and context. White polygons (houses) or light grey lines (streets) might be a better solution for the adjustment problem in this example by stimulating the visual area V3 for contrast processing.

Impact of the attention-guiding design methodology on the task difficulty. The task difficulty depends on the effort required to notice the most relevant information that is coded in point symbols, and on the cognitive adequacy of the geovisualisation design that is characterised by attention-guiding variables.

The distribution of the number of ranking values coding the task difficulty of processing relevant information with attention-guiding attributes shows that 59.9% of subjects ranked the variable 'size' as excellent to solve the task in case 1 (Table 12). The task difficulty seems to decrease when visually processing the variable 'size'. However, only 35.7% of subjects considered 'contour' as being appropriate (excellent and good) to solve the task. 35.7% of subjects ranked 'contour' as being a satisfactory variable to encode the most relevant class. This outcome can be related to the above mentioned contour processing problem. The same can be stated for the variable 'saturation' that 26.2% considered as being satisfactory for task solving. Besides the variable 'size', 'value' has been proved to be appropriate for task solving. 38.1% of subjects ranked 'value' as being good for visualising relevant information in case 1 (Figure 57).

The most relevant information in the upper left part of the visualisation might be promptly localised by subjects due to high responsiveness in the 'saturation' processing area V4 that is additionally involved in figure-ground segregation and the representation of salient objects. However, a mean rank (Friedman-Test) that was calculated to determine the 'winning' variable in case 1 positioned ‘saturation’ at the fourth place. The variable ‘size’ was ranked as the best attention-guiding attribute while the variable ‘contour’ was considered as the least favourable one (Table 13).

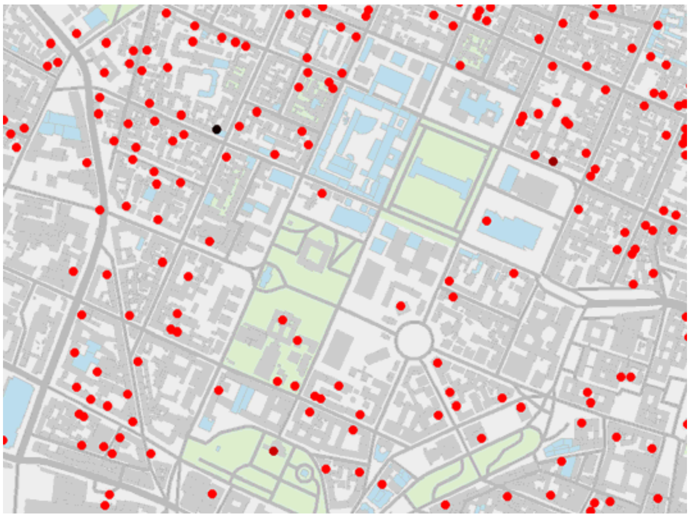


Figure 57. Visualising relevance classes with the variable ‘value’ in case 1.

The distribution of the number of ranking values coding the task difficulty in case 2 shows that amongst ‘size’ (45.2%) a lot of subjects (40.5%) considered ‘value’ as being sufficient for task solving (Table 14). However, due to missing visual hierarchies and corresponding geographical information layers that support users in visual scanning, most subjects ranked the variables ‘contour’, ‘hue’, and ‘saturation’ as satisfactory for guiding visual attention.

Figure 58 shows the test example of colour ‘hue’ where subjects were asked to sign the most relevant information. Although 27 subjects (64.3%) related the red point symbol to the first class almost 28.6% considered the third class (yellow point symbol) as the first one (Table 10). These misguided scan paths probably result from responsiveness of the visual area V3 to intensity contrast processing and V4 to figure-ground segregation due to colour contrasts between yellow and dark grey. To tackle this problem of too high colour contrasts that hinders users in ranking classes it is again crucial to follow the principle of visual hierarchies and to reduce the degree of saliency of the spatial context information.

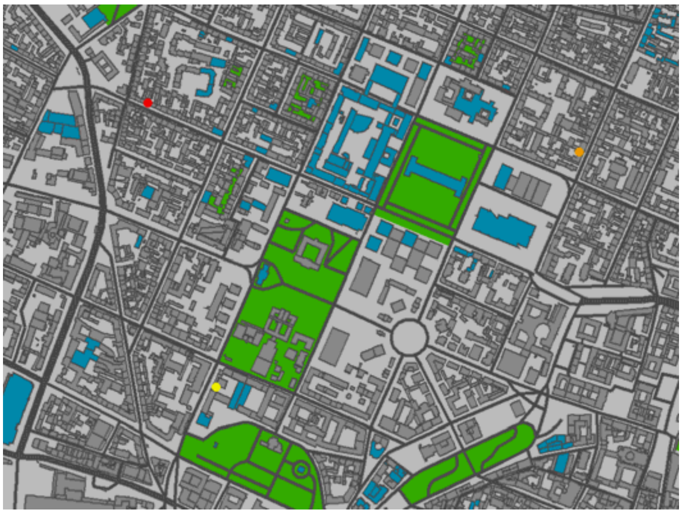


Figure 58. Visualising relevance classes with the variable ‘hue’ in case 2.

An example of colour ‘hue’ coding is shown in Figure 59. The total of 36 subjects (85.7%) related the target object to the first class (Table 11). When observing this attention-guiding design, one can recognise that the yellow point symbol in the lower left side of the figure has lost its high contrast although it reveals the same ‘hue’ as the dot in the lower part of Figure 58. The decreasing saliency of the context information has provoked a decreasing saliency of the third class symbol. Only two subjects (4.8%) related the orange point symbol and four subjects (9.5%) the yellow point symbol to the first relevance class.

Figure 59. Visualising relevance classes with the variable ‘hue’ in case 3.

In case 2, the mean rank (Friedman-Test) again revealed that the variable ‘size‘ was ranked as the most favourable attention-guiding attribute. The variable ‘value‘ was considered as the least favourable one. The distribution of ranking values coding the task difficulty in case 3 shows that the variable ‘size’ effectively codes ranking values when following the attention-guiding design principles. Especially the principle of conciseness of visualising information in a salient way makes ‘size’ so powerful in guiding visual attention to the information of interest. 92,9% of subjects ranked ‘size’ as being excellent (61.9%) or good (31%) for guiding scan paths (Table 16). Figure 60 depicts the attention-guiding geovisualisation where relevant information is coded with the variable ‘size’.

Figure 60. Visualising relevance classes with the variable ‘size’ in case 3.

Additionally, 18 subjects (42.9%) ranked the variable ‘contour’ as being excellent and 12 subjects (28.6%) as being good for coding relevance classes. Hence, the attention-guiding design methodology has been proven to be more cognitively adequate as in case 1 where ‘contour’ was considered as the less favourite variable to guide visual attention. In addition the filtered objects in case 3 have led to the reduction of information complexity (Figure 61). While 16.7% of the subjects considered class 4 as the most relevant class in case 1 (Table 9), only 9.5% of the subjects considered ‘contour’ coding as being sufficient for the task solving and 2.4% ranked contour coding to fail the task (Table 16).

Figure 61. Visualising relevance classes with the variable ‘contour’ in case 3.

This mismatch of locating relevant information (case 1) and ranking task difficulty (case 3) with the variable ‘contour’ probably results from the reduced information complexity in case 3 where the fourth relevance class is not considered in the user’s query. Hence, the number of distractive irrelevant information was significantly reduced to avoid a misguidance of visual attention. Although the variable ’size’ was ranked as the best attention-guiding attribute in case 3, the oversize of relevant point symbols could still implicate a loss of information because they might overlap with second-rate relevant objects.

To verify the impact of the attention-guiding design methodology on the task difficulty, the degree of agreement in the ranking of the variables revealed that apart from the variable ‘saturation’ all analyses significantly proved a high level of agreement between the subjects when ranking the task difficulty.

The variable ‘size’ was significantly ranked as the best attention-guiding attribute in all design cases. When comparing the distribution of tasks difficulties in the attention-guiding design methodology with the distribution in the other design cases, the highest percentages are related to the rankings excellent and good in the attention-guiding methodology while in the first two cases subjects ranked the task difficulty as satisfactory. For this reason, the attention-guiding design methodology has indeed an impact on the task difficulty.

Attention-guiding strengths of proposed variables. By comparing the distribution of the ‘winning‘ attention-guiding variables in two sets of map tests the variable ‘size‘ has won four times of four possible winning cases. Figure 62 exemplifies a winning case of ‘size’ when being compared with ‘contour’ that is ranked as the second winnning variable.

Figure 62. ‘Size’ is the winning variable in case 3 when it is opposed to ‘contour’.

This winning case is also accomplished by comparing more than two target objects. Figure 63 shows the outcome of the computational attention model when opposing three relevant objects of the variable ‘size’ and ‘contour’. The model detects the first three larger symbols before guiding the attention to contoured point symbols due to dominating colour, intensity and orientation contrasts. Although ‘size‘ can be considered as the most potential variable, other comparisons proved that specific variables are also appropriate to guide attention in case 3.

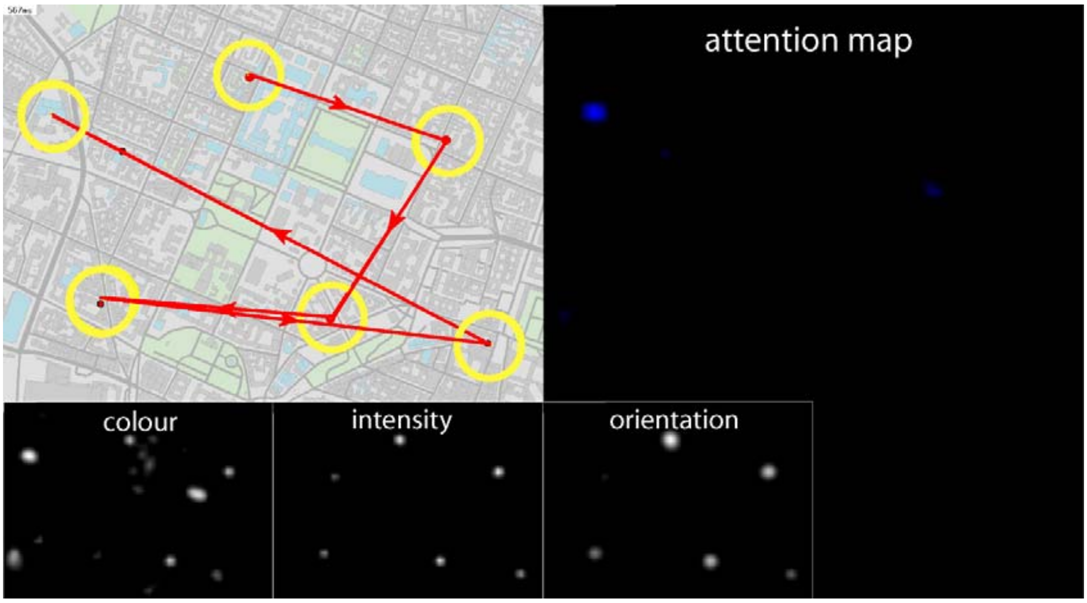


Figure 63. Outcome of the attention model when opposing ‘size’ to ‘contour’.

Another example shows the potential of ‘contour’ to guide attention when not being related to the variable ‘size‘. Figure 64 shows the ’winning’ case of ‘contour‘ when being related to ‘value‘. 97.6% of subjects attributed the first class to ‘contour’ (Table 23).

Figure 64. 'Contour' is the winning variable in case 3 when being opposed to 'value'.

This winning case is also accomplished by comparing contour targets with value targets in the attention model. Figure 65 shows the model outcome. Before reaching the value target, the first three predicted scan paths are guided to the contour targets due to high colour, intensity and orientation contrasts.

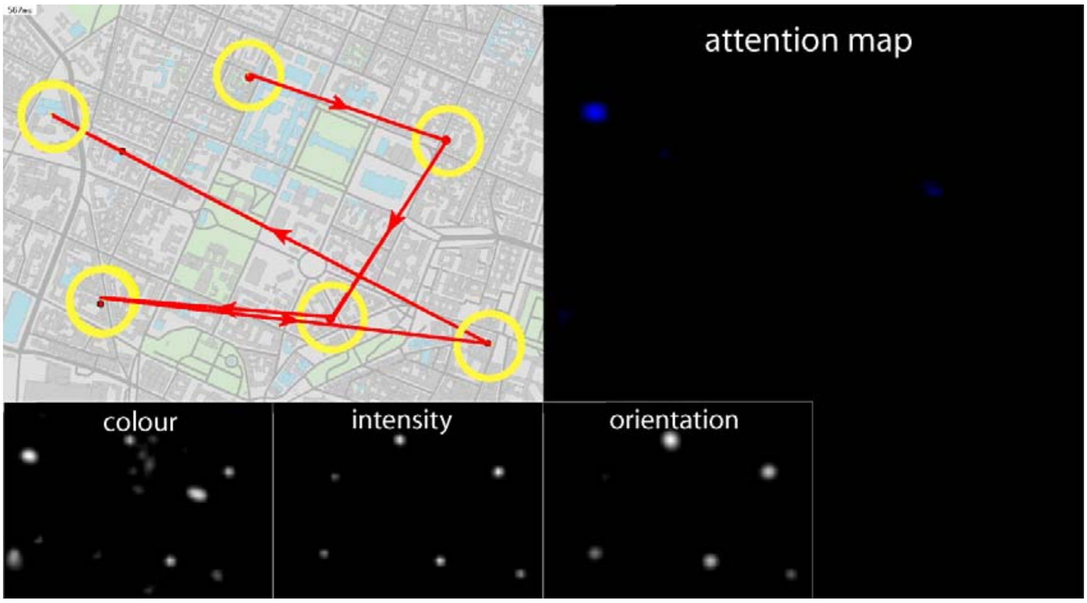


Figure 65. Outcome of the attention model when opposing 'contour' to 'value'.

8. Evaluation with the eye movement recording method

The results of the paper-and-pencil test have indicated that the attention-guiding approach is a beneficial design method to support users in visually scanning geographic information. This chapter is dedicated to the evaluation of the cognitive design methodology with the eye movement recording method. It was conducted in collaboration with psychologists of the Ludwig Maximillians University and the Max-Planck Institute of Psychiatry in Munich.

8.1 Research questions

In contrast to the paper-and-pencil test, the eye movement recording method measures concrete parameters that help to acquire knowledge about the visual scanning strategy and efficiency of users when processing the three design cases. Based on the hypotheses that graphical variables in geovisualisations are internally combined to geographic information and that the attention-guiding design methodology releases user's capacity limitation of visual scanning, the eye movement recording evaluation is used to answer the same research questions formulated in the context of the paper-and-pencil test.

The relevant eye movement parameters for this work are ‘time’ (time required to accomplish the task), ‘degree’ (degrees of scan paths), ‘number of fixations’, ‘repetitions of fixations’ (number of re-fixations), and ‘duration of fixations’. In the following, coarse interpretations of the parameters are related to the research questions to illustrate their significance for cognitive design. These interpretations are regarded as loosely bound guidelines for interpreting eye movement parameters in geovisualisation and do not claim to be universally valid:

(1) *Which design methodology allows users to promptly locate the most relevant information?*

The smaller the values of parameters the more efficient is the design methodology.

(2) *Do these design methodologies have an impact on the task difficulty?*

The larger the values of visual scanning parameters the more difficult is the task.

(3) *Which potential attention-guiding variables are more appropriate than others to guide a user's scan paths to relevant information?*

The smaller the values of parameters caused by one variable, the more appropriate is this variable to guide a user's attention.

(4) *How do these variables vary in their property to guide attention in different complex geovisualisations ?*

The smaller the values of parameters caused by a design case, the more appropriate is this design case to guide attention.

In contrast to the paper-and-pencil test, participants were not asked to rank the task difficulty. Moreover, it must be noted that a higher value of ‘repetition of fixations’ does not necessarily indicate a higher task difficulty. Users can re-fixate information to assure themselves that specific information was visually processed. On the other hand, the ‘number of fixations’ does not necessarily correspond to the exact quantity of visually processed geographic objects. Users are able to visually process information without directing their focus of attention to its location.

Figure 66 illustrates two examples where subjects declared to detect the relevant point symbols without having directed their focus of attention to each single geographic object (see section 3.1). A blue point depicted in the gaze plots represents a single gaze fixation (focus of attention) where information is processed in detail. The red line illustrates the scan path. Because of the mainly bottom-up driven task to visually scan for the three relevant point symbols, the locations of gaze fixations and scan paths cannot be identically related to the location of relevant information. Users are able to consider geographic information as relevant without the need to position the gaze fixation on the relevant information itself.

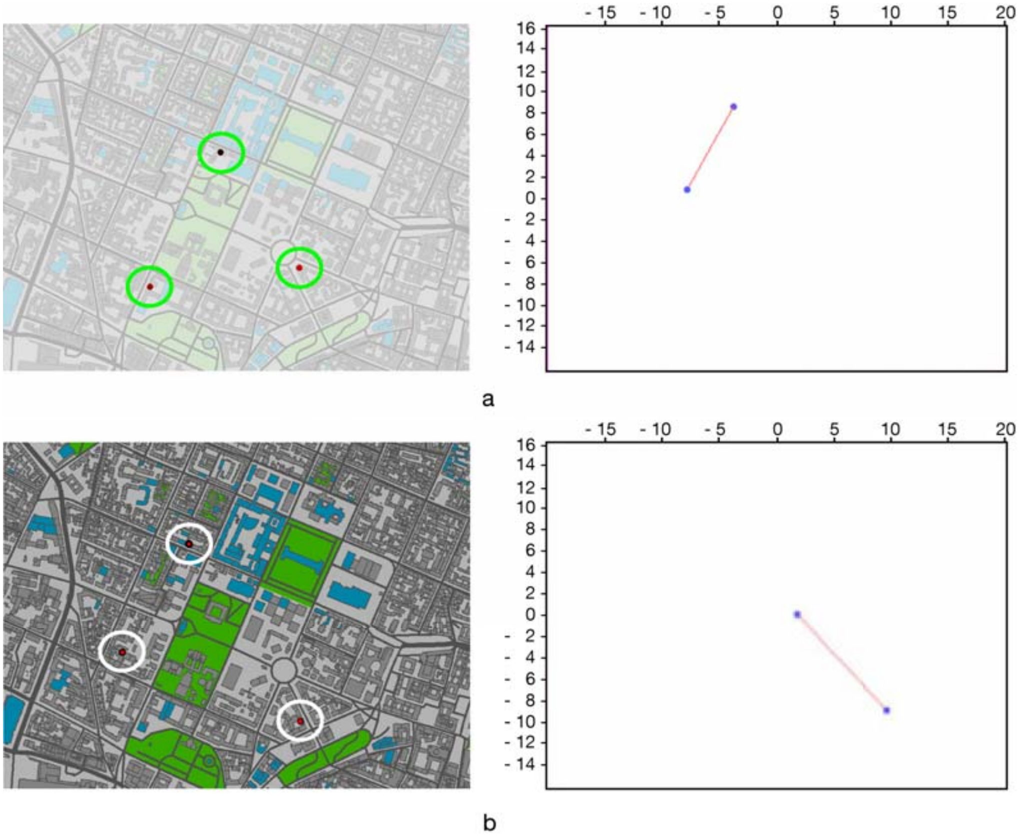


Figure 66. The impact of global and local information processing on scan path sequences. a) Information coded with ‘hue’ in case 3 and the corresponding gaze plot, and b) information coded with ‘contour’ in case 2 and the corresponding gaze plot.

This phenomenon can occur in attention-guiding geovisualisations (case 3) where the design is adapted to visual scanning abilities of users (Figure 66a, b) as well as in geovisualisations (e.g. case 2) that are suggested to be not sufficiently adapted to the users visual skills. Both examples show that the gaze plots consist of two fixations, although subjects were asked to detect three symbols. The reason for these visual scanning patterns can be found in characteristics of the centre-surround mechanism and in functions of visual brain areas (see chapter 3). The centre-surround mechanism is deeply involved in visual scanning strategies by allowing users to quickly process information in a global mode before ‘switching’ to a more detailed local mode. The scene-based scanning of geovisualisation gives users the possibility to process geographic information in a fast and global context-dependent manner in a first step before slowing down the scan path to a local mode. After having maintained a rough representation of the geographic context information users then guide the focus of attention to detailed local information that is captured by the wider field of attention and the smaller focus of attention in a second step (see section 3.2). During the global processing of geographic information in Figure 66, the relevant information located in the antagonistic surround was visually captured by both subjects without the need to fixate the objects to process the third symbol in more detail. Instead, the subjects visually processed the third symbol during global processing of the geovisualisation where it was captured by the wider field of attention. This phenomenon can

probably be related to the ability of covert attention that allows users to move attention to the opposite direction of eye movements (see chapter 3.1).
Bearing in mind that visual stimuli enter the retina in 20-60 ms (see section 3.1) and that the eye movement recording system records fixations within a spatial area of 1° with a minimum duration of 100 ms, some fixations may not be recorded because of too fast visual scanning speed.

The flexible skill of global and local processing illustrates the complexity of a user's scanning ability in comparison to the attention-model that strictly calculates the position of the focus of attention. In contrast, a scanning pattern of a task that involves more top-down processing reveals more precise locations of gaze fixations (Figure 67).

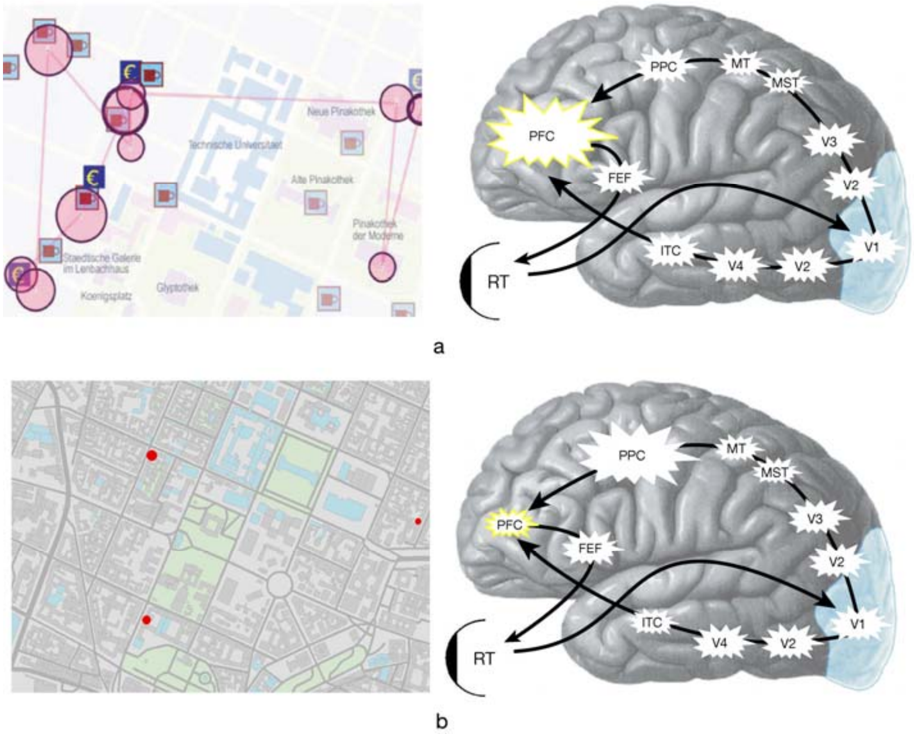


Figure 67. Visual processing of a) the location and semantics, and b) the location of geographic information, and responsive visual areas.

To decode a geographic symbol users combine single stimuli to meaningful information. Figure 67a illustrates that this converting process takes place in the association area 'prefrontal cortex' (PFC). When processing the geovisualisation all functions of visual areas are more or less stimulated based on their specific functions (see Table 2). It is suggested that the middle temporal cortex (MT) and the medial superior temporal cortex (MST) that participate in motion processing show low responsiveness because the variable 'motion' is not used to code relevant information. The prefrontal cortex reveals high responsiveness because of top-down processing like decoding the symbols for coffee shops (cup) and ATP's (€), and analysing their spatial distance. When focussing on relevant information, the duration of gaze fixations is long because the user has to process a symbol in detail (e.g. processing the shape of the cup and attributing the symbol to the meaning of 'coffee shop' by retrieving gained knowledge from working memory) before guiding the scan path to the next symbol of interest. Correspondingly, users have to fixate and visually scan each symbol in more time-consuming detail. This scanning strategy is reflected in the ranking list of psychological attention-guiding attributes (see Table 1) where the semantic category of visual information is ranked as a probable non-attribute for guiding visual attention.

Figure 67b shows the variable ‘size’ encoding three relevant classes of undefined geographic information in design case 3 that is based on the attention-guiding methodology. In addition to the middle temporal cortex (MT) and the medial superior temporal cortex (MST) it is suggested that the form and shape processing area ‘inferotemporal cortex’ (ITC) exhibits low responsiveness because of missing information that is coded in detail. In contrast, it is suggested that the visual area ‘posterior parietal cortex’ (PPC) on the ‘where path’ is highly sensitive based on its functions such as representing local bottom-up guided salient stimuli in a topographic saliency map. Neurons in the posterior parietal cortex represent the location of a salient stimulus to allow users to direct the attention to that stimulus without the need of processing it in detail (see section 3.6). Correspondingly, it is suggested that the prefrontal cortex concerned with the visual analysis of information is less sensitive because users are asked to decode a limited amount of semantic content (more or less relevant) of the visualised point symbols embedded in a geovisualisation with reduced visual complexity.

8.2 Test methods

The eye movement recording evaluation was conducted by using the same chronology of randomised geovisualisations applied in the paper-and-pencil test (see Figure 50 and 51). The task on demand was: *Please search for the relevant information that is coded in three point symbols and say ‘yes’ when you have found all three point symbols.* The test persons were introduced to the test by visually scanning three different examples.

Subjects. 15 participants (5 male, 10 female) with a mean age of 28 years (range: 22-38) took part in the study. Like in the paper-and-pencil test, the test persons are untrained.

Inclusion and exclusion criteria. The subjects were examined by means of routine measures to exclude those with impaired visual functions. All participants had normal or corrected-to-normal vision. Eight subjects were excluded due to signalling problems of the eye movement recording system. Subjects with glasses were excluded but subjects wearing contact lenses were included. Because of impaired visual acuity, one subject was excluded.

Experimental environment. The evaluation was conducted with the iVIEW-SMI system at the eye movement recording laboratory, Max-Planck Institute of Psychiatry in Munich. A gaze fixation is recorded within a spatial area of 1° with a minimum duration of 100 ms.

8.3 Test results

The statistical analysis of the test results was conducted with SPSS 12.0. To compare multiple means, the analysis of variance (ANOVA with Greenhouse-Geisser correction) was used to compute differences in search times (mean search time required to accomplish the task), degrees of scan paths (mean degree of scan paths), number of fixations (mean number of gaze fixations), repetitions of fixations (mean number of recurred gaze fixations), and durations of fixations (mean time of fixations). When significant main effects occurred, additional t-tests were performed to compare the three cases of geovisualisation in more detail. Data from two subjects (degree, number of fixations, repetition of fixations, and fixation duration) that was recorded with the eye movement system is missing for the variable value and hue in case 1.

Abbreviations: SD (Standard Deviation), t (test value), df (degrees of freedom), p (significance), n.s. (not significant)

Table 25 illustrates the standard deviations of visual scanning parameters when processing ‘contour’ in the three design cases. Case 3 (attention-guiding geovisualisation) reveals the lowest time spend on solving the task, the lowest degree of scan paths to find the relevant information, the lowest number of fixations needed to find the information of interest without employing re-fixations, and the lowest value of fixation durations to scan the geovisualisation. The ANOVA revealed significant differences in all visual scanning parameters for the variable ‘contour’.

contour				
	Case 1	Case 2	Case 3	p
time (SD)	5.49 (1.90)	3.01 (1.88)	1.95 (0.75)	<.001
degree (SD)	77.75 (35.28)	32.77 (15.42)	21.51 (9.12)	<.001
number of fixations (SD)	10.33 (5.50)	5.33 (2.89)	3.33 (1.40)	<.001
repetition of fixations (SD)	1.33 (1.84)	0.33 (0.62)	0.00 (0.00)	.019
duration of fixations (SD)	0.21 (0.04)	0.20 (0.04)	0.18 (0.02)	.031

Table 25. Visual scanning parameters when processing ‘contour’.

A t-test (paired) is performed to analyse the significant differences of the visual scanning parameters for ‘contour’. Table 26 shows the outcomes that reveal significant differences when comparing visual scanning parameters. All case comparisons show significant differences except the comparison of case 2 with case 3 when analysing the repetition of fixations. When visually processing ‘contour’, the time required to accomplish the task is significantly different for all case comparisons. To visually detect contour information, users spend the longest time for case 1 and the shortest time for case 3. This trend of the required length of time is reflected in the high values of ‘degree’, ‘number’, ‘repetition’, and ‘duration of fixations’ in case 1, and the low values in case 3, respectively.

contour			
time	t	df	p
case 1 / case 2	4.29	14	.001
case 1 / case 3	7.07	14	<.001
case 2 / case 3	3.02	14	.009
degree			
case 1 / case 2	5.62	14	<.001
case 1 / case 3	7.01	14	<.001
case 2 / case 3	4.43	14	.001
number of fixations			
case 1 / case 2	3.72	14	.002
case 1 / case 3	4.88	14	<.001
case 2 / case 3	3.06	14	.009
repetition of fixations			
case 1 / case 2	2.19	14	.046
case 1 / case 3	2.81	14	.014
case 2 / case 3	2.09	14	n.s.
duration of fixations			
case 1 / case 2	0.92	14	n.s.
case 1 / case 3	2.79	14	.015
case 2 / case 3	2.17	14	.048

Table 26. Significant differences between geovisualisation cases when processing ‘contour’.

Table 27 summarises the standard deviations of visual scanning parameters when processing the variable ‘hue’ in the design cases. Like ‘contour’, ‘hue’ is effectively processed in case 3. Except for the parameter ‘duration of fixation’ that reveals no significant differences, all parameters of case 3 show high performance of users in relation to case 2 and case 1. The values of visual scanning parameters in case 1 are higher than average when compared to case 2 and case 3. All parameters reveal high values, indicating that visually scanning for information coded with the variable ‘hue’ raised task difficulty.

hue				
	Case 1	Case 2	Case 3	p
time (SD)	16.04 (11.53)	3.67 (1.13)	2.55 (1.18)	.001
degree (SD)	204.09 (184.67)	48.61 (27.25)	37.06 (26.26)	.004
number of fixations (SD)	27.21 (21.99)	7.21 (1.67)	5.21 (2.86)	.003
repetition of fixations (SD)	7.29 (8.57)	0.43 (0.65)	0.21 (0.58)	.009
duration of fixations (SD)	0.20 (0.04)	0.21 (0.03)	0.19 (0.03)	n.s.

Table 27. Standard deviations of visual scanning parameters when processing ‘hue’.

Table 28 depicts the more detailed outcomes of the t-test revealing that all case comparisons show significant differences in the listed parameters. The parameter ‘duration of fixation’ was not analysed because of missing significant differences in the ANOVA.

hue			
time	t	df	p
case 1 / case 2	4.20	14	.001
case 1 / case 3	4.43	14	.001
case 2 / case 3	4.31	14	.001
degree			
case 1 / case 2	3.35	13	.005
case 1 / case 3	3.45	13	.004
case 2 / case 3	1.24	14	n.s.
number of fixations			
case 1 / case 2	3.48	13	.004
case 1 / case 3	3.81	13	.002
case 2 / case 3	2.74	14	.016
repetition of fixations			
case 1 / case 2	3.07	13	.009
case 1 / case 3	3.03	13	.010
case 2 / case 3	0.82	14	n.s.

Table 28. Significant differences between geovisualisation cases when processing ‘hue’.

Table 29 summarises the values of visual scanning parameters when processing the variable ‘saturation’ in the design cases. Like ‘hue’, the parameter ‘duration of fixation’ reveals no significant differences. When visually scanning for information that is coded with ‘saturation’, users accomplished the task more efficiently in case 2 (filtered but cognitively inadequate) than in case 3 (attention-guiding geovisualisation).

saturation				
	Case 1	Case 2	Case 3	p
time (SD)	5.39 (3.10)	2.89 (0.72)	3.21 (1.92)	.004
degree (SD)	87.78 (74.12)	37.94 (15.84)	42.69 (25.52)	.018
number of fixations (SD)	10.20 (7.02)	5.45 (1.36)	5.67 (2.82)	.025
repetition of fixations (SD)	1.93 (1.71)	0.00 (0.00)	0.40 (0.73)	.001
duration of fixations (SD)	0.19 (0.03)	0.19 (0.02)	0.19 (0.03)	n.s.

Table 29. Standard deviations of visual scanning parameters when processing ‘saturation’.

Table 30 shows the outcomes of the t-test. All case comparisons show significant differences except the comparison of case 2 with case 3 when analysing the degree of scan paths. Users needed the least time to accomplish the task in case 2 because of low degrees of occurred scan paths and few gaze fixations to detect information of interest.

saturation			
time	t	df	p
case 1 / case 2	3.29	14	.005
case 1 / case 3	2.89	14	.012
case 2 / case 3	-0.82	14	n.s.
degree			
case 1 / case 2	2.82	14	.014
case 1 / case 3	2.36	14	.034
case 2 / case 3	-0.62	14	n.s.
number of fixations			
case 1 / case 2	2.80	14	.014
case 1 / case 3	2.21	14	.044
case 2 / case 3	-0.23	14	.823
repetition of fixations			
case 1 / case 2	4.38	14	.001
case 1 / case 3	3.29	14	.005
case 2 / case 3	-2.10	14	.054

Table 30. Significant differences between geovisualisation cases when processing ‘saturation’.

size				
	Case 1	Case 2	Case 3	p
time (SD)	2.61 (1.20)	2.20 (0.61)	2.21 (1.08)	n.s.
degree (SD)	29.20 (12.90)	28.47 (12.14)	24.51 (11.18)	n.s.
number of fixations (SD)	5.07 (2.74)	4.07 (1.10)	4.60 (2.82)	n.s.
repetition of fixations (SD)	0.40 (0.83)	0.00 (0.00)	0.20 (0.41)	n.s.
duration of fixations (SD)	0.19 (0.02)	0.19 (0.02)	0.19 (0.03)	n.s.

Table 31. Standard deviations of visual scanning parameters when processing ‘size’.

Table 31 summarises the values of visual scanning parameters when processing the variable 'size'. The analysis reveals no significant differences in one of the visual scanning parameters when comparing the design cases. When visually searching for information coded with the variable 'size' users accomplished the task with minimal differences in the parameters of the design cases. While case 2 and case 3 show approximately the same values of scanning parameters, users had only a little more difficulties to detect the relevant information in case 1.

Table 32 summarises the values of visual scanning parameters when searching for information coded with the variable 'value'. Like 'hue' and 'contour', 'value' exhibits significant differences in all three cases except for the duration of fixations.

value				
	Case 1	Case 2	Case 3	p
time (SD)	11.07 (5.08)	2.55 (0.98)	1.85 (0.55)	<.001
degree (SD)	172.29 (114.09)	34.36 (12.52)	23.12 (9.47)	<.001
number of fixations (SD)	20.07 (13.27)	5.86 (2.32)	3.79 (1.58)	.001
repetition of fixations (SD)	4.71 (5.15)	0.36 (0.50)	0.14 (0.36)	.007
duration of fixations (SD)	0.19 (0.03)	0.19 (0.02)	0.19 (0.02)	n.s.

Table 32. Standard deviations of visual scanning parameters when processing 'value'.

Table 33 illustrates the outcomes of the t-test. All comparisons show significant differences except the comparison of case 2 with case 3 when analysing the repetitions of fixations. The users spent the least time to solve the task in case 3 indicated by the low degree of scan paths and the small number of fixations required to locate information of interest. When comparing the visual scanning parameters of case 1 with parameters of case 2 and case 3, it is surprising that users have to spend more time to solve the task, especially require more fixations and repetitions of fixations indicated by the unusually high degree of scan paths.

value			
time	t	df	p
case 1 / case 2	6.26	14	<.001
case 1 / case 3	6.81	14	<.001
case 2 / case 3	4.11	14	.001
degree			
case 1 / case 2	4.35	13	.001
case 1 / case 3	4.88	13	<.001
case 2 / case 3	4.19	14	.001
number of fixations			
case 1 / case 2	3.75	13	.002
case 1 / case 3	4.65	13	<.001
case 2 / case 3	3.28	14	.005
repetition of fixations			
case 1 / case 2	3.04	13	.010
case 1 / case 3	3.25	13	.006
case 2 / case 3	1.15	14	n.s.

Table 33. Significant differences between geovisualisation cases when processing 'value'.

Table 34 depicts the ANOVA results of visual scanning parameters when directly comparing the attention-guiding variables in case 1. Significant differences can be observed in all comparisons. When processing ‘hue’ in case 1 users needed the longest time to accomplish the task, followed by ‘value’. This is in accordance with the values of the ‘degree’ of scan paths, the ‘number’ and the ‘repetition of fixations’. Although users performance is rather low when processing ‘hue’ and ‘value’ in case 1, the duration of fixation reveals no significant differences. The variable ‘size’ reveals by far the lowest values indicating that users felt comfortable to accomplish the task in case 1 when information is coded with the variable ‘size’.

	Case 1					
	contour	hue	saturation	size	value	p
time (SD)	5.49 (1.90)	16.04 (11.53)	5.39 (3.10)	2.61 (1.20)	11.07 (5.08)	<.001
degree (SD)	77.75 (35.28)	204.09 (184.67)	87.78 (74.12)	29.20 (12.90)	172.29 (114.09)	.003
number of fixations (SD)	10.33 (5.50)	27.21 (21.99)	10.20 (7.02)	5.07 (2.74)	20.07 (13.27)	.002
repetition of fixations (SD)	1.33 (1.84)	7.29 (8.57)	1.93 (1.71)	0.40 (0.83)	4.71 (5.15)	.012
duration of fixations (SD)	0.21 (0.04)	0.20 (0.04)	0.19 (0.03)	0.19 (0.02)	0.19 (0.03)	n.s.

Table 34. Significant differences between attention-guiding variables in case 1.

Table 35 shows the outcomes of the parameter ‘time’ when comparing all variables in case 1. All comparisons show significant differences except ‘contour’ vs. ‘saturation’ as well as ‘value’ vs ‘hue’. The variable ‘contour’ is faster to locate than ‘value’. No significant difference is observed between ‘contour’ und ‘saturation’, while ‘contour’ is again faster detected than ‘hue’. In turn, ‘size’ is more appropriate to guide attention in case 1 than ‘contour’ as well as ‘saturation’ opposed to ‘value’. There is no significant difference between ‘value’ and ‘hue’ but ‘size’ is faster detected than ‘value’, ‘saturation’ and ‘hue’. Finally users need less time to detect ‘saturation’ when opposed to ‘hue’.

case 1			
time	t	df	p
contour / value	-4.45	14	.001
contour / saturation	0.11	14	n.s.
contour / hue	-3.70	14	.002
contour / size	-5.81	14	<.001
value / saturation	3.59	14	<.001
value / hue	-1.73	14	n.s.
value / size	6.25	14	<.001
saturation / hue	-3.38	14	.005
saturation / size	3.77	14	.002
hue / size	4.35	14	.001

Table 35. Significant differences in ‘time’ between attention-guiding variables in case 1.

Table 36 tabulates show a the outcomes of the parameter ‘degree’ when comparing all variables in case 1. Except the comparison of ‘contour’ with ‘saturation’ and ‘value’ with ‘hue’, all comparisons reveal significant differences.

case 1			
degree	t	df	p
contour / value	-3.40	13	.005
contour / saturation	-0.51	14	n.s.
contour / hue	-2.51	13	.026
contour / size	5.54	14	<.001
value / saturation	2.29	13	.039
value / hue	-5.98	13	n.s.
value / size	4.64	13	<.001
saturation / hue	-2.26	13	.042
saturation / size	3.17	14	.007
hue / size	3.44	13	.004

Table 36. Significant differences in ‘degree’ between attention-guiding variables in case 1.

Table 37 contains the outcomes of the parameter ‘number of ‘fixations’ (t-test) when comparing all variables in case 1. Except the comparison of ‘contour’ with ‘saturation’ and ‘value’ with ‘hue’, all comparisons reveal significant differences.

case 1			
number of fixations	t	df	p
contour / value	-2.72	13	.017
contour / saturation	0.07	14	n.s.
contour / hue	-2.93	13	.012
contour / size	3.23	14	.006
value / saturation	2.23	13	.044
value / hue	-1.33	13	n.s.
value / size	4.33	13	.001
saturation / hue	-2.68	13	.019
saturation / size	2.75	14	.016
hue / size	3.66	13	.003

Table 37. Significant differences in ‘number of fixations’ between attention-guiding variables in case 1.

Table 38 illustrates the outcomes of the parameter ‘number of ‘fixations’ (t-test) when comparing the variables in case 1. In comparison to the ‘number of fixations’ the ‘repetition of fixations’ shows little significant differences. The highest value of ‘repetition of fixations’ of the variable hue (see Table 34) results from the significant difference when comparing ‘hue’ to ‘contour’ and ‘size’. Table 39 depicts the ANOVA results of visual scanning parameters when comparing the attention-guiding variables in case 2. There are no significant differences in ‘repetition of fixations’.

case 1			
repetition of fixations	t	df	p
contour / value	-2.33	13	.037
contour / saturation	0.90	14	n.s.
contour / hue	-2.85	13	.014
contour / size	1.68	14	n.s.
value / saturation	1.64	13	n.s.
value / hue	-1.29	13	n.s.
value / size	3.15	13	.008
saturation / hue	-2.14	13	n.s.
saturation / size	3.15	14	.007
hue / size	2.96	13	.011

Table 38. Significant differences in 'repetition of fixations' between attention-guiding variables in case 1.

	Case 2					
	contour	hue	saturation	size	value	p
time (SD)	3.01 (1.88)	3.67 (1.13)	2.98 (0.72)	2.20 (0.61)	2.55 (0.98)	.008
degree (SD)	32.77 (15.42)	48.61 (27.25)	37.94 (15.84)	28.47 (12.14)	34.36 (12.52)	.035
number of fixations (SD)	5.33 (2.89)	7.21 (1.67)	5.45 (1.36)	4.07 (1.10)	5.86 (2.32)	.004
repetition of fixations (SD)	0.33 (0.62)	0.43 (0.65)	0.00 (0.00)	0.00 (0.00)	0.36 (0.50)	n.s.
duration of fixations (SD)	0.20 (0.04)	0.21 (0.03)	0.19 (0.02)	0.19 (0.02)	0.19 (0.02)	.025

Table 39. Significant differences between attention-guiding variables in case 2.

Table 40 shows the results of the parameter 'time' when comparing the variables in case 2. There are no significant differences in parameters related to 'contour'. When searching for information coded with the variable 'size' users spent the least time to accomplish the task on demand followed by 'value'.

case 2			
time	t	df	p
contour / value	1.12	14	n.s.
contour / saturation	0.26	14	n.s.
contour / hue	1.36	14	n.s.
contour / size	2.01	14	n.s.
value / saturation	2.29	14	.038
value / hue	5.67	14	<.001
value / size	-3.00	14	.010
saturation / hue	3.41	14	.004
saturation / size	5.05	14	<.001
hue / size	6.89	14	<.001

Table 40. Significant differences in 'time' between attention-guiding variables in case 2.

Table 41 shows the results of the parameter ‘degree’ (t-test) when comparing the variables in case 2. There are only two significant differences when comparing ‘value’ with ‘hue’ and ‘hue’ with ‘size’. When processing ‘hue’ in case 2 users employed the highest ‘degree’ of scan paths to detect the important information and the lowest ‘degree’ to detect ‘size’.

case 2			
degree	t	df	p
contour / value	-0.36	14	n.s.
contour / saturation	0.90	14	n.s.
contour / hue	1.96	14	n.s.
contour / size	0.83	14	n.s.
value / saturation	2.29	14	n.s.
value / hue	1.15	14	.035
value / size	-1.45	14	n.s.
saturation / hue	1.46	14	n.s.
saturation / size	1.78	14	n.s.
hue / size	2.71	14	.017

Table 41. Significant differences in ‘degree’ between attention-guiding variables in case 2.

Table 42 shows the results of the parameter ‘number of fixations’ (t-test) when comparing the variables in case 2. There are six significant differences. Especially the difference when comparing ‘hue’ to ‘size’ reflects that users need additionally about 3 fixations to detect the variable ‘hue’ (see Table 39). To visually scan for information coded with the variable ‘hue’, users needed the highest number of fixations in accordance with the highest degree of scan paths (see Table 39).

case 2			
number of fixations	t	df	p
contour / value	-0.40	14	n.s.
contour / saturation	-0.16	14	n.s.
contour / hue	2.32	14	.003
contour / size	1.76	14	n.s.
value / saturation	-0.27	14	n.s.
value / hue	2.30	14	.037
value / size	-2.78	14	.015
saturation / hue	3.60	14	.003
saturation / size	2.47	14	.027
hue / size	5.92	14	<.001

Table 42. Significant differences in ‘number of fixations’ between attention-guiding variables in case 2.

Table 43 depicts the results of the parameter ‘duration of fixations’ when comparing the variables in case 2. Only three significant differences can be stated. However, the standard deviation of ‘duration of fixations’ ranges from 0.19 to 0.21 (see Table 39), indicating that durations are relatively equally distributed.

case 2			
duration of fixations	t	df	p
contour / value	1.94	14	n.s.
contour / saturation	2.36	14	.034
contour / hue	0.37	14	n.s.
contour / size	2.08	14	n.s.
value / saturation	0.33	14	n.s.
value / hue	2.30	14	.037
value / size	-0.23	14	n.s.
saturation / hue	2.14	14	n.s.
saturation / size	0.66	14	n.s.
hue / size	3.62	14	.003

Table 43. Significant differences in ‘duration of fixations’ between attention-guiding variables in case 2.

Table 44 depicts the ANOVA of visual scanning parameters when comparing the attention-guiding variables in case 3. There are no significant differences in ‘repetition’ and ‘duration’ of fixations. When visually scanning for ‘value’, users needed the least time to accomplish the task, followed by ‘contour’ and ‘size’.

In contrast, to detect ‘saturation’ users needed the longest time to find relevant information, which corresponds to the high degree of scan paths and the high number of fixations. Although no significant differences are calculated for the repetition of fixations, it is outstanding that users also needed a high repetition of fixations when searching for ‘saturation’ in case 3.

	Case 3					
	contour	hue	saturation	size	value	p
time (SD)	1.95 (0.75)	2.55 (1.18)	3.21 (1.92)	2.21 (1.08)	1.85 (0.55)	.007
degree (SD)	21.51 (9.12)	37.06 (26.26)	42.69 (25.52)	24.51 (11.18)	23.12 (9.47)	.005
number of fixations (SD)	3.33 (1.40)	5.21 (2.86)	5.67 (2.82)	4.60 (2.82)	3.79 (1.58)	.028
repetition of fixations (SD)	0.00 (0.00)	0.21 (0.58)	0.40 (0.73)	0.20 (0.41)	0.14 (0.36)	n.s.
duration of fixations (SD)	0.18 (0.02)	0.19 (0.03)	0.19 (0.03)	0.19 (0.03)	0.19 (0.02)	n.s.

Table 44. Significant differences between attention-guiding variables in case 3.

Table 45 gives information about the parameter 'time' when comparing the variables in case 3. Only four significant differences can be observed where the variable 'saturation' takes part in the comparisons to 'contour', 'value' and 'size'.

case 3			
time	t	df	p
contour / value	0.62	14	n.s.
contour / saturation	2.79	14	.015
contour / hue	-1.98	14	n.s.
contour / size	1.41	14	n.s.
value / saturation	3.07	14	.008
value / hue	2.62	14	.020
value / size	1.79	14	n.s.
saturation / hue	1.70	14	n.s.
saturation / size	2.53	14	.024
hue / size	-1.56	14	n.s.

Table 45. Significant differences in 'time' between attention-guiding variables in case 3.

Table 46 shows the information about the parameter 'degree' when comparing the attention-guiding variables in case 3. Due to the high degree of needed scan paths to detect the information of interest, the comparison of 'saturation' with all variables revealed significant differences. Moreover, a significant difference can be seen by comparing 'value' to 'hue' because of the high value of needed degrees when processing 'hue' (37.06 SD) vs. value (23.12) (see Table 44).

case 3			
degree	t	df	p
contour / value	-0.72	14	n.s.
contour / saturation	3.44	14	.004
contour / hue	-2.46	14	.027
contour / size	2.19	14	.046
value / saturation	3.12	14	.008
value / hue	2.80	14	.014
value / size	0.44	14	n.s.
saturation / hue	0.77	14	n.s.
saturation / size	3.42	14	.004
hue / size	-1.93	14	n.s.

Table 46. Significant differences in 'degree' between attention-guiding variables in case 3.

Table 47 reveals information about the parameter 'number of fixation' when comparing the attention-guiding variables in case 3. Five comparisons of attention-guiding variables are not significant. As a result of long search time and high degrees of scan paths, the comparison of 'saturation' with 'contour' and 'value' shows significant differences. Additionally, when comparing 'hue' with 'contour' and 'value', significant differences can be observed because of the high number of fixations needed to detect information coded with hue.

case 3			
number of fixations	t	df	p
contour / value	-0.66	14	n.s.
contour / saturation	2.75	14	.016
contour / hue	-2.36	14	.033
contour / size	2.04	14	n.s.
value / saturation	2.45	14	.028
value / hue	2.43	14	.029
value / size	1.40	14	n.s.
saturation / hue	0.67	14	n.s.
saturation / size	1.45	14	n.s.
hue / size	-0.55	14	n.s.

Table 47. Significant differences in ‘number of fixations’ between attention-guiding variables in case 3.

Although ‘size’ was declared as one ‘winning variable’ of the paper-and-pencil test, there are no significant differences when comparing all cases.

8.4 Discussions

For a proof of the attention-guiding concept, the evaluation of the three design cases (cognitively adequate geovisualisation but with unfiltered information, cognitively inadequate geovisualisation but with filtered information, and cognitively adequate geovisualisation and with filtered information) is discussed in the following.

The cognitive adequacy of the design approach is analysed by evaluating the visual scanning efficiency of users (see section 2.7) for the three cases of geovisualisation design. High visual scanning efficiency of geovisualisation is proven when the information complexity is reduced to decrease the cognitive workload and to increase the performance respectively. The parameters ‘searchtime’, ‘degrees’, and ‘number of fixations’ are of prime interest to judge the speed and accuracy of visual scanning.

To process three relevance classes of information coded with ‘contour’, the attention-guiding design proved to allow users the efficient scanning of relevant information. In contrast to case 1 and case 2, users spent the shortest ‘time’ (1.95 sec.), lowest ‘degrees’ (21.51°) and smallest ‘number of fixations (3.33) to solve the task (see Table 25). When processing ‘contour’ in case 1 users needed the longest ‘time’ (5.49 sec) and the highest ‘number of fixations’ (10.33) for visual scanning. This result is reflected in the high value of the ‘degree’ of scan paths (77.75°), that indicates an ineffective visual search compared to case 3. Although case 1 consists of visual hierarchies to stimulate the centre-surround mechanism and functions of visual brain areas involved in figure-ground segregation (V2, V4, ITC) users had difficulties to rapidly find the information of interest. All variables in case 1 revealed this trend because gazes of users were distracted by unfiltered information. Figure 67 illustrates the distractive effect of unfiltered information coded with ‘value’ in case 1 that has led to slow and inaccurate visual scanning of geovisualisations.

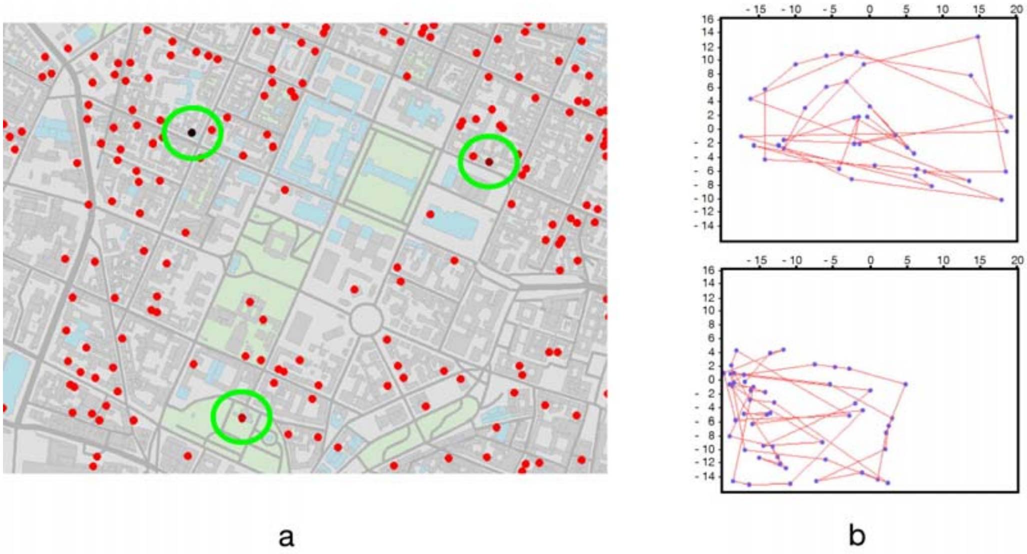


Figure 68. The distractive effect of unfiltered information a) information coded with ‘saturation’ case 1 and b) two corresponding gaze plots.

In comparison to results of the paper-and-pencil test that considered all attention-guiding variables as being potential attractors, the visual scanning parameters reveal that ‘saturation’ is more effectively processed in case 2 than in case 3. Because no significant difference between both cases in ‘time’ and ‘degree’ exists (see Table 31), saturation might be a potential variable to visualise relevance classes even if the complex context information is saliently visualised. Figure 68 depicts the visualisation of relevant information with ‘saturation’ in both cases and the corresponding gaze plots.

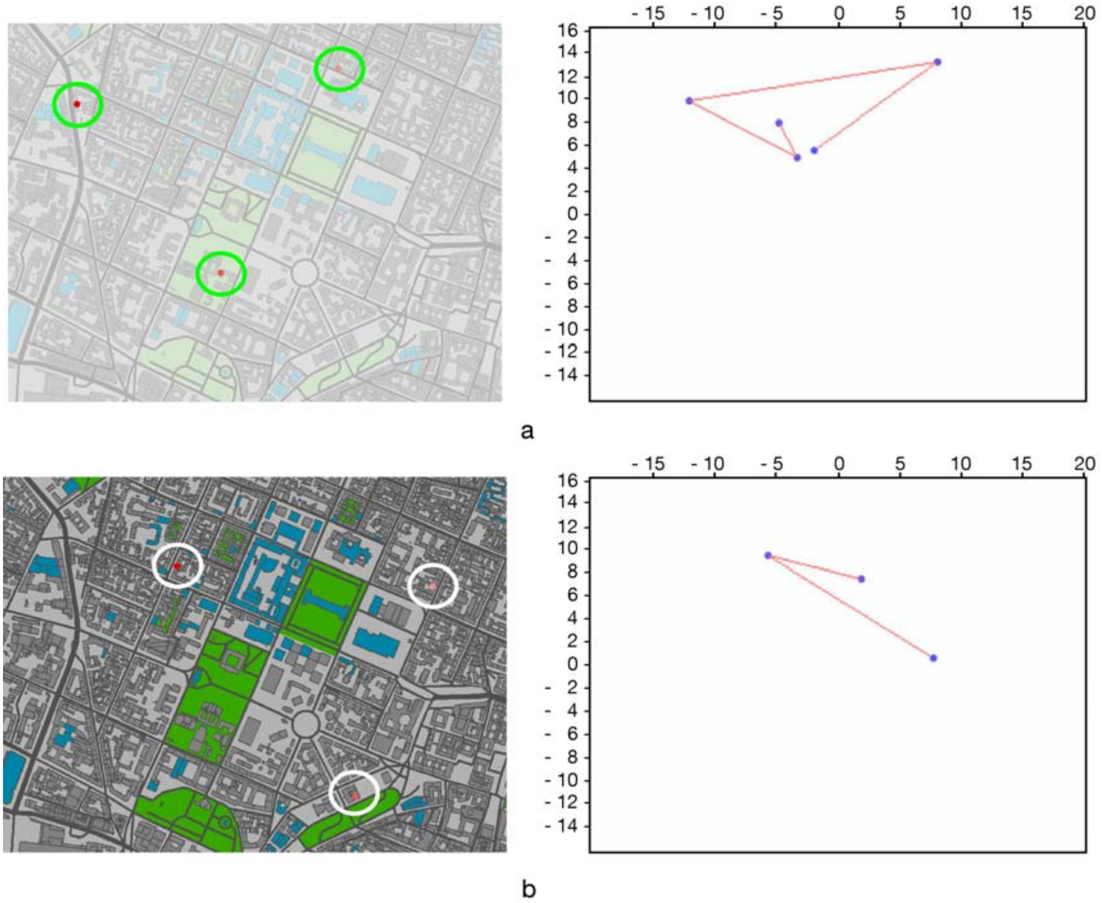


Figure 69. Visual scanning for the variable ‘saturation’ in a) case 3 with the corresponding gaze plot and b) case 2 with the corresponding gaze plot.

When comparing the number of fixations between case 2 and case 3 a significant difference can be stated (see Table 30). The mean number of fixations is 5.67 in case 3 and the in case 2 5.45. The statistical analysis revealed that some subjects employed ‘repetition of fixations’ in case 3. This can probably be attributed to the low saturation value of the point symbol in the upper right corner coding the ranking class 3. Users had to re-fixate this symbol before solving the task. Bearing in mind the adjustment problem of context information (see section 7.4) the results of the eye movement recording reveal a second question when adjusting values of ‘saturation’: *What degree of saliency decrease can be processed by the user without loosing relevant information?* Hence, ‘saturation’ supports users in promptly locating one or two relevance classes in case 3 but worsen the visual scanning performance of further classes because of too low intensity contrasts. This visual scanning deficiency in the attention-guiding design is restricted to the variable ‘saturation’ and demands a careful adjustment of ‘saturation’ when coding relevance classes.

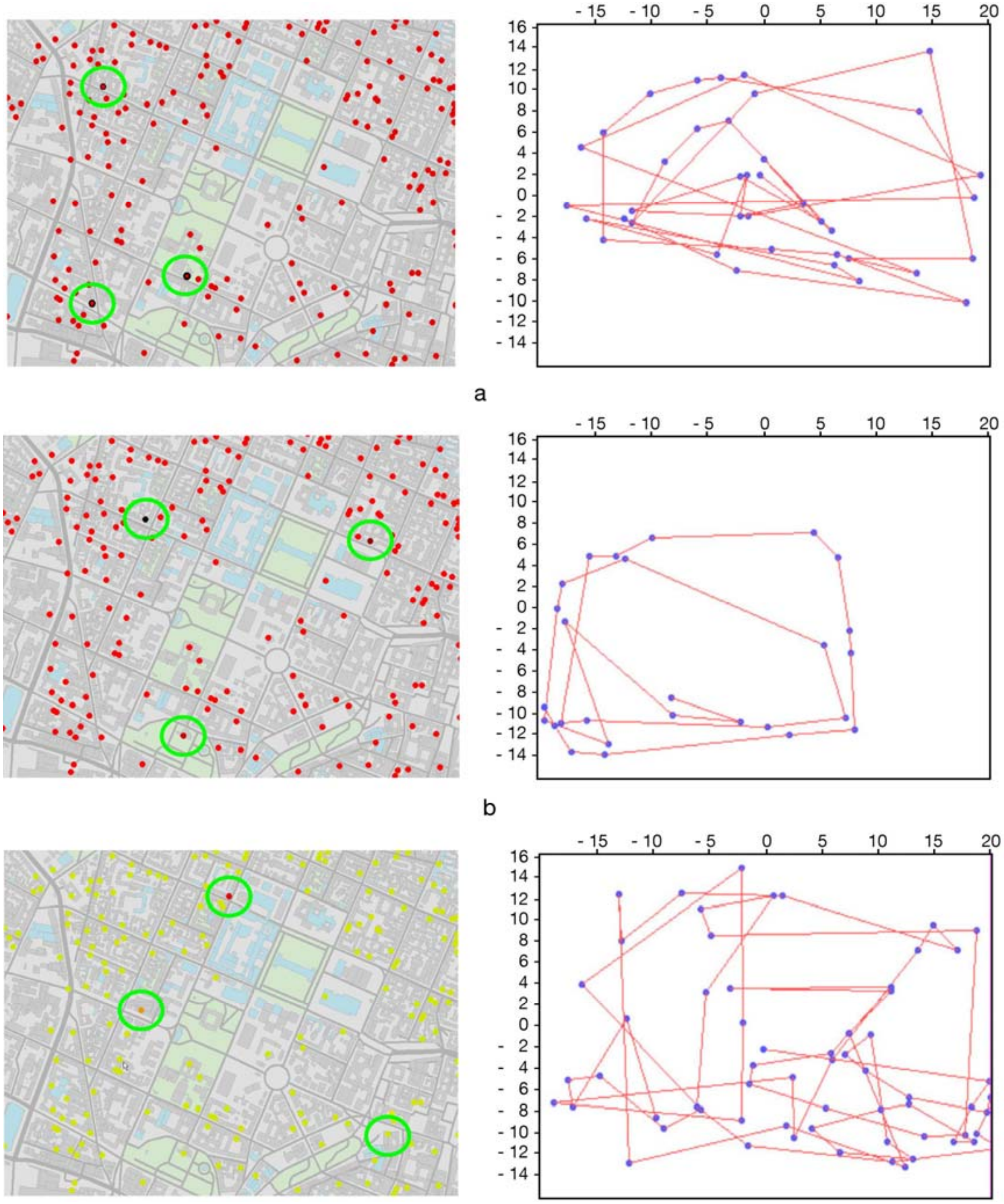


Figure 70. Relevance classes in case 1 coded with a) ‘contour’, b) ‘value’, and c) hue, and corresponding gaze plots.

Like the outcomes of the paper-and-pencil test, the statistical analysis of the eye movement recording confirms that the attention-guiding approach is the most suitable to visually scan for relevant geographic information. Except for the abovementioned adjustment problem of 'saturation' in case 3, the visual scanning parameters illustrate that all variables effectively guide a users attention to relevant information when following the proposed design methodology.

While the statistical analysis of the paper-and-pencil test does not reveal differences between case 1 and case 2, the visual scanning parameters of the eye movement recording show significant differences in the cognitive adequacy between both cases except for the variable size (see Table 31). The variables 'contour', 'hue', 'saturation', and 'value' reveal significant differences between the parameters when analysing the paired t-tests of case 1. Whenever case 1 was related to the parameters 'time', 'degrees', and 'number of fixations' of case 2 and case 3 it shows significant differences except for the variable 'size'. Figure 70 depicts the design case 1 for the variables 'contour', 'value' and 'hue'.

Just as 'size' is determined in section 7.4 as the 'winning' variable, case 1 can be regarded as the 'loosing' design methodology. The distractive effect of the unfiltered class 4 obligated users to investigate a high number of fixations and saccades. The visual scanning patterns consist of complex sequences of scan paths that are characterised by high degrees. When visually processing case 1 users showed low performance due to high information complexity and an increasing cognitive workload. Hence, the visual scanning efficiency of users was low. Although case 1 is considered as cognitively adequate, the visual scanning performance is largely affected by visual distractors in form of unfiltered information. Users had less difficulty to solve the task when visually scanning the design examples of case 2. When comparing all design cases, the attention-guiding approach (case 3) proved to be more adapted to the users cognitive skill (i.e. more cognitively adequate) than other design approaches. Furthermore, the distractive influence of unfiltered information (case 1) has a greater distractive impact on the performance of a user than the distractive influence of context information in the visual foreground of geovisualisations (case 2).

The effectiveness of proposed variables to guide user's attention to relevant information is evaluated by analysing the ANOVA results of visual scanning parameters and comparing the visual scanning parameters of attention-guiding variables in all design cases. When visually scanning for information in the design case 1 subjects needed 2.61 seconds to find the most relevant information coded with 'size' followed by 'saturation' (5.39) and 'contour' (5.49) (see Table 34). In contrast, to decode geographic information coded with the variable 'hue', the average time to solve the task is 16.04 seconds indicating that the task performance was low when visually processing the geovisualisation depicted in Figure 70c. The distractive effect of unfiltered information in case 1 is additionally reflected by analysing the parameters 'degree', 'number' and 'repetition' of fixations. When searching for 'hue', subjects employed the average number of 27.71 fixations and 7.29 repetitions of fixations and 204.09 degrees of scan paths to detect the relevant information followed by value (20.07 / 4.71 / 172.29) that is illustrated in Figure 70b. Accordingly, the attention-guiding strengths of the variable 'size' is underlined by the parameters 'number of fixations' (5.07), 'repetition of fixations (0.40), and 'degree' (29.20).

In contrast to case 1 users were able to quickly locate (2.55 seconds) relevant information coded with 'value' following 'size' (see Table 32). The attention-guiding strength of the variable 'size' is illustrated in Figure 71. Although the design case 2 is not based on the principles 'visual hierarchy' and 'conciseness' the subject visually scanned the geovisualisation in 2.08 seconds (mean time: 2.20 seconds) by employing five gaze fixations (mean number: 4.07) to solve the task. The scan path from the point symbol in the lower left corner to the point symbol on the right side of the geovisualisation reveals that the most relevant information in the upper left corner was processed in a more global mode. The location of the second fixation does not correspond to the location of the largest size symbol. After having processed the first symbol in a more local manner, the second symbol was captured by the field of attention during global processing before the subject switched into a more local mode to detect the third symbol. The local processing of the third symbol is furthermore characterised by short frequencies and high degrees of the scan paths between the second and last fixation.

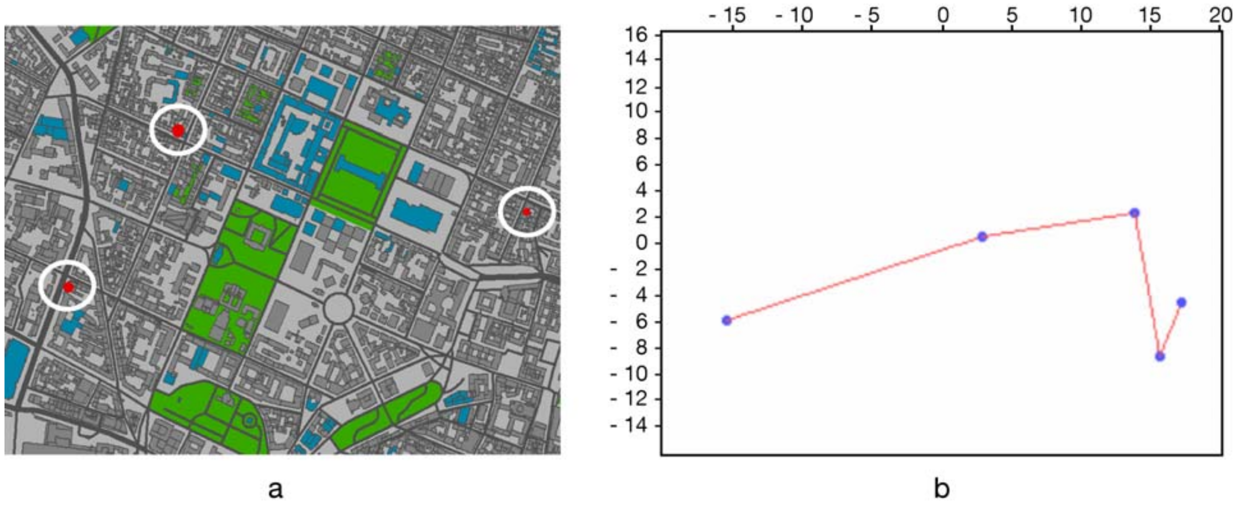


Figure 71. a) Visual scanning for ‘size’ in case 2 and b) a corresponding gaze plot.

Figure 72 gives information of a user’s visual scanning strategy when processing relevant information coded with the variable ‘hue’ in case 2. The scanning pattern reveals a more local processing of relevant information because the location of gaze fixations correspond to the location of visual targets. The subject visually scanned the geovisualisation in 3.66 seconds (mean time: 3.67 seconds) by employing seven gaze fixations (mean number: 7.21) to solve the task. In contrast to ‘size’ where the average degree of scan paths is 28.47, the average degree of scan paths in this example is 48.61 reflecting the higher number of fixations and indicating a more time-consuming scanning strategy.

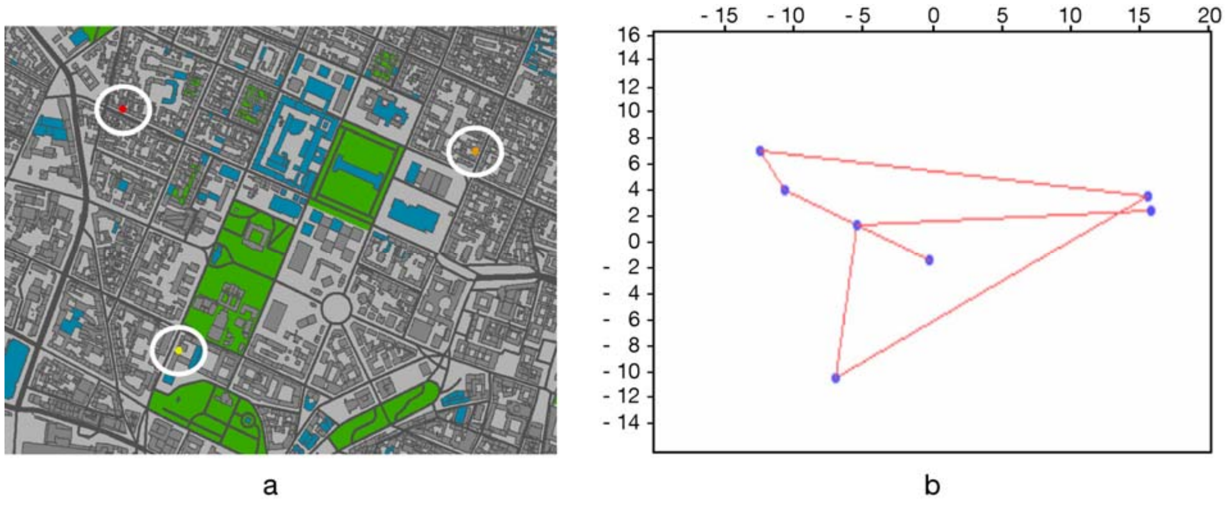


Figure 72. a) Visual scanning for ‘hue’ in case 2 and b) a corresponding gaze plot.

To identify the ‘winning’ variable in the attention-guiding methodology it is necessary to analyse the visual scanning parameters illustrated in Table 44 and the corresponding t-tests. Although ‘size’ is promptly located in an average time of 2.21 seconds, the variables ‘value’ (1.85 seconds) and ‘contour’ (1.95 seconds) proved to be more suitable to guide a user’s attention to relevant information. The attention-guiding strength of ‘contour’, ‘value’, and ‘size’ is reflected in their degrees of scan paths (21.51 / 23.12 / 24.15) opposed to ‘hue’ (37.06) and ‘saturation’ (42.69). However, a high degree of scan paths does not automatically indicate a low performance. If relevant geographic information is highly distributed, users are forced to increasingly change the direction of scan paths although the information of interest is coded with attention-guiding attributes. A more aligned positioning of relevant information would probably reveal lower degrees of scan paths. To avoid this effect, the relevant information in case 3 was positioned by approximately maintaining the same distances and directions of locations (see Figure 73).

Figure 73. Chronological order of the winning variables a) 'value', b) 'contour', c) 'size', d) 'hue', and e) 'saturation'.

One reason for the suitability of ‘value’, ‘contour’, and ‘size’ to guide visual attention in case 3 can be related to the functions of the visual brain areas V2, V3, and V4 involved in colour hue processing, contour processing, and size processing. Moreover, V2 and V4 are concerned with figure-ground segregation and detecting salient objects. Figure 74 illustrates the responsiveness of visual areas when processing the ‘winning’ variables.

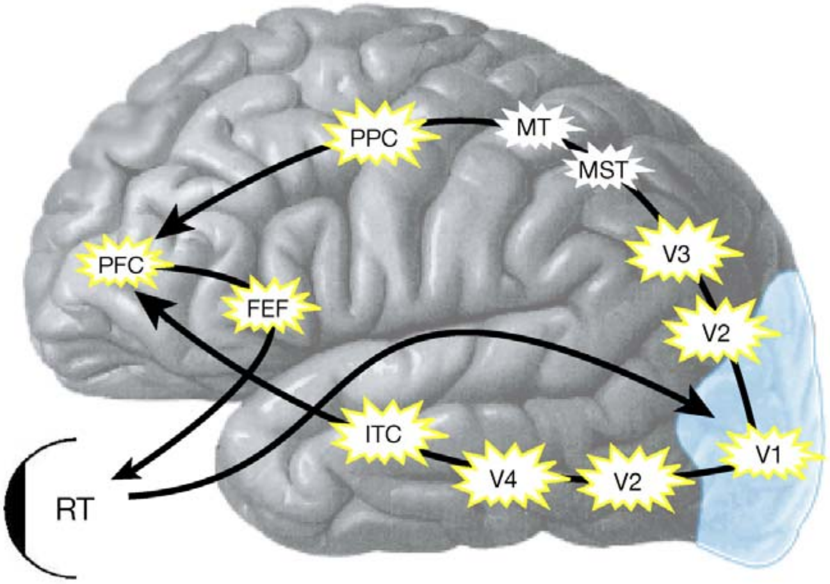


Figure 74. Brain areas showing high responsiveness when processing the ‘winning’ variables ‘value’, ‘contour’, and ‘size’.

Based on the design approach to systematically stimulate visual areas along the signals processing pathways and to release the signal converting system, the evaluation of visual scanning patterns reveals that the attention-guiding design approach is desirable to optimise visual geographic information processing. This visual scanning capability rapidly decreases when processing the variables ‘hue’ and ‘saturation’ (Figure 73d, 73e), probably because of too low information contrast between the focal and the context information.

The outcomes of the eye movement recording underline the necessity of the proposed design principles and the cognitive adequacy of the developed attention-guiding design methodology. Implementing attention-guiding variables in the attention-guiding design methodology significantly enhance the visual scanning efficiency of geovisualisations.

8. Conclusions and outlook

The main hypothesis of this research is that combining cognitive and usability issues in geovisualisation design can significantly improve the performance of visual geographic information processing and consequently contribute to a better acceptability of geographic information systems. On the theoretical basis of external geovisualisation and internal visual information processing a conceptual framework for developing attention-guiding geovisualisation is proposed to confirm this hypothesis. Within this framework the cognitively adequate visualisation as a criterion of systems usability and the relevance-based filtering of geographic information as a criterion of system's utility are integrated in an attention-guiding design methodology with the intention to effectively guide a user's visual attention to relevant geographic information. The cognitive evaluation proved the feasibility and potential of the attention-guiding design approach.

The conceptual framework contributes to the reinforcement and extension of cognitive research in GIScience. To summarise, this research has accomplished the following tasks:

- interdisciplinary approach of cognitive research in GI science and cognitive psychology
- synthesis of research findings from external geovisualisation and internal visual information processing
- integration of cognitive and usability issues in attention-guiding geovisualisations
- implementation and cognitive pre-evaluation of the attention-guiding design methodology in pixel-based and vectorised geovisualisations
- cognitive evaluation of vectorised attention-guiding geovisualisations
- statistical confirmation of the efficiency of the cognitive approach within a geographic information system

The investigations of user abilities of visual information processing is in line with recommendations of GI scientists (e.g. Meng 2003, Lobben 2004, Dykes et al. 2005) and geovisualisation research agendas (MacEachren & Kraak 2001, Slocum et al. 2001, Chinchor et al. 2005). A number of research issues worth a discussion here.

Cognitive research in GI science. Chapter 1 has illustrated the evolution and application of cognitive research in GI science. One important issue is the absence of underlying cognitive theories to adapt geovisualisation to user's capability of visual information processing, although several cognitive approaches were proposed by researchers to conceptualise the interrelation between geographic data, geovisualisation design, and the user who visually processes these geovisualisations in the geographic space (e.g. MacEachren 1995, Ware 2004). These concepts represent potential approaches to model geographic information processing. Due to the complexity of visual geographic information processing, it is obvious that some concepts result in complex frameworks (e.g. Koláčný 1969). Moreover, cognitive research concerned with the adaptation of computer's capability of geographic data processing to user's cognitive skill of visual geographic information processing is insufficient because of missing investigations of internal cognitive processes. A possible way of closing this research gap is to open the black box, i.e. to first study the internal characteristics of information processing and to integrate acquired knowledge in the design of geovisualisations in a second step. The existing mismatch between technology-driven and user-centred research can be adjusted by collaborating with cognitive psychologists. Because of this interdisciplinary research, GI scientists profit from the standardised evaluation methods for establishing a contemporary taxonomy of graphical variables.

Visual geographic information processing. This work does not mean to serve as an exhaustive explanation of visual geographic information processing due to the complex internal processes of involved brain areas that are far from being understood in their entirety. Rather, it offers a cognitive approach that is based on the functional partition of visual geographic information processing, i.e. to support visual geographic analyses by stimulating specific functions of visual brain areas involved in visual scanning. Here, the proposed design methodology solely focuses on effectively visualising the location of relevant information. This does not necessarily implicate that the underlying semantics of the relevance classes can be easily decoded. In other words, someone is probably able to promptly locate the most important information and to relate this information to spatial dimensions. However, if the symbolisation is not appropriate to encode the semantics of the information displayed, users have to employ more mental effort, which will decrease the efficiency of visual information processing. Further research in the field of semiotics can help to investigate the potentials of symbolisation to produce a stronger activation of visual brain areas along the ‘what’ path. The outcome of such studies will probably help to optimise the speed and accuracy of decoding the meaning and relevance of geographic information. The cognitive approach of attention-guiding geovisualisation can serve as a starting point for a more systematic, and consistent design of geovisualisations.

Investigation of the design methodology. All graphical variables and possible combinations can be implemented in geovisualisations that guide user’s attention. It is therefore important to evaluate new promising graphical variables. For example, the variable ‘motion’ including its sub-dimensions might considered as a potential variable to guide the attention of users to relevant information due to high responsiveness of visual brain areas along the ‘what’ pathway. With regard to the concept of visual hierarchies, it is of interest to study the design of the spatial context information. An important research question is how to regulate the salience degree of irrelevant information and how to tackle the overlap of important information when using the variable ‘size’.

In addition to the above mentioned investigation of designing visual semantics, the following cognitive research tasks are of interest in the long run.

- integration of further cognitive and usability issues by e.g. involving topical or situational relevance or by focusing on the tasks of geographic data exploration
- extension of design principles and cognitive design methodologies to reduce information complexity and enhance visual scanning efficiency
- optimisation and realisation of the visual scanning efficiency model to advance geovisualisation design and to provide a basis for cognitive evaluation methods
- investigation and standardisation of cognitive evaluation methods to establish a scientific basis for empirical research and to improve knowledge acquisition of visual geographic information processing
- establishment of an up-to-date taxonomy of graphic variables for geovisualisations

All these tasks will contribute to the overall acceptability of geographic information systems and geovisualisations needed for fast and accurate decision-making processes.

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