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# Design Guidelines for Effective Visualisations on the Basis of Empirical Studies

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# Design Guidelines for Effective Visualisations on the Basis of Empirical Studies

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# Abstract

The need for human maintenance of complex systems and monitoring huge data is present in many fields of informatics. This especially applies for Traffic Management Systems (TMS), which need to visualise highly dynamic spatio-temporal datasets, such as from Floating Car Data (FCD), in order to improve their quality of service [22]. This quasi-real-time data from individual vehicles is a new and cost-effective source for traffic data because there is no need for additional hardware or maintenance, but due the massive amount of data this also poses new challenges for visualisation techniques.

To work properly with visual information systems their design has to meet the principles of human perception. A well designed visualisation efficiently conveys the desired information to the targeted audience considering the task of the visualisation (i.e. exploration, confirmation, presentation).

This thesis aims to improve the understanding of human perceptual and cognitive processes by studying the comprehensive literature to spatial and temporal information and visual displays of such information. Current TMS, which use FCD, and their requirements get described and their advantages as well as disadvantages are shown.

This work gives an overview of relevant theories and results of empirical studies in the fields of the human visual system and animation. It further provides a catalogue of design guidelines which are categorised in the following context groups: visual perception, geographic data, perception of motion, monitoring tasks and interaction.

The guidelines were developed with the help of Spence' and De Bruijn's framework for theory-based interaction design [21] which extracts knowledge of empirical results and forms it in a simply structured way to better inform interaction designers. The aim is to provide all the information necessary so that it is possible for designers to apply them correctly without having a deep understanding of cognitive theories. The thesis therewith is supporting the design of complex, dynamic visualisations in order to accomplish optimal visualisation techniques for traffic management displays.

# Kurzfassung

In vielen Bereichen der Informatik müssen große Datenmengen von Menschen überwacht und verwaltet werden. Dies trifft vor allem bei Verkehrsregelungssystemen zu, welche Quasi-Echtzeit Daten, wie sie zum Beispiel von Floating Car Daten geliefert werden, geografisch visualisieren müssen um angebotenen Dienste zu verbessern [22]. Die Verwendung einzelner Fahrzeugdaten ist eine neue und kostengünstige Methode Verkehrsdaten zu sammeln, da keine externen Sensoren an Straßen installiert und verwaltet werden müssen. Aufgrund der Menge an entstehenden Daten ergeben sich neue Ansprüche und Herausforderungen an die Informationsvisualisierung.
Um einen fehlerfreien Umgang mit visuellen Informationssystemen zu ermöglichen, muss deren Gestaltung der menschlichen Wahrnehmung gerecht werden. Eine gut gestaltete Visualisierung übermittelt die gewünschte Information spezifisch an das Zielpublikum in Anbetracht der Funktion der Darstellung (dh. Erforschung, Bestätigung, Präsentation).
Diese Diplomarbeit hat zum Ziel, Wissen über menschliche visuelle und kognitive Prozesse mittels weitgreifender Literatur zu Visualisierung räumlicher und zeitlicher Information und deren Darstellungen zum besseren Verständnis aufzubereiten. Aktuelle Verkehrsregelungssysteme die Floating Car Daten verwenden und deren Anforderungen werden beschrieben, sowie die Vor- und Nachteile, welche eine Nutzung dieser Daten mit sich bringt, werden aufgezeigt.
Die Arbeit umfasst relevante Theorien und Ergebnisse aus empirischen Studien im Bereich der menschlichen visuellen Wahrnehmung und Animation. Sie stellt ferner einen Richtlinien-Katalog zur Verfügung, kategorisiert nach den Kontextgruppen visuelle Wahrnehmung, geographische Daten, Wahrnehmung von Bewegung, Monitoring und Interaktion.
Die Richtlinien wurden mithilfe von Spence' and De Bruijn vorgeschlagenen Rahmenbedingungen [21] abgeleitet, welche Wissen aus empirischen Ergebnissen extrahieren und dieses in einfach strukturierter Form für Designer anbieten. Das Ziel ist dem Designer die gesamte benötigte Information zu geben um die Richtlinien ohne weiterem Hintergrundwissen anwenden zu können. Damit möchte die Diplomarbeit Designer bei der Gestaltung komplexer, dynamischer Visualisierungen unterstützen, speziell um eine optimale Darstellung für Verkehrsregelungssysteme gewährleisten zu können.

# Contents

# CHAPTER 1

# Introduction

The definition of visualisation changed with the development in computer graphics and psychological insights from an *internal construct* in the mind to an *external artefact* representing data or concepts to support decision making [81]. The process of visualisation not only generates graphics but cognitive representations of reality, which enable new insights into data by revealing patterns and relationships of data [11]. Cognition stands for the higher mental processes that are used to acquire, store and use information [12].

Spence [69] emphasises the simple definition of visualisation as the formation of a mental image of something. Ware [81, p.10] states

> ”Visualization can act as an extension of cognitive processes, augmenting working memory by providing visual markers for concepts and by revealing structural relationships between problem components.”

To understand the effects of visualisations it is necessary to know how perception works and how we *perceive* and *use* external visualisations [81].

Since the human visual system is sensitive to movement [8, 39], animated objects are especially attention-grabbing. Research in human vision has intensified to efficiently add more depth to traditional information transfer channels, i.e. static pictures or plain text. The added value of animations in comparison to static graphics is, however, controversial [77, 83]. Additionally research indicates that the visual system can only track four to five distinct motion trajectories simultaneously in the same visual field [8, 57].

Recently Kriglstein et al. [39] gave a systematic literature review about animation with the outcome that there are still few evaluation studies on animation for time-oriented data. Evaluations rather address general questions than specific questions on animation.

The principles of the human visual system are well investigated and many guidelines for perceptually salient graphics [16, 24, 34] supported by empirical studies [19, 28, 52, 67] exist. Some of them can be applied to animated graphics but many open questions remain with regard to the perception of motion, and studies are partially contradictory [39, 40]. Contradictory results often rely on different contexts. In particular, it is not clear which visualisation concepts should be applied for the presentation of Floating Car Data (FCD) in Traffic Management System (TMS). Of course, these should be optimised with regard to the principles of human perception.

To visualise real-world problems, multivariate data has to be represented in a two-dimensional screen space with attributes mapping data to graphical elements [45]. Interactive visualisations can be seen as extended multivariate displays, which want to overcome problems of static graphics by manipulating the view on the data.

The need for human maintenance of complex systems and monitoring huge data is present in many fields of informatics [7, 11]. This applies especially for TMS, which need to visualise highly dynamic spatio-temporal datasets, such as from FCD [22, 41]. Technological progress enables to garner real-time data from individual vehicles for a better quality of service in TMS. This produces massive amounts of data and animation seems to visualise time-oriented data especially effective.

This work investigates the effective visualisation of time-oriented data. It combines relevant theories and compares studies from different fields with the aim to create guidelines on the basis of empirical results for an improved design guidance. The guidelines support designers in their decision making during the development of user interfaces, in which motion is used for displaying temporal data. They can be applied to complex systems with big screens, like in traffic control centres with detailed digital maps. Adapted to the perceptual and cognitive limits of the human mind, they lead to an optimal design of graphic displays with comprehensible animations, where the user perceives what was intended to present and gets supported in monitoring tasks.

In co-operation with the Telecommunications Research Center Vienna (FTW) the area of TMS and existing design guidelines are discussed. The literature research focuses on the fields of geographic and dynamic data visualisation, as well as on human perception.

The main research objectives are:

- First, to identify patterns in the results of empirical studies about the effectiveness of visualisations and to form this existing knowledge into guidelines so that they are applicable by interface designers.
- Second, to figure out optimal visualisation techniques for FCD in TMS.

To accomplish that this thesis reviews empirical studies related to information visualisation in order to provide a specific set of guidelines for the design of animations. The deduction of guidelines will be done with the help of Spence' and De Bruijn's framework for theory-based interaction design [21].

The overall outcome of the studies will be compared and dominating results will be formed to guidelines, whereas the context will be declared in which they are relevant. Supporting as well as contradicting studies will be given for each guideline.

Chapter 2 describes the state-of-the-art in human perception of motion and dynamic visualisations, especially visualisation methods of FCD in TMS. Chapter 3 gives an introduction to the human visual system for information visualisation focusing on the perception of motion and dynamic changes. Characteristics of monitoring tasks and change blindness will be discussed.

The findings of the collaboration with the FTW are used to describe the requirements and use cases for TMS in chapter 4. The variety of visualisation techniques lets one expect that there is a need for design guidelines to facilitate efficient visualisations.

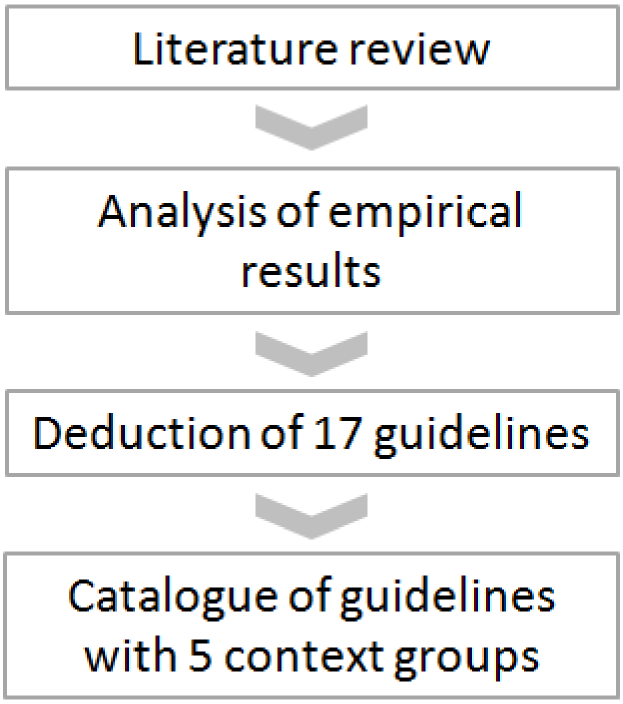


Figure 1.1: Approach of thesis.

In chapter 5 the guidelines and methodology of how they get derived will be described. Cognitive theories and references to dedicated empirical studies will be discussed. A compact catalogue of seventeen guidelines categorised into five context group follows. As a last part a critical reflection with comparison to related work and a summary will be given.

## CHAPTER 2

# State-of-the-art in Human Perception and Dynamic Visualisation

This chapter gives a brief overview of research in the fields of human perception, animation, evaluation methods and traffic visualisation. In addition existing design principles and approaches for their development will be discussed.

## 2.1 Perception of motion

In information visualisation the visual perception is based on dynamic virtual representations that either can be detailed or coherent, but not both at the same time. The virtual representation forms stable and coherent objects only for information needed for the task at hand, i.e. the common believe that a whole scene in the visual field is entirely represented in the human mind is wrong. The world is used as an external memory and due to visual disturbances we can fail to notice changes. This *change blindness* occurs when changes happen simultaneously with image flickers, eye blinks or real-world interruptions, even when those changes are made repeatedly and the observer knows that they will occur [57]. A more detailed treatment of this phenomenon will be given in the next chapter.

The construction of mental models for complex visual representations enables the filtering and abstraction for information of interest. Pre-attentive processes detect elements, that are evolutionary of interest, without effort at high speed. Hence, it is a necessity to know them when it comes to the design of elements which must be rapidly paid attended to [81]. Empirical studies show that extracted information of the pre-attentive process is perceptually salient rather than thematically relevant [19, 25, 42, 45].

The human visual system is less sensitive to moving spatial patterns, i.e. less sensitive to errors in regions with high spatial frequency patterns and movement. Yee et al. [86] exploit this reduced sensitivity to speed up the computation of global illumination in dynamic environments. Due to the eye's excellent ability to track objects in motion it is, however, not possible to apply this principle naively. The eye reduces the velocity of the areas of interest with respect to the retina to nullify the loss of sensitivity due to motion. By using a robust model of visual attention, Yee et al. [86] employed a method to predict where viewers direct their attention, which enables them to accurately derive the viewer's spatio-temporal sensitivity to the scene.

### Research in animation

Graphical displays use space to organise information in order to facilitate memory and inference by externalising information and simultaneously applying the power of spatial inference to other domains [77]. Animated visualisations present an increased amount of information in a more restricted time. To support processing of increased information in animations it is necessary to keep the cognitive load within the limited bounds of available capacity [42].

Nossum and Opach [53] state that animations support the users in their limited cognitive memory for a better knowledge creation process. Though, many animations are difficult to perceive and especially for novices the use of animation can be distracting instead of conveying the presented information. The general belief that animated graphics benefit in effective visualisations is questioned by Tversky et al. [77]. They argue that the lack of comparability of static and animated graphics generally leads to the wrong conclusion that animations are efficient per se and that user studies fail due to used procedures. In their paper they further point out that the efficiency promised by those evaluations are a consequence of the increased amount of information which comes within those animations or the use of interactivity.

Interactivity as a known factor to facilitate performance and the progress of learning can be used to overcome the drawbacks of animation. It is shown that in some situations graphics are not as effective as other media. Tversky et al. [77] also argue that for three-dimensional (3D) displays and animated graphics there is no evidence of an improvement in performance, speed, accuracy or memory for data and that animations are not universally preferred.

Animation speed can influence the ability to identify changes in the animation. Kriglstein et al. [39] and references therein describe that slower speeds are preferable so that it is possible to form consistent mental models. Robertson et al. [59] suggest that the control of animation speed can be beneficial.

Other studies state that animation can reveal subtle space-time patterns that are not evident in static representations, even to expert users who are highly familiar with the data [32].

The viewer of an animation needs to actively pay attention to the presentation in order not to miss some of the information, because animations display frames with changing content. Disappearance and split attention are mentioned as the most notable issues associated with map animations [32, 53]. Disappearance occurs when the user misses information due to passage of time whereas split attention occurs when the user is focusing on a particular area of the animation, e.g. the legend, so that he does not perceive the information in the main window.

Successfully animated graphics follow the congruence principle as well as the apprehension principle. According to them, structure and content of the external representation should correspond to the desired structure of the internal representation to be readily and accurately perceived and comprehended [77]. Another well-studied fact is that animations should be slow and clear. Schematic graphics, which are reduced to the essential information are preferred in comparison to realistic but rich ones [8, 77].

Nossum presents *semistatic animations* [53] as a new concept of map animation, where temporal information is integrated in each frame to overcome the aforementioned issues. A ”history view” shows information from past and future frames in every single frame of the animation, which enables better transparency of the information without the need to control the animation’s flow. Additionally the temporal legend is integrated in the history view to counteract on the split attention problem and support the perception of the temporal reference.

### Design principles

Guidelines for the design of information displays exist for different contexts. They assist the design in different ways including guiding a process, providing general and specific principles, capturing previous experiences or communicating good solutions [50]. The reuse of pre-designed solutions is an approach to utilise and apply design knowledge. Different contexts may render this impossible but if related taxonomies of cognitive work systems are developed instead, appropriate design methodologies could encourage the utilisation of existing design knowledge across different work domains [55].
Sutcliffe [71] describes claims that are design advices for specific scenarios, as an alternative to the representation of Human Computer Interaction (HCI) knowledge. He further suggests to generalise claims for future reuse. Bridging representations that build on models of interaction allow to create appropriate recommendations for designers from theory. But there are scalability problems when applying cognitive theories directly to design.
Spence [69] recently pointed out that cognitive and perceptual insights acquired by psychologists are too generic for the direct application by interaction designers. The knowledge needs to be formed in way to improve design guidance without the need for an extensive background research.
Spence et al. [21, 69] indicate that precise definitions of contexts, including human behaviour and intentions, are needed for the generation of applicable design guidelines. With the concept of *Design Actions* they demonstrate how cognitive theories can be formed into context sensitive guidelines for designers. This framework uses specific human behaviour to serve as a bridging mechanism and constitutes a detailed context. The aim is to create many detailed design actions, which are each relevant to a specific context.
Mayer’s seven design principles for multimedia presentations [44] are based on the cognitive theory of multimedia learning, according to which corresponding pictorial and verbal representations together improve meaningful learning. Mayer’s studies prove this theory and form the first principle as the ”Multimedia Principle”. The rest of the studies focus on the difference between effective and ineffective uses of animation. The ”Spatial Contiguity Principle” and the ”Temporal Contiguity Principle” state that deeper learning occurs if corresponding elements are near to each other in time and space respectively. Mayer’s ”Coherence Principle” advices to leave out irrelevant elements for deeper learning whereas the ”Modality Principle” argues that animation with narration results in better learning than animation with on-screen text. If using auditory and visual channels, the overload of one is less likely. The ”Redundancy Principle” also advices to leave out on-screen text if animation and narration is used together to prevent overloading the visual channel. The ”Personalisation Principle” suggests to style explanations conversationally, rather than a formally. This can be explained due to the fact, that people try

harder to understand an explanation when they get personally addressed.

Chang introduces a framework for structuring existing guidelines on the basis of Gestalt-based principles [16], which shall further support the development of new guidelines. The Gestalt theory, which states that ”the whole is greater than the sum of its parts” attempts to explain how we organise individual elements into groups and the way we perceive and recognise patterns. This theory from 1920 is still used for visual display design and will be further discussed in chapter 3.

Nesbitt introduces MS-Guidelines [50] for multi-sensory displays of abstract data. Categorised in levels of detail they support design considerations for vision, sound, touch and evaluation of the display. In comparison to traditional visualisation frameworks Nesbitt includes perception of events in time and how information is interpreted from temporal changes. General guidelines for perception and information display as well as more specific guidelines are provided for spatial visual metaphors and for direct and temporal visual metaphors. Temporal visual metaphors are summarised as movement, alarm and transition events.

## 2.2 Visualisation methods for floating car and likewise data

When visualising high traffic rates, the impression of data volumes, traffic flow and large-scale patterns are of interest [81]. Trajectory analysis searches for patterns in the movement of objects and contributes to the design of the space in which objects move, for example TMS. Nowadays we are able to track massive numbers of objects with detailed information for each (i.e. time, position), but the analysis of multiple attributes along all trajectories at the same time is difficult with current visualisation methods. Scheepens et al. [61] use a smoothing technique to show trends in object's trajectories by producing a density map which can encode further attributes next to speed and direction. Andrienko and Andrienko [5] show a method for spatial generalisation and aggregation to abstract the essential information of trajectories and to create flow maps. The level of data abstraction can be controlled by the user. Rinzivillo [58] suggests progressive clustering for the presentation of multiple trajectories.

Floating Car Data (FCD), also called probe vehicle data, is tracking data collected by a Global Positioning System (GPS). They usually contain recordings like speed and location but can as well provide more vehicle specific variables like the temperature or volume inside the vehicles in the future. Traffic Management System (TMS) aim to visualise these multivariate travel time information from individual vehicles in their road networks at the best to enable a better quality of service.

FCD are used for accurate traffic assessment and prediction as well as for related services such as accurate routing and navigation [22, 54, 79]. The visualisation can further uncover patterns in the spatial and temporal distribution of trajectory data and hence discover hot spots [78].

Current systems retrieve FCD from taxi fleets, public transport, private cars and combinations of those to visualise travel time maps [22, 78, 85]. Network operators have both short and long-term goals to guarantee quality of service. Often simple colour codes for speed rates from red and yellow to green are used to represent traffic fluidity in road networks, see e.g. Fig. 4.2.

A project in Hefei presents their results using real-time FCD from taxi fleets. Because they only cover a limited percentage of links per time interval, a substitution of information from historic

time series for missing values is done. Wang et al. [79] state that spatial resolution has to be improved to avoid biased results.
The Coordinated Highways Action Response Team (CHART) visualises the traffic situation for Maryland by an information layer on Google Maps. Speeds are encoded in three categories by coloured arrows, whereas the corresponding lane is represented by the pointing direction. Traffic Events such as incidents, congestions and special events are marked with squared icons, which have further partly similar colour encodings. Special closures, as for example bridges are displayed with an extra icon, which can be seen in Fig. 2.1.

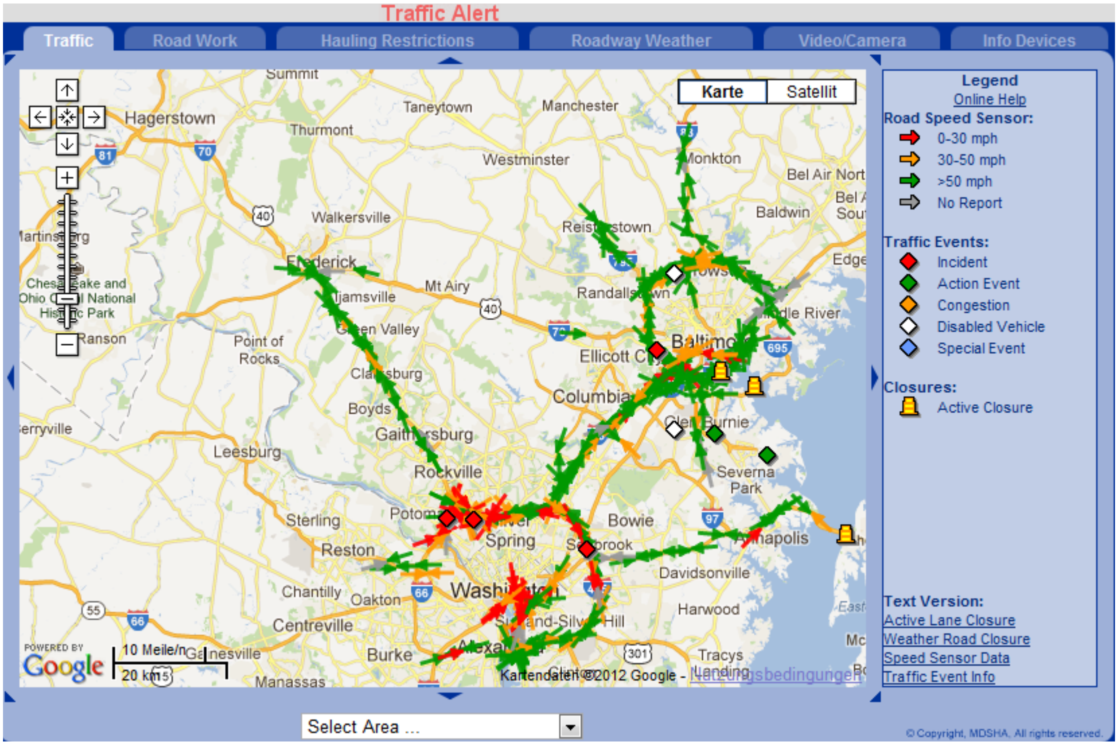
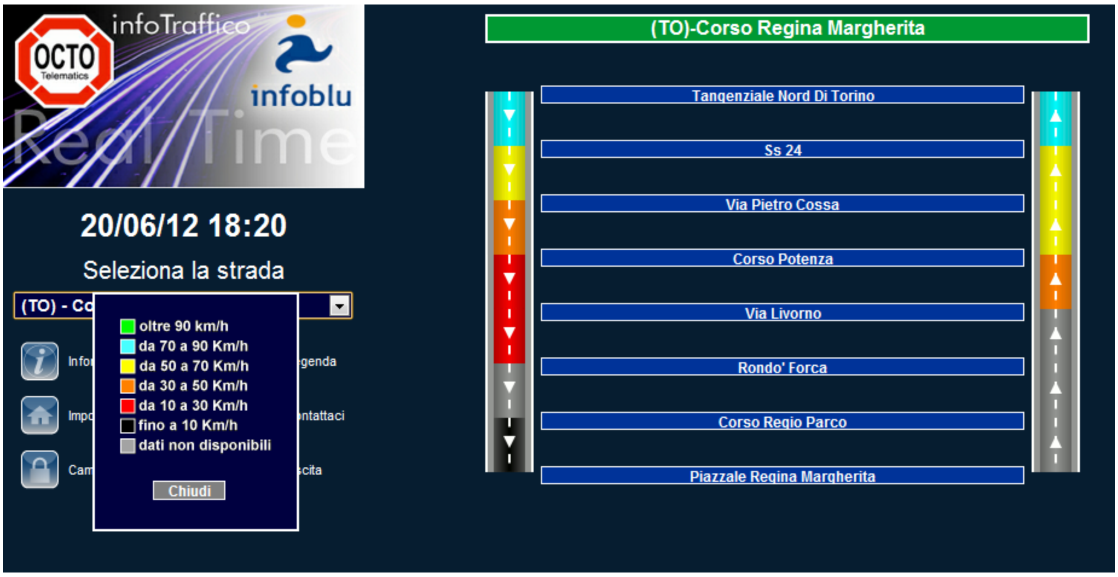


Figure 2.1: CHART - Coordinated Highways Action Response Team on the web [72].

Selecting the superimposed icons provides more detailed information (e.g. source, reporting time, measured road speed, direction, closed lanes) of speed detectors, incidents or closures.
A large-scale working application using FCD from about 600 000 cars to deliver real-time traffic speed information is presented in Fabritiis et al. [22]. It covers the Italian motorway network and some important arterial streets located in major Italian metropolitan areas and integrates a short term traffic forecast based on current and historic FCD. Traffic displays of single motorways, metropolitan areas (Fig. 2.2) and the entire Italian network (Fig. 2.3) can be selected for presentation. Travel speeds between links in the network are colour encoded between six intervals starting from lower than 10 km/h (black) to more than 90 km/h (green), see legend in Fig. 2.4.
Wörner and Ertl [85] visualise a real-world dataset of public transport vehicle movements in

Figure 2.2: Roma [74].

Figure 2.3: Italian motorway network [74].



🟩 oltre 90 km/h
🟦 da 70 a 90 Km/h
🟨 da 50 a 70 Km/h
🟧 da 30 a 50 Km/h
🟥 da 10 a 30 Km/h
⬛ fino a 10 Km/h
⬜ dati non disponibili

Figure 2.4: Display of a single motorway [74].

multiple views, consisting of a table view, a diagram view and a map view featuring linking and brushing. Graphical representations of data sequences get visualised in the diagram view, wherein it is possible to zoom and pan while a vertical line represents the cursor position. The table view displays the actual data where the data type gets highlighted by different background colours.

Multiple datasets can get overlaid for a good comparison of speed graphs or stacked, which gives a better overview over the course of a day. Over-plotting enables adding an average graph and displaying the standard deviation which shows up local conditions such as intersections or traffic as well as outliers that deviate from the common path, see Fig. 2.5. Such outliers can further be investigated in the table view.

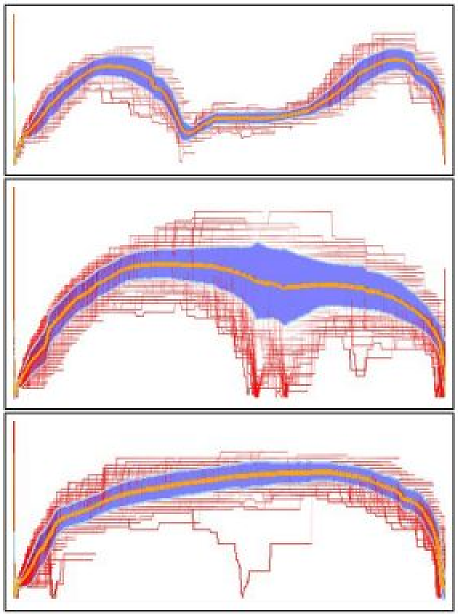


Figure 2.5: Diagram view of public transport vehicle movements [85].

The map view shows the corresponding vehicle positions if a graph is selected in the diagram view. Displaying jerks possibly shows up locations where conflicts happen, e.g. the rate of change of the acceleration of a vehicle along a route.
Wörner and Ertl [85] are interested in larger scale patterns and want to support the user in finding facts of interests by including more analysis tools. They suggest to identify different classes for trips and an automatic detector of outliers.
A novel hybrid simulation technique for real-time traffic visualisation combines continuous and discrete methods to use the advantages of both. Dynamic regions in the network are governed by either agent-based simulations that shows individual vehicle or continuum simulations that maximise efficiency. Switching the simulation method in a region enables observing certain phenomena and meeting performance requirements. For future work it would be interesting to use this technique to investigate the influence of individual vehicle behaviour to the overall traffic flow [64].

### Representation of Place and Space

Today's most prevalent visualisation of spatial information is the map [63]. The visualisation of physical spatial views and overlaying information onto objects, called ”augmented reality”, is the state-of-the-art technology in geographic visualisation systems. With the help of smartphones maps can be easily accessed on the streets. Map users get overlaying information on the map with location based places in geographic visualisations [13].

Interaction design is one of the most challenging areas in Human Computer Interaction (HCI) and interaction techniques are of special importance in the use of maps and will be further discussed in chapter 3.

## 2.3 Evaluation methods for information visualisations

The empirical evaluation of visual representations conducted with potential users possibly reveals potential problems and indicates actions to improve the quality of the visual representation [45]. The information visualisation research community has grown and well established itself, but there are still comparably few empirical studies which assess new solutions and theories [19, 37]. The difficulty of evaluating information visualisations is recognised by the community which asks for more qualitative evaluations to approach this problem. Generalisation, precision and realism can not be addressed equally in one study with current existing methodologies and therefore the choice of an appropriate research method for a specific content and a particular goal is of importance [15].

Empirical evaluations can be done by quantitative studies, like controlled experiments and qualitative studies, e.g. interviews. Both aim to provide feedback on the functionality, effectiveness, efficiency, and usefulness of a visual representation [45].

Methodological approaches for the evaluation of information visualisations should be rather qualitative than quantitative, especially because the interaction with it yields insights rather than information. Researchers argue that the measurements of time and error are not sufficient due to the exploratory nature of visualisation. Qualitative approaches can emphasise on the human reasoning processes as a whole to show up new patterns within data in contrast to the measurement of task performances [55].

Observation and interviews are the qualitative methods in empirical approaches, which typically result in continuous records or log files, e.g. video and audio tapes, discrete field notes or regular journal entries that mark events as they occur. With experimenter observations, thinking-aloud protocol or collecting participant's opinions laboratory studies often contain qualitative methods that enrich the quantitative results of laboratory experiments, e.g. giving explanations, raising new questions or confirming results [15].

*Observations of an experimenter* are subjective but can possibly offer explanation during interpretation. The *Thinking-Aloud Protocol* encourages participants to speak out loud what they are thinking during fulfilling a task in an experiment. They give additional insights but are not natural for the participant and reduce the realism of the study. Though the advantage of hearing the participants thoughts and plans out-weighs these disadvantages. The variation ”talk aloud” wants participants to announce their actions instead of their thoughts. The *collection of participant opinions* and preferences in quantitative studies is usually done by a questionnaire with pre-defined answers. As an example, to rate the participants attitude they ask the questions ”did you like it?” and give a Likert scale with a range of answers from ”strongly disliked” to ”strongly liked” [15].

Qualitative evaluation of visualisations can be done by traditional surveys as well as unobtrusive data gathering, e.g. by eye-tracking [15, 53]. Recent empirical studies have employed eye-tracking to analyse the perceptual saliency of graphics and individual visual analytical skills [19, 25, 37]. Recordings of eye movements are very useful to identify where problem areas are in system use and how the information might be processed [20].

*In situ observational studies* are field studies where the experimenter observes activities as they take place in situ and ideally remains unobtrusive. This can be hard to achieve in an actual setting but ideally after some time the observer fades into the background. Observations can also be recorded on video and analysed with eye-tracking technology. This methodology offers high realism and a rich context, but data collection and analysis is expensive. There are many other empirical methods for gathering primarily qualitative data, such as participatory observation, laboratory observational studies and contextual interviews [15].

Coltekin, referring to Noton and Stark's scan-path theory from 1971, suggests that eye movements have a strong correlation to moderating internal mental power and the scheme of visual activity. Eye movement analysis can be used to uncover visual analytic strategies of individuals and further enables to identify differences in group visual analytic activity patterns and strategies [19].

Nossum and Opach conclude from their experiments [53] that eye-tracking as a method for evaluating cartographic animations is a valuable tool to provide insights into the user's behaviour, which is not easily accessible from other methods. Furthermore they suggest to combine the eye-tracking technique with other evaluation methods in order to get a more diverse picture of the user's behaviour, especially when animated maps are used. With thinking-aloud protocols alone it might not be possible to understand the user behaviour in complex tasks, when the cognitive load is too high for the user to describe his inference making [20].

Empirical laboratory experiments are still difficult to publish because there is always a trade-off between generalisability, precision, and realism. When empirical results get published they should be detailed enough to make the processes fully comprehensible. The chosen methodology and why it fits to the situation and research goals should also be stated [15].

To this end, it appears that evaluating visualisations and designing appropriate methods is still a strong remaining challenge and is not a straightforward thing to do.

CHAPTER 3

# The Human Visual System

In this chapter cognitive theories concerning animation are presented. Perceptual phenomena (e.g. change blindness), the Gestalt Laws, working memory and attentional behaviour will be discussed. Additionally characteristics of monitoring tasks and types of changes are outlined.
HCI aspects in general have been discussed quite broadly in information visualisation in recent years. For an overview see e.g., Kerren et al. [36], Ware [81] or Ward [80].
The full scope of perception includes results from decades of research and theory about optics, colour and visual salient properties for static graphics. They are fundamental but in the course of this thesis it is not possible to go into detail for all of them. Elaborated information, summarised in a well structured way can be found in Ware's book [81] ”Information Visualization. Perception for Design”.
Ward et al. [80] give comprehensive information about the physiology of the human visual system. Weiskopf's work [84] specifies about the role of colour in flow visualisations and gives design guidelines for the use of colour for best motion perception.

## 3.1 Perception

Memory is the common ground for perception and reasoning. To understand how visual representations are perceived, cognitive psychology differentiates between three types of memories based on their memory retention (sensory, short-term and long-term memory). The properties of the sensory and short-term memory have important implications for visual representations [45].
Bertin proposed the visual variables theory in 1967 to describe the graphics system containing seven visual variables (position, size, colour, hue, shape, texture and orientation). He also called them retinal variables, because they can be processed effortlessly without any short-term and long-term memory work, as if the retina were doing all the work [27].
Pre-attentive processes of the sensory memory perceive information without conscious control almost instantaneously and therefore are fundamental for the design of visualisations. Psychological studies identified visual properties that ”pop-out” of the environment within less than 10

milliseconds due to pre-attentive processes. Ware categorised them into colour, form, movement and spatial position. Fig. 3.1 shows examples of form attributes [45, 81].

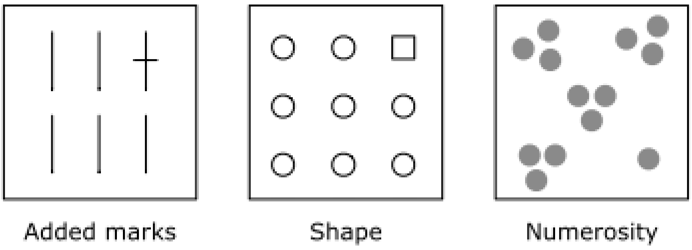
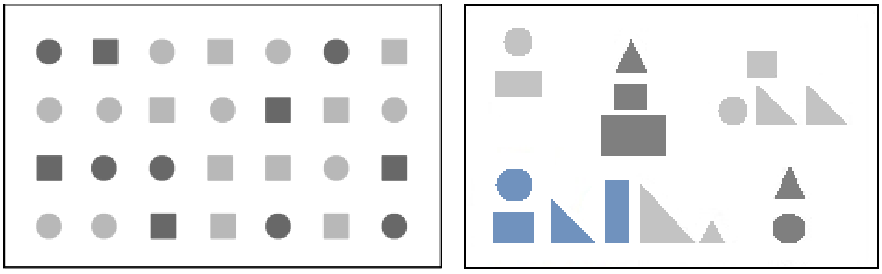


Figure 3.1: Examples of pre-attentive attributes of form [45].

Attributes of movement are the most effective attention grabbers and can be established as *flicker* and *motion* [45].
The mapping of information happens in the short-term memory, also called working memory, which can hold about seven items. Visualisations should support capacities of time and amount of information that can be kept in mind [45, 81]. In general the interaction techniques scrolling and split windows should be avoided as they cost a lot of memory space [45].
Combinations of two or more features are not automatically pre-attentively identified as seen in Fig. 3.2. Objects with the similar attributes of shape and lightness do not pop out together (Fig. 3.2(a)) but objects with same lightness independent of shape do instead (Fig. 3.2(b)).



(a) Colour and shape [45]. (b) Colour and spatial grouping.

Figure 3.2: The combination of pre-attentive attributes does not automatically lead to a pre-attentive conjunction.

Ware shows up conjunction pairs that build exceptions and still work pre-attentively together:

- Spatial grouping and colour: through the fast identification of visual clusters spatial grouping works pre-attentive together with colour (see Fig. 3.2(b)).
- Stereoscopic depth can get pre-attentively processed with colour or movement.
- Convexity or concavity can be conjuncted with colour.

- Motion and target shape can also be used together.

As a counter-example to the spatial grouping and colour conjunction the combination of shape and colour conjunction is not working, which is further illustrated in Fig. 3.3. The combination of stereoscopic depth and colour can be used to highlight items in order to support a pre-attentive search [10].

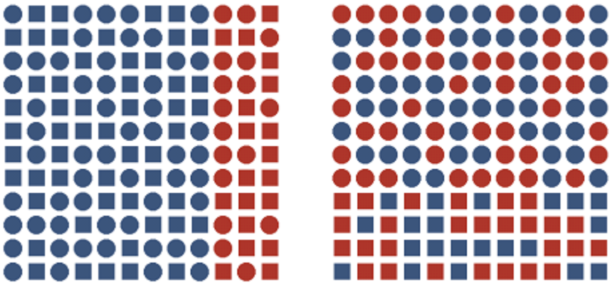


Figure 3.3: Combination of the attributes shape and hue, whereas region segregation works on the left though shape varies randomly in the two regions but does not work on the right for same shapes due to random hues [33].

The dual coding theory says that cognitive subsystems are separately dealing with different kinds of information. Thus for images and words exist different subsystems for the cognitive processing, but cross-references are needed to conceptually integrate them. Time and space can be used for that. Several studies show that it is possible to perceive events like hitting, pushing, and aggression when geometric shapes are animated in a simple way. Static graphics can not do that without words. Hence, animation brings graphics closer to words with their capacity to express causality [81].

The perception of objects was explored by Gestalt theorists from 1920 on and their theory is still valid today. Gestalt's basic principle is that *the whole is not the simple sum of its parts, but has a greater meaning than its individual components* [45]. Further principles try to explain the human perception and its organisation of visual elements into groups. The Gestalt Law's can offer insight into the design of visual representation. More detailed information can be found in [45, 82]. Novices as well as experts perceive paths of moving objects not accurately to the laws of physics, e.g objects are perceived closer to horizontal and vertical than they are. The perception apparently is rather governed by Gestalt-like perceptual principles [77].

Furthermore the perception of motion can not be apprehended when it happens too fast, e.g. the trajectory of a wagon wheel in rotation or the complex interaction of galloping horses' legs. The correspondence problem describes the limit of an object's movement until it becomes confused with another object on the next frame. The limited amount of the movement can be increased by giving the object different shapes and varying other graphical attributes, e.g. orientation and colour [77, 81].

Regarding the design of visualisations it is important to know the cognitive limits of memory and the effects of controlled behaviour.

Pre-attentive processes are not altered by memories, i.e. attention has no cumulative effects on visual perception. When a viewer looks several times on a scene the new pre-attentive representation appears to be identical to its representation before the viewer focused his attention on it [45].
Spatial or temporal aspects in the perception of motion, listed by Blok [11] are:

- Appearance / disappearance: A new phenomenon emerges or an existing one vanishes.
- Mutation: An attribute of an existing phenomenon transforms in its nature (from rain to snow) or in its level of measurement (increase or decrease).
- Movement: The spatial position and/or the geometry of a phenomenon changes along a trajectory or performs a boundary shift.

Examples for such changes in the spatial domain can be found in Fig. 3.4.

### Attention

Visual attention is influenced by stimulus driven (bottom-up) and knowledge based (top-down) processing. Bottom-up processing automatically directs attention to visual stimuli without volitional control. The top-down process, on the other hand, is a directed volitional process where attention is focused to objects relevant to the observer's goal. Because the bottom-up process provides the context for the top-down process, the bottom-up process is fundamental to the visual attention [25, 86].
Rensink [57] states that focused attention is needed to see change. He proposes a triadic architecture for the explanation of how visual perception works, see Fig. 3.5.
The first non-attentional processes rapidly create proto-objects across the visual field and only focused attention, guided by setting information layout and gist, stabilises these volatile proto-objects to a coherent object. As long as the proto-objects are held in a coherence field, they form an object with both temporal and spatial coherence.

### Change blindness

We miss large changes to objects from one view to another because we do not hold a detailed view from our environment in mind. We need focused attention to perceive and remember objects in our view. This robust effect, called *change blindness*, can exist over long time (up to 50 seconds) and can be induced when changes occur simultaneously with image flicker (see Fig. 3.6), eye movements (saccades), eye blinks, real-world interruptions, gradually changes, etc. The image flicker in Fig. 3.6 induces change blindness due to brief grey frames G between successive images A and A'. When the image A with the statue and a high background wall and a modified image with a lowered wall A' are displayed in the following order: A, G, A', G, A, G, and so on, the grey frames induce flicker and therefore change blindness occurs for the wall in the background.
A popular example for change blindness induced by a real-world interruption is the replacement of a conversation partner during an interruption. When asking observers for a direction, they

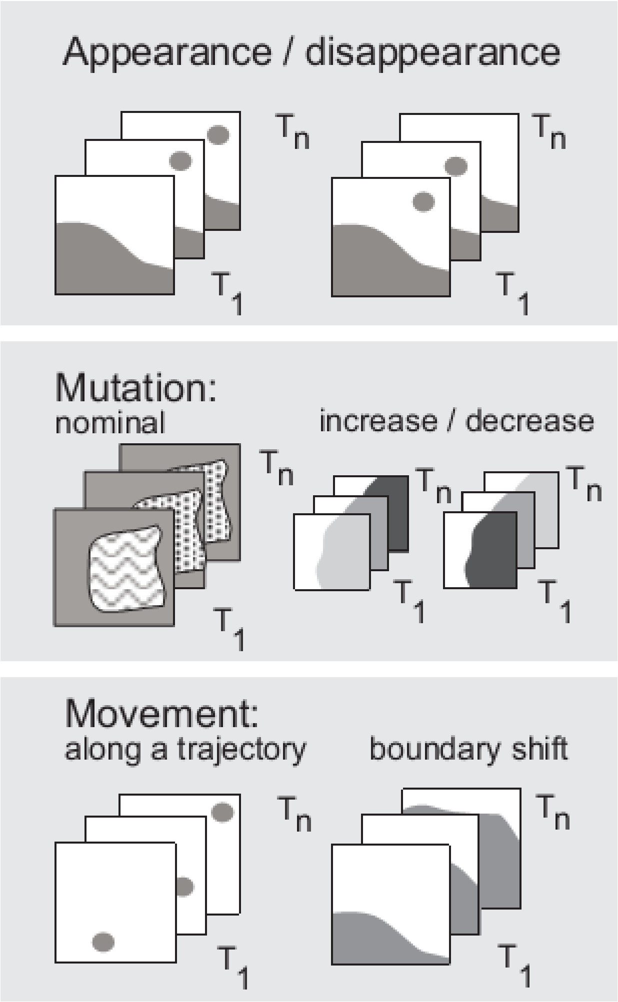


Figure 3.4: Basic characteristics of change in the spatial domain [11].

often did not notice that the asking person got replaced by a different person while an interruption by a door being carried between them [67].

Change blindness can be used to make ”hidden” changes for any (unattended) transition in an image that could otherwise potentially intrude into the awareness of an observer and distracts him in another task. This can be established by making the transition during a saccade or blink, or making the transition sufficiently gradual that it does not draw attention [57].

Without attention it is even possible to not perceive objects at all, what is further called *in-attentional blindness*. A comprehensive review on in-attentional blindness can be found in Simons and Chabris [67].

The useful field of view is the area with focal attention where perception is most effective. It depends on the density of information given but for the notice of moving objects it is widened because the human visual system is very sensitive to motion. Therefore attracting attention to

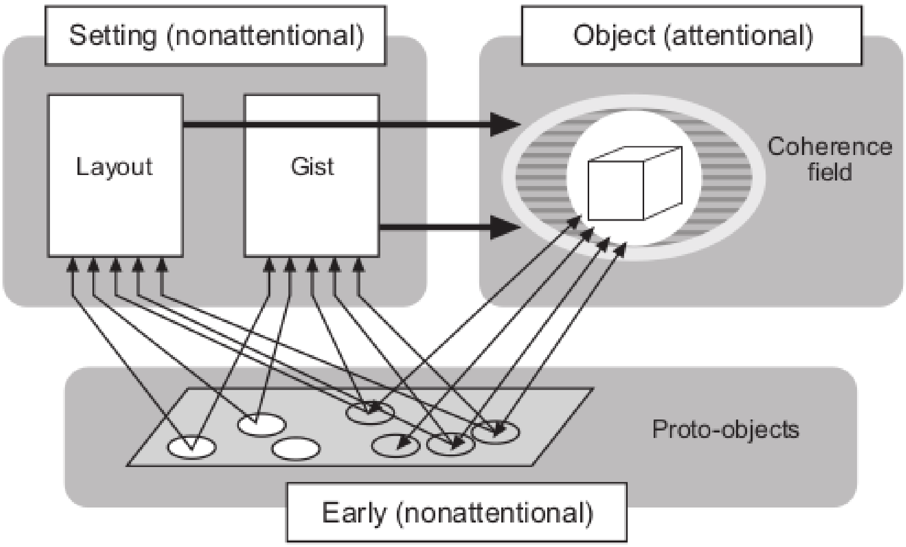


Figure 3.5: Model of visual information processing by Rensink [57], graphic taken from Blok [12].

information outside this field of view with blinking lights or moving targets is easy but also auditory cues work well. Ware [81] describes overflow, visual disturbances and animation speed next to change blindness as issues that can disturb the identification of changes.

The coherence theory of attention [57] attempts to explain the change blindness, mentioned above. If changes happen in unfocused and unattended areas, they escape the human visual processing even when we know about that issue [55, 57]. Rensink consequently suggests to reduce the visual events in animations to a minimum in order to avoid the loss of valuable information [57].

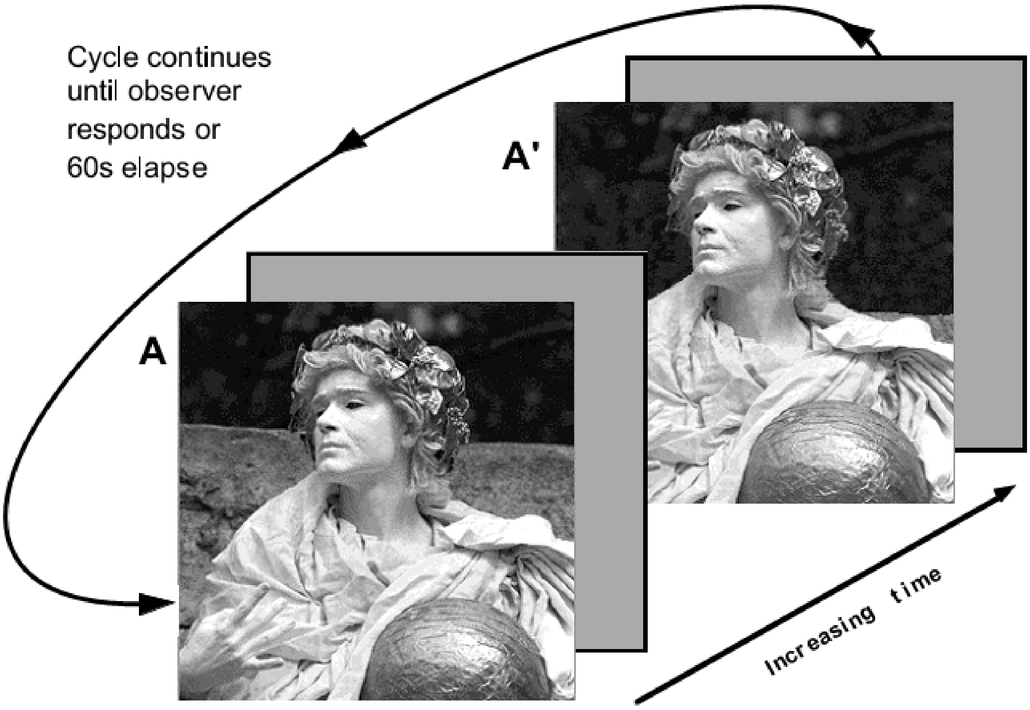
The number of objects that simultaneously can be tracked is limited, as well as the level of detail in a coherence field. Research indicates that four to five distinct items in an image can be accessed at one time, with only a few properties for each item [8, 81].

One aspect of visual attention related to supervisory control is creating an effective way to gain the attention of the user [81].

Motion attracts attention as described in Ware's book [81] and references therein. The onset of motion of an object generally produces a shift of attention to that object as well as the appearance of a new object attracts attention to the new object.

## 3.2 Characteristics of monitoring tasks

In real-time monitoring situations the user's attention has to get attracted to a new event while interrupting him in his primary task. This interrupting signal needs to be perceived outside of the field of view and if ignored, should stay reminding the user. It should not disturb the primary



!

Figure 3.6: Change blindness induced by flicker [57].

working task and should allow to transfer various levels of urgency.
For operators it is important to become aware of patterns of events [81]. Geometric, temporal and thematic characteristics of data are interesting for domain specialists of geographic phenomena. They want to see anomalies, ongoing processes, relationships in space, causes and trends. The identification of change and its developments are of interest. Changes can be classified in short time (recent developments) and long time (trends) series [11]. Table 3.1 breaks the monitoring tasks according to the types of change.

| **Task / Series** | Short-term | Long-term |
|---|---|---|
| Identification | of change - Which? | What process? Trend? |
| Comparison | of changes - Anomalies? | Relationship or causes? Anomalies? |

Table 3.1: Classification of monitoring tasks for spatio-temporal data [11].

Domain experts are interested in new phenomena, the disappearance of existing ones and changes in geometric, thematic and temporal characteristics. To act in case of undesired developments observers look for changes over *short series*. Monitoring spatio-temporal behaviour over *longer series* enables to gain insights in processes and relationships and to detect trends [11].
Factors by Ware [81] which possibly influence visual scanning patterns are:

- Users may minimise eye movements
- Oversampling of channels with infrequent information
- Operators exhibit dysfunctional behaviours in high-stress situations
- Operators exhibit systematic scan patterns without task relevance

## 3.3 Interaction in information visualisation

Interaction can be described as communication between user and the system, as well as direction manipulation and instantaneous change. Interaction techniques are the features that provide users with the ability to directly or indirectly manipulate and interpret representations in information visualisations [87].

One view is rarely sufficient to convey all the information contained in the data. Visualisations experience a lack of space for the representation of the whole data set when a certain amount of data is exceeded. The key to developing an effective visualisation is to provide intuitive controls for setting and customising different views that will be of most use to the typical user. Scrolling and zooming operations are needed if the entire data set can not be presented at the resolution desired by the user [45, 80].

Interactive visualisations support cognition in the process of problem solving and can help to overcome the difficulties of perception and comprehension in animations. With the help of interaction possibilities, e.g. close-ups, zooming, alternative perspectives and control of speed, visual exploration of the data is possible by changing the perspective on the data [11, 77].

For working with time-oriented data advanced interaction techniques are important. Interaction helps users in understanding the visual mapping in an iterative process. Focusing on different parts and changing perspective on the data allows the user to become confident about it. Abstraction is requires to give an overview about data. An abstracted view enables to identify parts on which one want to focus on for more detailed examination [1, 65].

Ware [82] describes three feedback loops for interactive information visualisation: Manipulation, Exploration and navigation and Problem-solving. Manipulation includes selection and modification. With exploration and navigation the user is able to form a cognitive spatial model of the data. In problem-solving the user generates hypotheses and refines the insight on the data.

Yi et al. [87] identified several user intents for interaction and introduced a list of categories that describe on a high level why users would like to interact:

- Select: Mark something as interesting. Selecting items of interest is useful to keep track of elements that would otherwise get lost in a large dataset.
- Explore: Show something else. Exploring enables users to examine a different subset of data cases.
- Reconfigure: Show a different arrangement. Reconfiguring allows users to change the perspectives onto the data by changing the spatial arrangement of representations.

- Encode: Show a different representation. Encoding enables users to alter the fundamental visual representation of the data including its visual appearance (e.g., colour, size, and shape). Changing how the data is represented, for instance changing a pie chart to a histogram users want to uncover new aspects of relationship.
- Abstract/Elaborate: Show less detail or elaborate more detail. The abstraction of a data representation can be adjusted between seeking more of a broad, contextual view of the data to examining the individual attributes of the data.
- Filter: Show something conditionally. With filtering users can change the set of data items being presented based on some specific conditions. Only items that meet user specified criteria are presented.
- Connect: Show related items. Highlight associations and relationships between data items that are already represented. Connect further enables to show up hidden data items that are relevant to a specified item.

In their study they also found interaction techniques that either do not fit in any or not only in a single category. They further point out that other operations known from different types of application (undo/redo, change of configuration) can act as interactive elements but are not included in their categories because they are not unique to information visualisation.

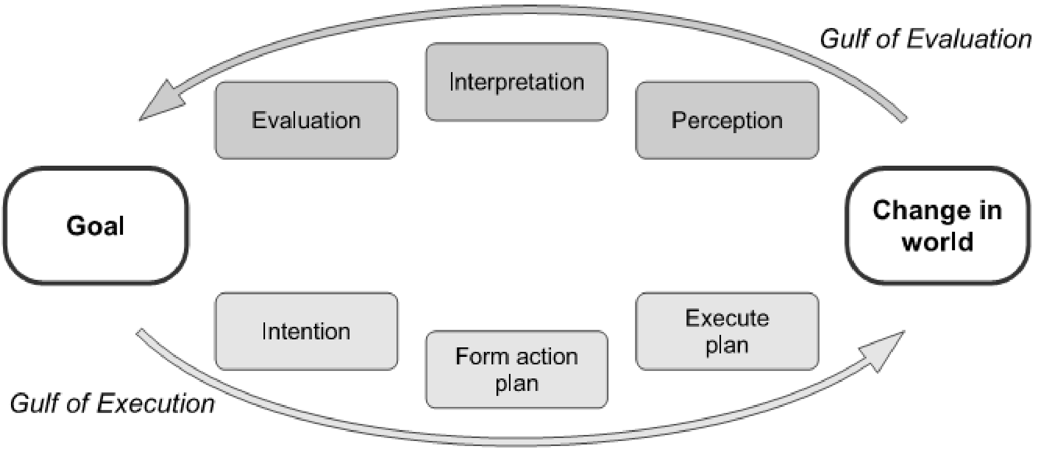


Figure 3.7: Norman's model of interaction (adapted from Norman,2002) [1].

On this basis Aigner et al. [1] describe fundamental interaction concepts and how interaction is performed. Norman's model of interaction describes a Gulf of Execution to reach a change in the world. To define a goal an intention has to be articulated and an action plan needs to get formulated, what is called the Gulf of Evaluation in Norman's Action Cycle, see Fig. 3.7. Then the plan can be executed to reach the change in world.
The following interaction interfaces distinguish various uses of space, time, or visual effects [18]:

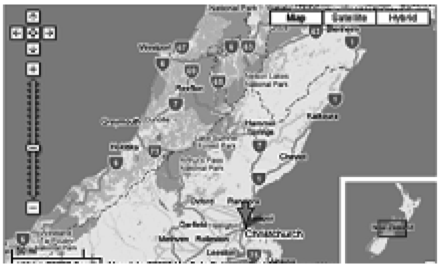


Figure 3.8: Example of an overview + detail display [18].

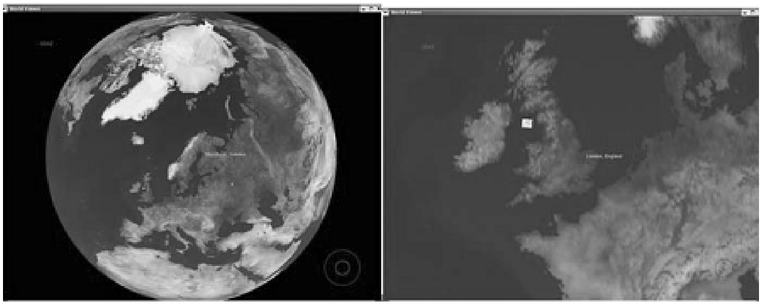


Figure 3.9: Example of zoom displays using temporal separation for detailed and contextual views [18].

- Overview + Detail: Display contains an overview and detailed view of an information space simultaneously (Fig. 3.8).
- Zoom: Changing the level of detail within temporal separation or without (Fig. 3.9).
- Focus + Context: Displaying the focal region within surrounding context. This can be done with the fisheye technique where the region of interest gets magnified while the surrounding gets distorted (Fig. 3.10).
- Clues: Items get visually modified to direct the user's attention to elements of interest, e.g highlighted or suppressed items.

The clue category depends on the availability of semantic information about elements in the dataset, and can be used to enhance any of the other three techniques.

### Possible issues in interactive visualisations

One usability issue would be navigation problems while using the interaction technique ”zoom” when there are no orientation features in high zoom levels any more, called ”Desert Fog” (Jul and Furnas 1998, as cited in Cockburn et al. [18] ). The user loses orientation because of missing context hints that would give information about the current zoom level. Providing a zoom scale and an overview view in parallel counteract on this issue.

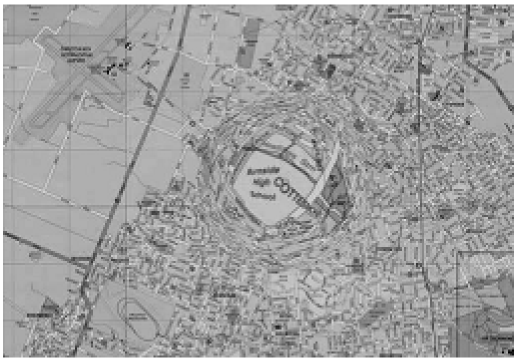


Figure 3.10: Example of a focus + context interface using the fisheye technique to show detailed information of a focused region within surrounding context [18].

Another problem is called split attention, due to what users may fail to see changes if their attention is at the interacting control.

CHAPTER 4

# Traffic Management Systems (TMS)

FCD is qualitative traffic information that enables accurate traffic assessment and the prediction of accurate routing and navigation [22, 54, 79]. The visualisation of FCD can uncover patterns in the spatial and temporal distribution of trajectory data and hence, possibly shows up hot spots [78].

The use of FCD raised interest in the domain of traffic visualisation because of its cost-effectiveness compared to other traffic data sources [22, 79]. Typically stationary devices had to be installed across the street network to collect the traffic data, which caused a lot of infrastructure and maintenance costs. Since FCD come from individual vehicles no additional hardware on the road network is necessary. Furthermore the data measurements can be analysed and used for modelling traffic conditions along any measured link because they do not originate from a single source [70, 79].

However, FCD also pose new challenges as to process a heavy traffic load coming from the huge number of vehicles, that entails costs at various levels [14].

TMS aim to visualise large scale real-time FCD in their road networks at the best to enable a better quality of service. TMS using FCD enable short term traffic forecasting based on current and historical FCD, offering alternative routes for congestions and show up hot spots, like problematic exits and bottlenecks in the road network.

Current applications using FCD for instance are Cityrouter, for German cities and Inrix, which is used by Google Maps and MS Live Maps. The basic problem for such systems is an insufficient penetration rate [54].

However, OCTOTelematics [22] proposed to reach a penetration rate of 3% in the Italian motorway network and according to field tests, the accuracy of their system in estimating current link travel speeds is about 90%. A short-term speed prediction with categorical speed visualisation is freely accessible on the OCTOTelematics web site [74].

FCD visualisation needs to address the impression of data volumes, traffic flow and large-scale patterns in high traffic rates [81]. The questions are how to present the available data in the best possible way and how to handle the possible lack of data. Real-time traffic monitoring also needs to handle voluminous amounts of data and dynamic change in data rates. To balance

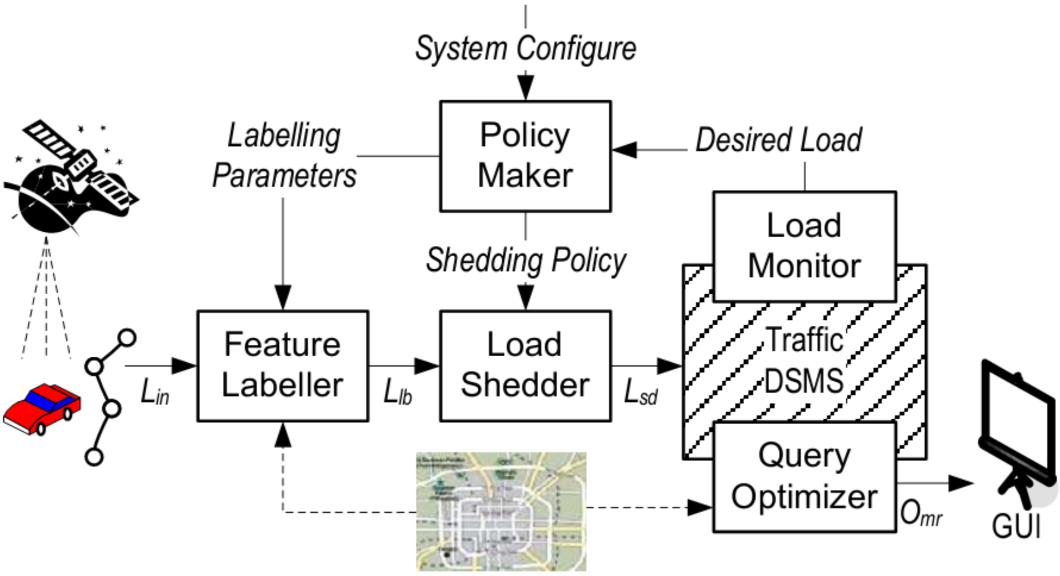


Figure 4.1: Data Stream Management System [41].

monitoring accuracy and timeliness Liu et al. [41] propose a framework to decide which data gets processed and which gets dropped. Incoming data stream preprocessing should lead to accurate and spontaneous visualisation.

Their FCD-based Traffic Data Stream Management System (DSMS) and its preprocessing steps are shown in Fig. 4.1. A load monitor and query optimiser frame the Traffic DSMS which contributes to the visualisation of large datasets. The load monitor keeps watching the system load continuously and provides information for policy makers to make load shedding decision.

If the traffic monitoring system is in normal state, the FCD stream will be passed into the Traffic DSMS and queries get accurately answered. When overloading is detected, a policy maker generates labelling parameters and shedding policies for the load shedder. The load shedder activates and starts to discard the FCD stream to a desired load level according to the features given by the feature labeller. This load shedding technique handles large scale FCD streams and considers speed changes over a road as an important parameter and updates the system only if the speed changes.

Another research field specialises on data reduction techniques to minimise the communication between vehicles and the control centre [14, 49].

## 4.1 Requirements for trajectory analysis

A minimum number and uniform distribution of vehicles is necessary to cover quality of service for a road network. Having a large amount of vehicles for a given spatial area creates an accurate

picture of the traffic condition in time and space [54].
A fundamental requirement on the FCD is its statistical consistency [22]. The number of travelling cars needs to achieve a significant penetration level. Furthermore the transmission rate of single cars needs to be adequate. Pfoser et al. [54] provide a flexible, web-services-based architecture to simplify the connection of new FCD sources to support the increase of the penetration rate.

> ”The reliability of travel time estimates based on FCD highly depends on the percentage of floating cars participating in the traffic flow.”
> Fabritiis et al. [22, p.197]

For lower penetration of floating car the reliability of travel time estimates is affected by traffic conditions and road link capacities. A lower percentage of floating cars is required in more congested traffic condition while a higher percentage of floating cars is needed in low flow conditions [22]. FCD having a high level of redundancy on the other hand allows dropping of overlapping traffic information [41].

## 4.2 Travel time maps

Travel Time Maps [54] illustrate the traffic situation by matching the tracking data to a road network. Current speeds for road links in a map may be indicated by a simple colouring scheme e.g., green - yellow - red, like in Fig.4.2.

Figure 4.2: Example for colour encoding to visualise congestion in a road map of Hefei [79].

Travel times are desired on different resolutions and the Graphical User Interface (GUI) needs to support the selection of regions of interest and the change of zoom-levels in the traffic map [41]. The road’s attributes are saved in a multiple layer structure with each having a different resolution. A query for travel time then only is applied to roads in the respective layer in order to optimise processing times.

CHAPTER 5

# Guidelines for Effective Visualisations

This chapter describes guidelines for designers as factors to keep in mind during the design process, applicable without the need for detailed knowledge of cognitive processes. They are based on empirical user studies rather than experiences and personal preferences of designers. The methodology of the guideline deduction is inspired by Spence' and De Bruijn's framework for theory-based interaction design. Furthermore the general obstacle of re-using HCI knowledge will be discussed.

## Methodology

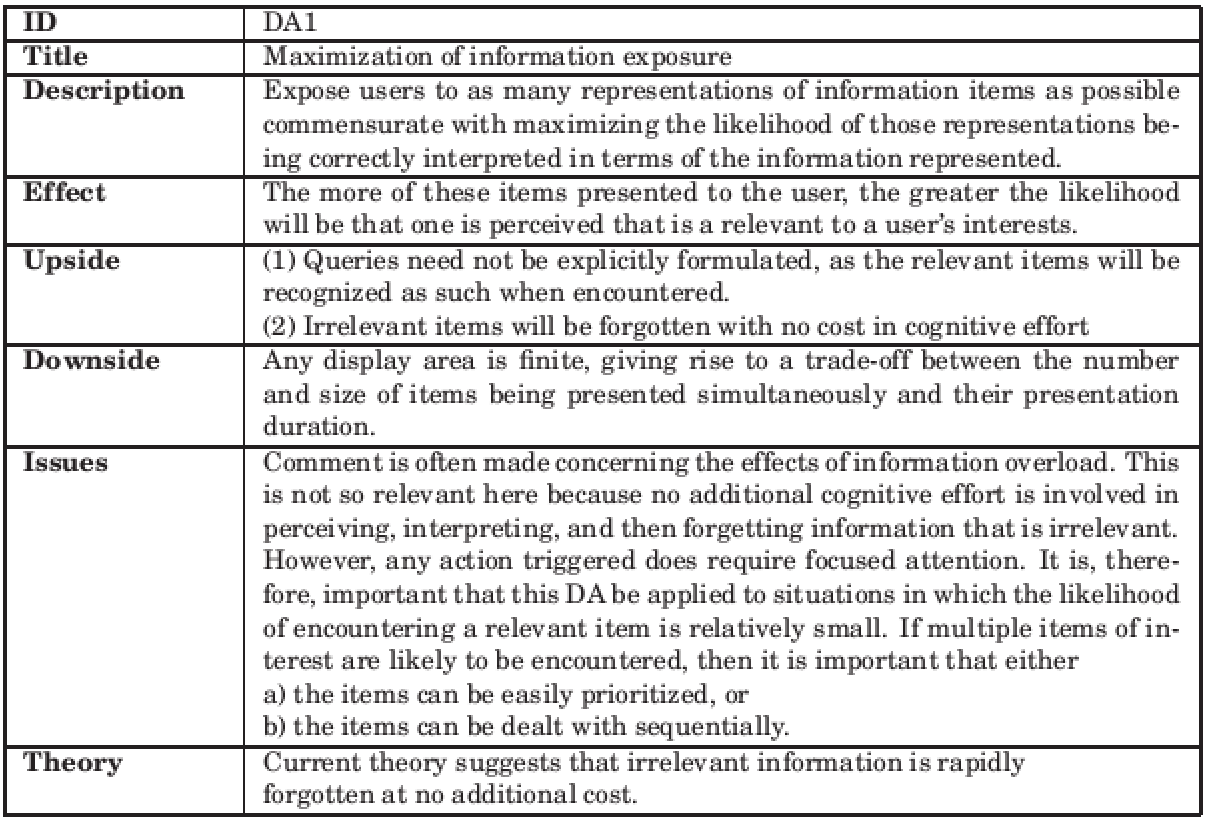
Well designed visualisations efficiently and accurately convey the desired information to the targeted audience considering the task of the visualisation, i.e. exploration, confirmation and presentation [80].

Designers have to consider the target audience as well as the purpose, but the former is most challenging because of the diversity of users and technology. Users range from children to senior citizens, from novices to experts and therefore come with different levels of abilities. Different user groups have to be taken into account, e.g. different screen sizes and network bandwidths [36]. Shneiderman [66] introduced the term ”universal usability” for the challenge to serve the general public.

Spence [69] recently pointed out that it is hard for designers to know and apply cognitive and perceptual insights which are acquired by psychologists. The existing knowledge needs to be made applicable for designers. They don't have the psychological background knowledge and time to research and read the concerning theories. Although there are many questions unanswered, there are also insights which can be useful in the design process and which should be brought into a form that informs designers better.

Using the concept of ”Design Actions” De Bruijn and Spence [21] demonstrate how this knowledge should be presented to improve design guidance. They elaborate how to derive guidelines that support interaction designer with the example of visual search. Their design actions are

described in a way that the underlying cognitive theory does not necessarily need to be known or understood by the interaction designer.
In an exemplary design action, see Fig. 5.1, the designer wishes to expose a user to as many relevant information items as possible. The design action suggests to maximise the information exposure. The justification therefore is that the more items are presented to the user, the greater the likelihood will be that one will be perceived that is relevant to the user's interests. The design action further includes an ”Upside” and ”Downside” section that describes advantages and tradeoffs respectively. Another section considers issues that are neither positive nor negative. It is important to note that design actions only work in the context of the relevant cognitive theory which is given as a last part of the design action.



| **ID** | DA1 |
|---|---|
| **Title** | Maximization of information exposure |
| **Description** | Expose users to as many representations of information items as possible commensurate with maximizing the likelihood of those representations being correctly interpreted in terms of the information represented. |
| **Effect** | The more of these items presented to the user, the greater the likelihood will be that one is perceived that is a relevant to a user's interests. |
| **Upside** | (1) Queries need not be explicitly formulated, as the relevant items will be recognized as such when encountered.<br>(2) Irrelevant items will be forgotten with no cost in cognitive effort |
| **Downside** | Any display area is finite, giving rise to a trade-off between the number and size of items being presented simultaneously and their presentation duration. |
| **Issues** | Comment is often made concerning the effects of information overload. This is not so relevant here because no additional cognitive effort is involved in perceiving, interpreting, and then forgetting information that is irrelevant. However, any action triggered does require focused attention. It is, therefore, important that this DA be applied to situations in which the likelihood of encountering a relevant item is relatively small. If multiple items of interest are likely to be encountered, then it is important that either<br>a) the items can be easily prioritized, or<br>b) the items can be dealt with sequentially. |
| **Theory** | Current theory suggests that irrelevant information is rapidly forgotten at no additional cost. |

Figure 5.1: An exemplary design action from De Bruijn and Spence [21].

To make the right design decisions one needs to know their consequences as well as their advantages and disadvantages and the context in which they perform [71]. Specifying the requirements of an application, i.e. the context, is the key to derive guidelines in sufficient detail.
It is not an easy task to interpret the results of empirical studies and derive design guidelines which are not too specific and not too general to make them applicable without additional interpretation effort. Serendipitously there exist common results where the community agrees on

some general recommendations and design guidelines. The aim is to extract the knowledge of empirical studies and suitably present it to the notice of interaction designers.
The deduction of the guidelines in my thesis was done with the help of the aforementioned framework for theory-based interaction design by Spence and De Bruijn and their concept of design actions. The guidelines are categorised into five context groups and derived in reference to the empirical results. Supporting as well as contradicting studies are given so that designers can see both up and downsides of a guideline.
In this chapter I refer to current results in literature and thereby use research studies to derive design guidelines. Empirical studies are given as an evidence for their validity in the respective context.
The guidelines are arranged in five groups that imply their application context:

In the next chapter I provide a compact catalogue of simply structured guidelines as suggested by Spence, to make them easier applicable for designers. I employ a tabular depiction and adopted the fields *Description, Effect, Upside, Downside, Issues* and *Evidence* from the structure of design actions to describe my guidelines. The guideline itself is kept short whereas the *Description* explains the guidelines in more detail. The *Effect* considers the outcome of the applied guideline. The sections *Upside* and *Downside* show up advantages and trade-offs. *Issues* give additional information and empirical studies, which are explained in detail in the current chapter as well as further readings are given as *Evidence*.

## 5.1 Visual perception - Guidelines for static representations

Thematically relevant information should be designed perceptually more salient to support spatial inference making and problem solving. Fabrikant and Skupin [25] defined the term *cognitive adequate depictions* for graphic displays that support internal visualisation capabilities and moreover augment mental visualisation capabilities for complex reasoning and problem solving. Developing effective visualisations adapted to the needs and cognitive abilities of the users can only be done by using pre-attentive attributes, see guideline 1. The remarkable human perceptual capabilities should not get underestimated and the strengths and limitations of human perception and reasoning have to be taken into account [36, 55, 56], see guideline 2 & 3.

Ware [81] describes common problems that can occur even though HCI knowledge was carefully considered during the design process. Depending on decisions of what information is presented and if the most appropriate method was used, misleading visualisations can lead to misinterpretation. He further states that it is important that a visualisation provides an accurate depiction of the data.

Static representations allow the conclusion of quantitative statements. The data can be explored without a time limit. The perceptual registration of visual content is called browsing.

Spence and De Bruijn [21] defined ”opportunistic browsing” and ”involuntary browsing” as two classes of browsing. With opportunistic browsing the user has the goal to acquire information, but with the attitude ”let's see what's there” he is unaware of it. To reach that goal Norman's Action Cycle (see Fig. 3.7) says that the intention needs to be articulated, an action plan has to be formulated and then the plan can be executed. While involuntary browsing this so called ”Gulf of execution” does not have to be gone through because the user in this case just has a latent interest.

This serendipitous acquisition of information happens if the user's eye gazes on an information item of his latent interests. Before the viewer fixates on a object there was little or no cognitive effort involved so that other activities could take place simultaneously.

### Guideline 1: Choose pre-attentive attributes according to data type.
### [Visual perception - Guidelines for static representations]

The principles of visual perception are important for mapping data effectively because some visual attributes are processed by visual perception more rapidly and efficiently than others. Pre-attentive attributes are described in detail in chapter 3.

The visual variables system, proposed by Bertin in 1967, contains seven variables position, size, value(colour), hue, shape, texture and orientation which can be used to create meaningful representations. Since then Bertin's theory got tested and adapted in various studies, resulting in colour, motion, orientation and size being undoubted good attention guiding visual variables [23, 27, 29]. Bertin's original variables plus motion, as it was later proved to be also pre-attentive processed, are shown in Fig. 5.2.

Some visual attributes work better than others and the designer needs to question the best presentation of the data at hand. Which pre-attentive attributes fit best for which data?

The mapping has to set focus on the most important conceptual attributes. If more data needs to be encoded, the conjunction of used attributes needs to get tested on its pre-attentiveness. Com-

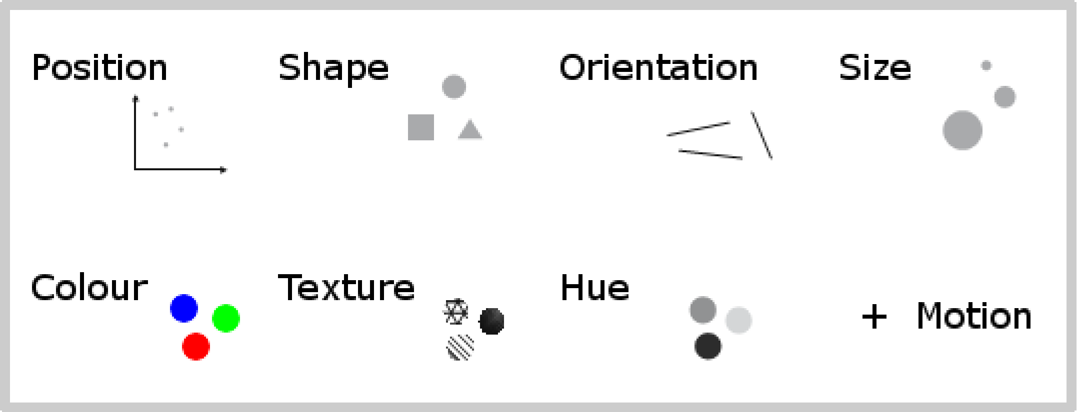


Figure 5.2: Pre-attentive visual variables by Bertin plus motion.

binations of attributes do not automatically work together the same way, as seen in Fig. 3.2(a). Combinations of two attributes that do work together are also described in chapter 3, e.g. spatial grouping with colour, see Fig. 3.2(b).

A universal ranking of pre-attentive attributes does not exist. Mazza [45] combines results from other studies to generate a rule of thumb for different data types. He assesses the suitability of attributes for quantitative, ordinal or categorical data types (see Fig. 5.3)

A generous limitation suggests not using more than four distinct values for different orientations and sizes, eight distinct values for hues and all the other visual pre-attentive attributes to less than ten distinct values [81]. A more restrictive general suggestion is limiting the number of distinctions for any attribute to a maximum of four [45].

To find out which regions in a display are salient computational vision models can be used. They model the visual saliency of a representation and predict visual attention based on empirical findings. The Itti model (Itti & Koch as cited in Garlandini and Fabrikant [29]) is a bottom-up models of visual salience that is interested in *where* instead in *what* a observer focuses and extracts the colour hue, colour value and orientation to compute feature maps. The feature maps get processed and combined to produce a saliency map of the representation that discovers its saliency peaks.

**Evidence** Cleveland and McGill empirically verified that some attributes are more accurate than others for judging quantitative values. Spatial positioning is one of the most accurate ways to perceive quantitative information [45].

Ware [81] proposes the guideline for designing effective visualisations as to use data-graphic mappings that are likely to be intuitive to the targeted audience. Bartram's studies [9, 10] show that motion does not interfere with other attributes like colour or shape.

Fabrikant et al. [25] show in their study that viewing behaviour and response time are influenced by display design independent of domain knowledge. They analysed the relationship of thematic relevance and perceptual salience in static weather map displays. Saliency of the display did not change the response accuracy but they found that perceptually salient elements draw viewer's attention to the dedicated information. These findings are applicable to any spatial display (static or interactive) and provide rare empirical evidence for generally accepted design practices, like the effects of visual variables, within the cartographic community.

| Attribute | Quantitative | Ordinal | Categorical |
|---|---|---|---|
| Color | | | |
| Hue | ✗ | ✗ | ✓ |
| Intensity | − | ✓ | ✗ |
| Form | | | |
| Orientation | − | − | ✗ |
| Length | ✓ | − | ✗ |
| Width | − | − | ✗ |
| Size | − | − | ✗ |
| Collinearity | ✗ | ✗ | ✗ |
| Curvature | − | − | ✗ |
| Spatial grouping | ✗ | ✗ | ✗ |
| Added marks | ✗ | ✗ | ✓ |
| Shape | ✗ | ✗ | ✓ |
| Numerosity | ✓ | ✓ | ✗ |
| Spatial position | | | |
| 2D position | ✓ | ✓ | − |
| Stereoscopic depth | ✗ | ✗ | ✗ |
| Concavity/convexity | − | − | ✗ |
| Movement | | | |
| Flicker | ✗ | ✗ | − |
| Motion | − | − | ✗ |

Figure 5.3: Overview of pre-attentive attribute mappings to different data types: Good matches marked by a check mark, limited matches by a minus sign and bad matches are crossed out [45].

### Guideline 2: Group elements to a maximum of five chunks. [Visual perception - Guidelines for static representations]

Cognitive load theory describes the amount and duration of mental processing that can be held in the working memory. Only a limited number of elements can be attended to at the same time. Chunks are built from a grouping effect of spatial structures in the external representation as well as in our working and long-term memory [24].

If objects on a display are perceptually salient they can be easily isolated to form a group of similar objects based on the objects attribute e.g. lightness in Fig. 3.2(a). A visual variable is called selective when it can be easily isolated to form a group of similar symbols based on this variable e.g., colour hue [29].

Users build mental model for spatial reasoning in working memory and the number of fragments that can be integrated in one model is usually small [24]. Users can access four to five distinct objects at the same time [8, 81] and therefore important elements in a display should not exceed this number. For non-interactive animations the cognitive load can be problematic because the viewer has no control of the visual and temporal properties of the display [26].

**Evidence** Early work by Kosslyn and Pomerantz in 1977, as cited in Engel [24] reported chunking in mental images that seem to relate to a basic spatial structure underlying the mental model. As an example, in the schematic figure of a human body the visual parts of an arm are chunked together.

Organising pieces of information into larger, meaningful units is a universal cognitive principle [24]. Designers probably know Gestalt-based principles that try to explain grouping effects. Multiple similar motions are also grouped, i.e. no computation of the individual motions is required [8, 10]. The brain has a strong tendency to group moving objects in a hierarchical fashion [81]. The number of chunks is important as it acts similar to the ability of tracking several objects simultaneously [77, 81].

Rosenholtz et al. [60] present an algorithm that predicts grouping in Gestalt displays, as well as information visualisations like diagrams. It can help to compare the structure of the presented information with the likely perceptual structure of a display and therefore is of use for designers who want to ensure that both structures agree, as near as possible.

Visual mental images are mental constructions in working memory of a specific representation. Grouping effects, for instance according to Gestalt laws, are integrated in the mental image during inspection of a representation. It also works in the other direction. The present groupings of a mental image are preserved when visual mental images are externalised into representations [24]. Actively guiding users' eye movements enhances the chance of problem solving substantially [25]. An upper limit for good map design is using at most seven data classes for static graphics. For animations the number is indicated to be lower [32].

We perceive regions grouped by proximity and feature similarity, grouping of curves by good continuation and groupings of regions of coherent texture [60]. The Gestalt ”principle of similarity” and ”principle of proximity” deal with grouping elements by similar attributes whereas former deals with appearance and latter with location. The principle of similarity is concerned with what items look like and the principle of proximity is more concerned with where items are placed in space [16].

### Guideline 3: Prefer 2D representations over 3D. [Visual perception - Guidelines for static representations]

Trivariate data is represented by two-and three-dimensional spatial views. Two-dimensional (2D) representations can't establish a one-to-one mapping between world spaces and map space. Static three-dimensional (3D) representations collapse three dimensions to two by displaying the third dimension through perspective with the disadvantage to not display the whole scene at once. 3D representations are strictly speaking only 2.5D, since the visualisation is restricted to a two-dimensional plane.

The downsides of 3D representations are occlusion problems and the difficulty of identifying the position of the graphical elements with respect to the axes.

Whether to use two-dimensional (2D) or 3D depends on which data has to be visualised and the analytic goals that have to be achieved. Furthermore the application background and user preferences influence this decision [2].

**Evidence** Springmeyer et al., as cited in Tory [75], observed the efficient use of 2D displays when precise relationships have to be established, whereas 3D is used to gain a qualitative understanding of the data.

Empirical studies have shown that 3D representations increase cognitive load, or the user's mental effort to correctly interpret the data represented. Only interactivity provides a benefiting use of 3D representation. 2D representations are clearer and more precise than 3D and are to be preferred over 3D representations [45]. Designers should choose 3D presentations only if it does not produce an overload and if interactivity is possible.

## 5.2 Geographic data - Guidelines for geographic visualisation

Computer-based geographic visualisation can build upon a large base of established cartographic knowledge. Well-known examples of static visualisations beyond geographic maps are thematic maps that display the spatial pattern of a theme such as climate characteristics or population density. Visualisation technology offers new possibilities for geographical visualisation tasks to explore, understand and communicate spatial phenomena [36].

Qualitative assessment methods using various interview and discussion techniques, participant observations or thinking-aloud protocols proved to be suitable for evaluating geographic visualisation tools [36]. Maps, especially road networks are visualised schematically and reduced to include only necessary information. Using different aggregations support different perspectives on the data, see guideline 4.

The cartographic community has generally accepted design practices. They apply a set of visual variables (e.g., size, colour hue, colour value, orientation) to mostly static 2D maps. Map displays should inhere a visual hierarchy that is congruent with thematic levels of relevance [25]. With the support of saliency models cartographers can develop map displays based on cognitive and perceptual principles. Fabrikant's study [25] shows that relevant information made perceptually salient draws on existent knowledge, because the comprehension of external displays depends on internal cognition, i.e. people need a relevant knowledge base to take advantage of the perceptually inspired display design. Spatial abstraction gives maps their unique power to communicate information [23], as you can see for instance in the cartogram in Fig. 5.4, which encodes the country populations.

Dynamic maps can visualise spatial change (fly-bys), chronological change (time series), and attribute change (re-expressions) [23], which will be further discussed in the next context group and guideline 8.

### Guideline 4: Use aggregates for the representation of large datasets. [Geographic data - Guidelines for geographic visualisation]

Displays with too many data points become cluttered and it is hard to analyse the data, because trends and patterns can not be seen anymore. The representation of large datasets can be simplified with the help of aggregates, which represent a group of data points so that fewer markers are needed and the display does not get crowded. The characteristics of the aggregates are derived from the group of elements. The most important characteristics are geographic location, time and category.

A challenge in the construction of aggregates [28] is choosing the granularity of the aggregation. The right granularity is an important factor for the effective visualisation and depends on the application domain and on the task at hand. For example, an application with highway incident data should be able to display incident numbers per year as well as per hour a day.

Aggregates can be pre-calculated and defined in the database if it is possible to predict the most useful aggregates. They can also be specified dynamically with the advantage of a dynamic granularity of the aggregation, but then the response has to be fast enough.

Depending on the application domain spatial exaggeration is more or less a critical factor. Especially in maps, data of interest need to be exaggerated, like e.g., highway widths on road maps

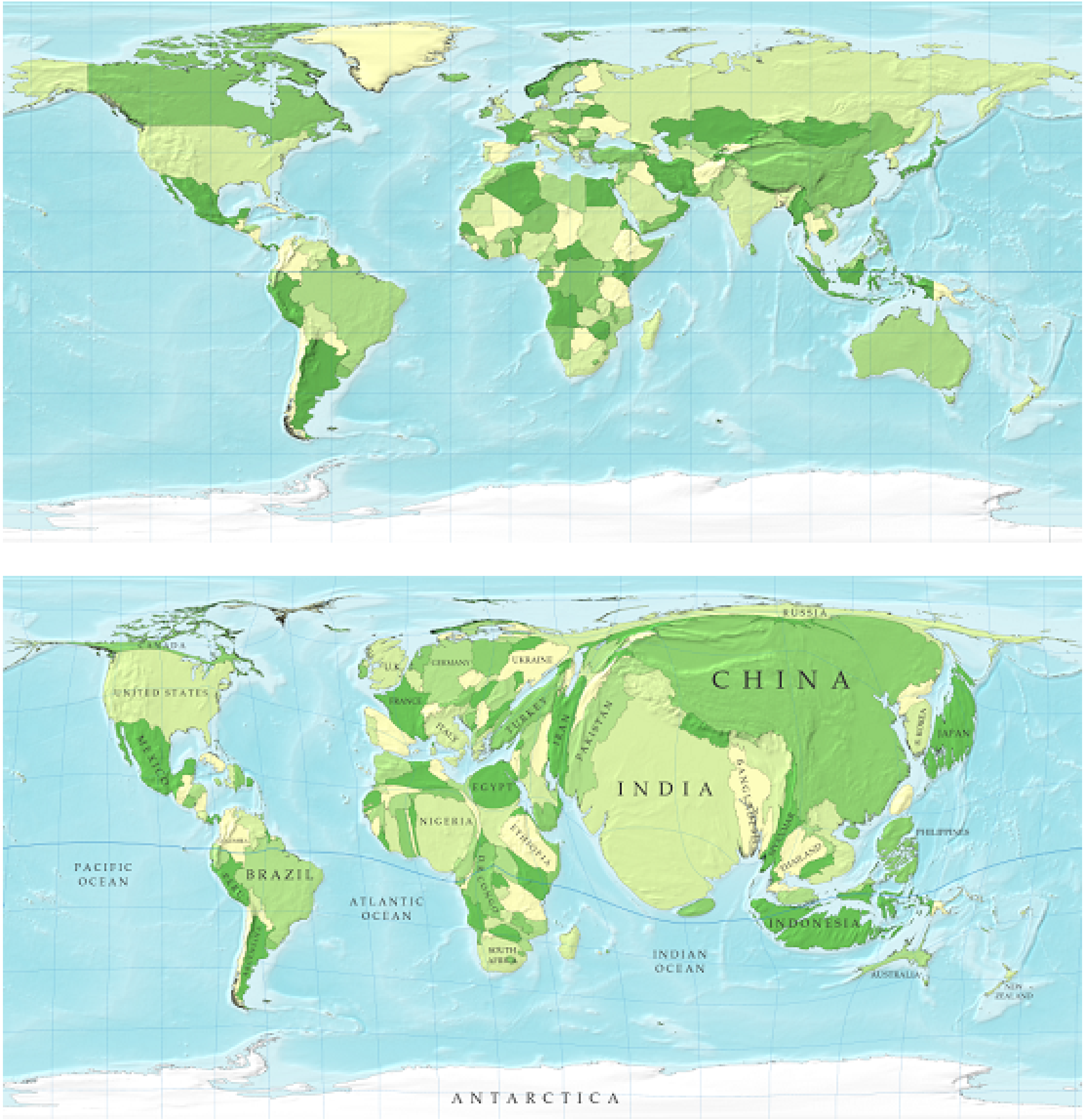


Figure 5.4: Geographical world map (top) and world population cartogram (bottom). In the cartogram the size of a country is proportional to the size of its population [51].

[31].

**Evidence** Harrower states that effective maps have to be highly generalised so that only the most important trends or features emerge [31]. A downside of aggregation are possibly hidden anomalies that can make analysis more difficult [59].

Geographic aggregates in the highway incident example above can be incidents grouped by their geographical distance to an highway exit, see Fig. 5.5. So the application can examine incidents related to an exit. Temporal aggregates in this case are incidents grouped by day of the week or days over a year. The week view shows that there are more incidents during the week than on the weekend, see Fig. 5.6. Categorical aggregates in this example are used to compare the number of vehicles in incidents, vehicle types and weather conditions [28].

Good exploratory tools allow the selection and combination of aggregates to give more information of the data. The interface needs to give control over the different aggregates and their detail views. For example, it should easily be possible to reset the selection and display all aggregates.

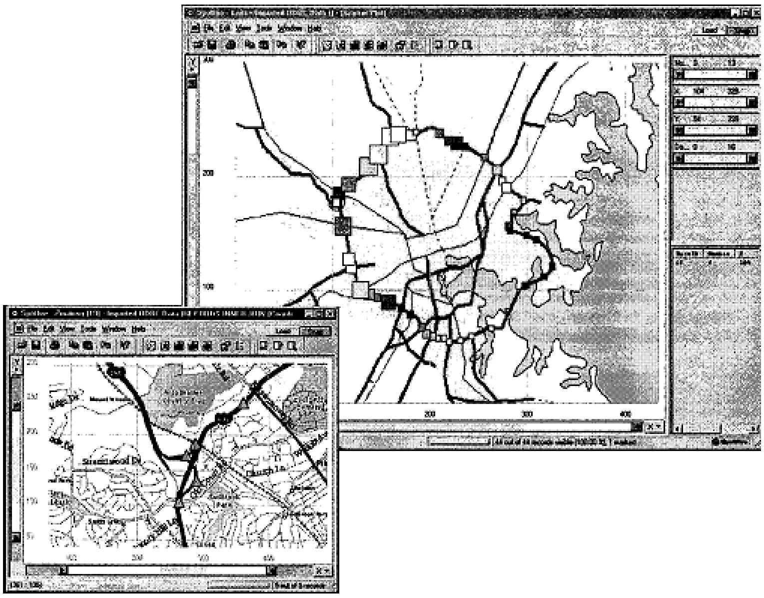


Figure 5.5: Exit aggregation of highway incidents with dual encoding: the size of the markers indicate the number of incidents, the colour depends on the distance to a response unit. A detailed map with the location of single incidents is shown in a separate view [28].

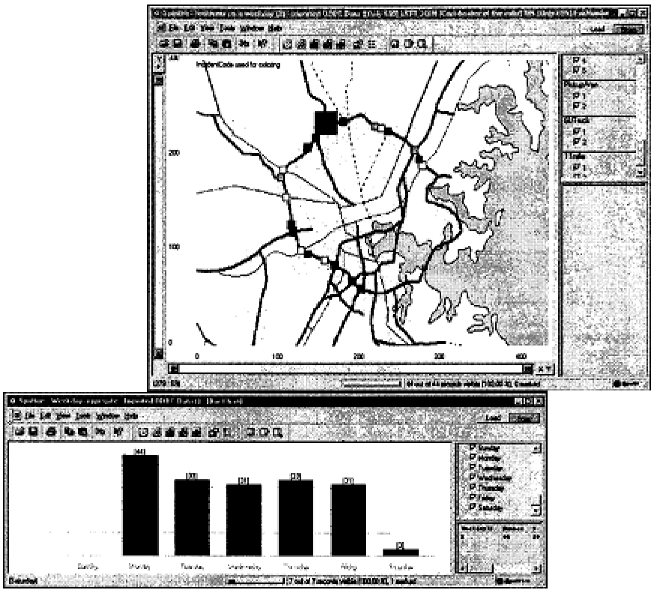


Figure 5.6: The bar chart displays the incident distribution during a week. The aggregate for ”Monday” is displayed in the map, summarising all the incidents on Mondays. [28].

## 5.3 Perception of motion - Guidelines for dynamic representations

A 2D representation can't establish a one-to-one mapping between world space and map space. Adding time as a fourth dimension challenges static representations to collapse four dimensions to two. 3D displays allow us to enhance contrast by manipulating the spatial z-value with the disadvantage to not display the whole scene at once. MacEachren [43] compares this to the situation with time in dynamic maps where we also lose the ability to see all data at once. In dynamic representations we enhance temporal features by manipulating the display time. In this action we have to rely on the spatio-temporal memory to link what we see with what we have seen before.

Dynamic representations have become very popular since graphic processing power has become faster and cheaper, but they also have to be designed well so that they are attractive and informative. The use of animation is controversial as I already mentioned above, but the community agrees upon a beneficial use of animation when designed well.

An animation is defined as a sequence of static graphic depictions (frames) that are perceived as fluid motion when shown with 24-30 frames per second [32]. Visual saliency models of static frames also allow to investigate complex and dynamic situations like animations [29]. Animation in visualisation is used for displaying transitions between one state and another [39, 59], the illustration of how something works [48, 89] and trends [76].

The power of animation is to show the interrelations among change in space (position), place (attribute) or in time [38]. Animations work effectively when the user has to focus on transitions of time-based data and needs to change the viewpoint to the data.

### The benefits of animation

Similar moving objects are grouped together, even if they are actually very far apart. There is evidence that similar moving nodes and edges in a drawing create a pop-out effect from a very large and potentially cluttered background [6, 8]. Tversky et al [77] question animation evaluations which have found animation to be beneficial, but they emphasise the possible benefit for presenting transitions.

The question is when to use animation? Archambault's results [6] suggest to use animation with tasks related to the dynamic evolution in the study of dynamic graph drawing but tasks that require the user to read topological information are better displayed via small multiples, see guidelines 5 & 6.

The power of animations lies in the micro steps that convey more information than possible with small multiple graphics [68]. Psychologists refer to the apparent motion problem, in which we perceive motion from discrete jumps in position between images [30]. The perception of fluid motion depends on the relationship between the duration of a frame in the animation being displayed, the frame rate in the animation and the distance of an object moving across the screen [30, 32].

### Temporal data structure

Information of spatio-temporal data can be linear or cyclic. Linear temporal structures change steadily while observed, whereas cyclic information is perceived as temporal patterns. Phenomena in information are perceived depending on the scale of a representation where the temporal regularity of a phenomenon is of interest [38].
Problems with animated graphics arise with disappearance, attention, confidence, and complexity. Due to the nature of animation information changes often, and the change from one moment to another can be quite significant. Therefore it is likely to miss important information or cues [31]. The aspects of change blindness are considered in guideline 7.
An animations story flow can be influenced by application of the dynamic variables display date, duration, order, rate of change, frequency and synchronisation [43]. They will be discussed in guideline 8.
Sequencing is a strategy to support the attention challenge by depicting the information in a logic and predefined sequence. The guidelines in the next context group ”Monitoring tasks” will address this design challenge.

### Guideline 5: Prefer small multiples for comparing tasks.
### [Perception of motion - Guidelines for dynamic representations]

Appropriate use of motion empowers users in exploratory data analysis [48]. Map readers respond more quickly and find more patterns correctly when using animated maps in comparison to small multiples [30].
It is easier to understand multiple static frames than to follow an animation because all the information is available at every point in the visualisation. One can examine the graphic in his own speed and jump back and forth as one likes, with the advantage that the content does not get lost or change while doing that.

**Evidence** There are studies suggesting that people mentally represent dynamic processes through a series of static small-multiple snapshots based on critical moments, i.e. moment of important change, rather than as a dynamic representation [30].
It is possible to use pictorial instructions for complex motions, like operating a machine and show the steps analogue to those in nature, each step portrayed in a separate frame [77].
Further studies show that animations can be confusing [88] and should just be used if it is impossible to present the data in static form [31].

### Guideline 6: Use animation for transitions.
### [Perception of motion - Guidelines for dynamic representations]

Animation is an effective way of presenting transitions [77]. Visual transitions establish coherence using visual ties to events occurring in adjacent frames in an animation. The amount of change and pacing between frames can be visually modified via techniques like fades.

A model of visual attention and spatio-temporal sensitivity is presented by Yee et al. [86] that exploits the limitations of the human visual system in perceiving moving spatial patterns so that unnecessary information can be left out without being noticed to save processing power.

**Evidence** Transitions can couple perceptual salience with thematic relevance between scenes in an animation. Comparison of saliency in animations with and without transitions shows that without transitions dominant visual properties within the frame grabs the attention instead of the changes from one frame to another [26].
The use of animated transitions is recommended for zooming interfaces, scrolling tasks, panning and zooming tasks and for playing back missed changes as they help understanding the spatial relationship between views and help users track changes. Chevalier's study explores the tasks in the text history re-visitation domain and tests animated transition techniques to make text changes understandable in the shortest possible time [17].
Studies show that animations can be confusing but Heer and Robertson, as cited in Zamann et al. [88], found that animated transitions between statistical visualisations work well and that staged transitions are preferred. Archambalt's results [6] also support that. Harrower suggests to give the user the possibility to stop the animation and proceed frame-by-frame as an solution for the ”Disappearance” problem [31].

### Guideline 7: Reduce visual events to a minimum in a display. [Perception of motion - Guidelines for dynamic representations]

Due to the effect of change blindness (discussed in chapter 3) Rensink [57] suggests to reduce the visual events in animations to a minimum.
Similar to the chunking guideline 2 the viewer experiences an overload of visual elements with moving objects.

**Evidence** Rensink [57] states that the generality and robustness of the change blindness effect indicates that it involves mechanisms central to our visual experience of the world. He describes the coherence theory of attention, see Fig. 3.5, and points out that the limited amount of information that can be attended to at one time is the reason why observers fail to see changes.
MacEachren [43] shows that in comparison to motion, static visual variables have less power to grab our attention. Small information changes are unlikely to be noticed and therefore individual frames of the animation should be relatively simple.

### Guideline 8: Use dynamic variables to control the animation flow. [Perception of motion - Guidelines for dynamic representations]

Dynamic variables expand the visual variables mentioned above with scene duration, rate of change between scenes, and scene order. With them motion can be influenced with the pace, from slow to fast, and character, from smooth to abrupt. The location of a temporal phenomenon as well as its attributes can get emphasised using dynamic variables. Furthermore they visualisation of change in a phenomenon's spatial, temporal, and attribute dimension can be controlled [23].

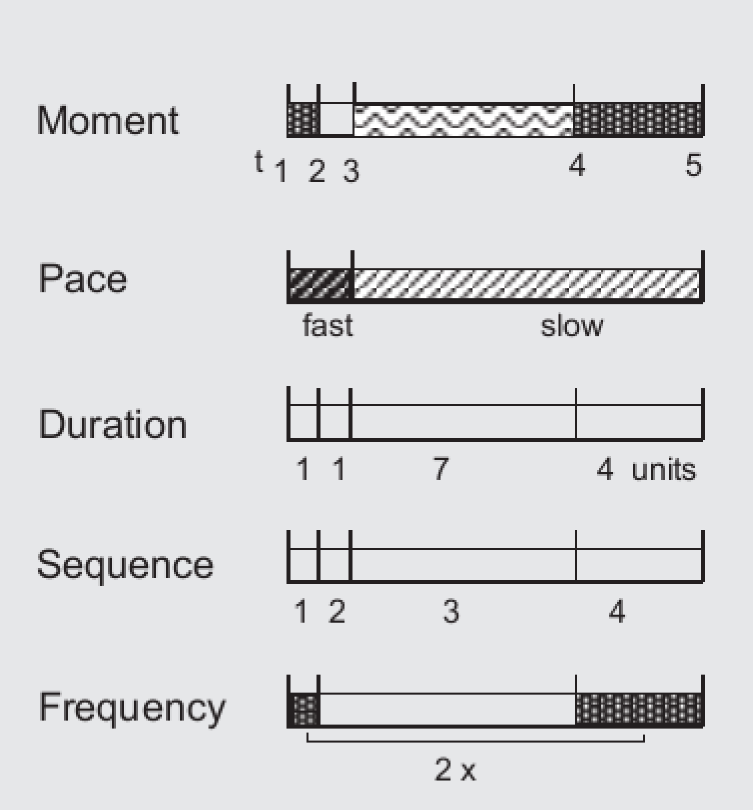


Figure 5.7: Characteristics of change in the temporal domain by Blok [11].

Characteristics of change in the temporal dimension get analysed and categorised by Blok [11] to describe the behaviour of dynamic geo-spatial phenomena. The proposed concept is visualised in Fig.5.7.
Fabrikant and Goldsberry [26] studied the difference of dynamic visual variables and levels of interactivity of dynamic displays compared to static displays. They empirically investigated the effects on knowledge construction processes using different dynamic variables. The use of these could potentially mitigate the change blindness effect, e.g. using visual transitions [32].

**Evidence** The dynamic variables display date, duration, order, rate of change, frequency and synchronisation can be used to control an animations story flow [43]. Most prominent of these variables are duration and order, which have a strong impact on the animation's narrative character [38]. Animation control by dynamic visualisation variables is also investigated by Blok [12]. Griffin et al. [30] focused on the factors animation pace, cluster coherence and gender that influence the map readers' ability to identify clusters. Different paces are more effective for identifying certain types of clusters due to pace and cluster coherence.
Most promising dynamic variables are motion and flicker [45]. Motion consists of direction and velocity, whereas flicker entails frequency and phase. Huber and Healey [35] examined the per-

ceptual properties flicker, direction of motion, and velocity of motion, resulting in suggestions for value differences to see differences in the three properties. To see coherent flicker a difference of at least 120 milliseconds is needed. A direction difference of at least 20° and a velocity difference at least 43° of subtended visual angle are needed to distinguish between different values. Flicker can be used to induce change blindness, e.g. to ”hide” changes from the observers attention.

### Guideline 9: Apply the congruence principle. [Perception of motion - Guidelines for dynamic representations]

Structure and content of the external representation should correspond to the desired structure and content of the internal representation. An effective external visual representation of routes for example, should be based on turns, because routes are conceived as a series of turns. The convergence of inventions across cultures and ages for using space to represent space and abstract concepts shows up the natural benefits of graphics. It suggests cognitive correspondences between mental spaces and real ones, e.g pictorial languages are found all over the world. Graphic communications in different domains (mathematics, geographic concepts) have used pictorial elements with natural cognitive correspondences in graphics [77].
Understanding a graphics organisation signifies cognitive effort that takes some time. The visual structure should be preserved during animations [17]. The user needs to accomplish confidence in the use of animations yet. Users have more experience interpreting static graphics and in animated visualisations one firstly needs to be confident of the consistency of the data [31]. If users see that they can control the animation and go back and forth to the data they are interested in, they will get a good experience in exploring the visualisation.

**Evidence** Garlandini et al. [29] mention as one key challenge for designing effective and efficient displays to congruently displaying thematically relevant information in a salient manner. Fabrikant et al. [25] state that displays should inhere a visual hierarchy that is congruent with thematic levels of relevance. They employed a bottom-up, saliency-based visual attention model to generate saliency maps that represent the focus of attention of the viewer. Perceptual salience can be coupled with thematic relevance by control of the visual variables in a scene of an animation and by control of dynamic variables between scenes in an animation, e.g. transitions [26].

### Guideline 10: Apply the apprehension principle. [Perception of motion - Guidelines for dynamic representations]

Effective graphics should conform to the apprehension principle, which says that structure and content of external representations should be readily and accurately perceivable and comprehensible. Simple graphics are more effective than more realistic ones if they abstract the essential conceptual information.

**Evidence** Essential conceptual information should correspond to natural organisation of the data, which sometimes is more discrete and sometimes more continuous. Animations are often too complex or too fast and the motion can not be accurately perceived, e.g. the trajectory of a wagon wheel in rotation or the motion of galloping horses' legs. Structure and content of external representations should be adapted to the internal representation. For example angles and lengths are generally categorised gross by viewers. Therefore finer distinctions in diagrams will not be accurately apprehended and routes do not need to have exact angles of turns and length of roads [77].

## 5.4 Monitoring tasks - Guidelines for representation of change

Conveying real-time changes and representations in time and space seem to be the most promising uses of animation [77]. There is evidence that animation supports preprocessing of spatial data [12].

In monitoring the detection of outliers or anomalies is an important task and animation is good for detecting such patterns. However, changes can happen unnoticed due to perceptual issues mentioned in the previous chapter, especially when the monitored area is large and contains several objects in motion.

In real-time monitoring situations the user's attention needs to get attracted to a new event while interrupting him in his primary task. This interrupting signal has to be perceived outside of the field of view and if ignored, should stay reminding the user. It should not disturb primary the working task and allow to transfer various levels of urgency [81].

One aspect of visual attention related to supervisory control is creating an effective way to gain the attention of the user [81]. The animation need to be slow and clear enough for observers to perceive movements, changes and their timing. Attention needs to be directed to critical changes and relations [77]. As mentioned before, motion is particularly suited to attract the user's attention due to its fast pre-attentive visual processing. Bartram showed that even motions in peripheral vision are particularly effective at grabbing attention [9], which leads to guideline 11.

Geometric, temporal and thematic characteristics of data are of interest for operators to detect patterns of events. They want to see anomalies, ongoing processes, relationships in space, causes and trends. Monitoring spatio-temporal behaviour over longer series enables to gain insights in processes and relationships and to detect trends [11]. In the application of real-time monitoring performance is a critical factor. With voluminous data temporal aggregations can be necessary to avoid load imbalanced, which is considered in guideline 12.

### Guideline 11: Use motion as notification element.
### [Monitoring tasks - Guidelines for representation of change]

Changes may not be perceived if the user's eye gazes elsewhere as where the change occurs. Therefore the user's attention needs to get guided to the point where changes happen.

Notifying elements should be designed in a way that they are not disturbing a primary task too much but on the other hand disturbing enough to attract the user's attention.

An information item is recognised as relevant after only 100 milliseconds. The conceptual short-term memory describes the processing of continually receiving visual stimuli. [21] First they are held in sensory storage for a very short time, in which they are unconsciously categorised by the knowledge stored in the long-term memory. Then the meaning of the visual input is interpreted

and if considered as not relevant it will be forgotten immediately or otherwise stored in the short-term memory.
Small periodic motions are significantly better signals than colour or shape cues across the entire visual field. Especially in the periphery such motions are more effectively detected and more accurately identified [9].

**Evidence** Bartram et al. [9] studied the use of variations in colour, shape, and motion to ”notify” viewers while they were engaged in a separate, attention-demanding task. Their result show several advantages for using motion as a notification mechanism.
Applying motion to a static glyph was significantly easier to recognise, compared to changing the glyph’s colour or shape. This finding held both when the glyph was near the centre of focus, and when it was located on the periphery of the viewer’s gaze. Experiments were conducted to measure how distracting each secondary motion cue appeared to a viewer. Flicker was the least distracting, followed by oscillating motion, then divergence, and finally movement over long distances.
An important finding is that motion does not seem to interfere with existing colour and form coding. This allows to communicate extra information through an object without changing its original codes which represent other variables.
McGrath and Blythe [46] also show that change of data can be better grasped with the help of motion than still before and after representations in the application domain of graph drawing. They examine network displays that manage status changes and show that with the introduction of motion the observer more likely perceives the information that was intended..
Results in Schlienger et al. [62] confirm the hypothesis that animation and/or sound improve change detection. Because sound brings information regardless of the user’s focus of attention, using the audio channel is a very appropriate modality for notification of changes.

### Guideline 12: Avoid load imbalances with the aggregation of temporal data. [Monitoring tasks - Guidelines for representation of change]

Aggregation of temporal data is necessary to avoid load imbalances in application with real-time data like, e.g. large-scale traffic monitoring. Temporal aggregation is analogous to static aggregation. The temporal sequence of traffic situations describes the spatial positions of all entities at a time moment. The problem is how to decide how much and which of the FCD records should be used or dropped in order to balance monitoring accuracy and timeliness. Liu et al. [41] observed that FCD data is often redundant (similar speed and location) so that dropping does not bring a loss of accuracy.

**Evidence** Phenomena in information are perceived depending on the scale of a representation where the temporal regularity of a phenomenon is of interest [38]. The existing methods for spatial, temporal, and attributive aggregation of movement data are discussed by Andrienko et al. [3]. Temporal aggregation can be visualised with a temporal histogram where the bars correspond to time intervals and proportional heights e.g. to the number of locations visited or the distance travelled. Spatial and/or temporal aggregation may be combined with attributive aggregation, which is done in the following way [4]: The value domain of an attribute is divided into subsets. If an attribute is numeric the value range is divided into intervals. Statistics about the objects that have attribute values from this subset are computed for each subset. An example for a combination of temporal and attribute aggregation is shown in Fig. 5.6.

## 5.5 Interaction - Guidelines for interactive event sequences

Interactivity facilitates learning and can help overcome the difficulties of perception and comprehension by allowing re-inspection with the help of close-ups, zooming, alternative perspectives and control of speed [77]. Therefore guideline 13 suggests to provide interaction possibilities in information visualisations. Recommended interaction techniques to support the user in the search for information are shown in guideline 14.
For working with time-oriented data advanced interaction techniques are important and letting the user control the animation is recommended in guideline 15.
Guideline 16 & guideline 17 go further into detail about the techniques ”zoom” and ”filter”.

### Guideline 13: Provide interaction possibilities.
### [Interaction - Guidelines for interactive event sequences]

Interaction possibilities improve visual exploration of the data by giving the user control over the perspective on the data [11]. Some interaction techniques are better than others, which can overload our cognitive capacities and therefore should be avoided, e.g. scrolling [45].

**Evidence** Tversky [77] states that interactivity might be the key to overcome the difficulties of perception and comprehension in animations and therefore should be included in animated visualisations. Nakakoji et al. [48] studied users interactions and on that basis identified requirements for interactive animated information visualisation systems. They have to help users comprehend the context when changes happen and when they happen and need to offer control over time and space, so that the user gets a feeling of the data.

### Guideline 14: Use the visual information-seeking mantra.
### [Interaction - Guidelines for interactive event sequences]

Users often adopt recurring sets of activities to reach a solution in complex problem solving processes. It is necessary to identify such sets of activities to be able to support them specifically by an appropriate design of the GUI [56]. Shneiderman [65] characterised following tasks at a high level of abstraction, which users wish to perform in information visualisation:

- Overview: Gain an overview of the entire collection.
- Zoom: Zoom in on items of interest.
- Filter: filter out uninteresting items.
- Details-on-demand: Select an item or group and get details when needed.

- Relate: View relationships among items.

- History: Keep a history of actions to support undo, replay, and progressive refinement.

- Extract: Allow extraction of sub-collections and of the query parameters.

An overview of the entire data let the users gain an understanding of the entire dataset, so that he can filter the data to focus on a specific part of particular interest. [45].
Zoom and filter will be further discussed in guideline 16 & guideline 17.
Details-on-demand enables to browse the details about individual items. A usual approach is to get more information by clicking on the item of interest.

**Evidence** Shneiderman's *Visual Information-Seeking Mantra* [65] describes a simple guideline for advanced GUIs and indicates how an information visualisation system can support users in the search for information: "Overview first, zoom and filter, then details-on-demand". The performance of a multi-scale search task is better when "overview + detail" facilities are combined with "zoom" [18].

### Guideline 15: Let the user control the presentation speed.
### [Interaction - Guidelines for interactive event sequences]

The duration of an animation is dependent on the type of the visualisation, i.e time-lapse, real-time or slow motion. The user should get control over the speed so he can spend more time on interesting parts [47].
If too fast, user can miss information, if too slow users may not see the motion at all or have problems with the Gestalt grouping [30, 73].
The speed of animation in presentations should be slow enough and if possible, controllable by the user. The presentation speed influences the ability to identify changes in the animation. Detailed studies addressing user control show that users did take advantage of the user control, but design measurements have to be applied to make user control beneficial [39].
Interaction elements should not be hidden, because often users think to only get what they see. Harrower [31] advises to use standard VCR-style controls (e.g. stop, start) for the presentation of interaction elements as they are widely understood and well know.

**Evidence** Harrower suggests to give the user control over the presentation speed and states that users often get frustrated if they do not have control over the presentation [31].
Kriglstein et al. [39] and references therein describe that slower speeds support the creation of consistent mental models. Robertson et al. [59] suggest that the control of animation speed can be beneficial.
Nakakoji's study [48] results in the need for control over the animation since animation means autonomous motions and users need to interact with them.

### Guideline 16: Use the interaction technique ”smooth zooming”. [Interaction - Guidelines for interactive event sequences]

Users typically have an interest in some portion of a collection, and they need tools to enable them to control the zoom focus and the zoom factor [65]. Zooming interfaces, which use a temporal separation between the views normally have controls to change the zoom level and a scale display of the level.
The effect of zooming in the domains of long-term memory, working memory and visual mental image is shown in Fig. 5.8. Zooming is a spatial operation during inspection of a visual mental image, focussing on a detail of an image. The shift of attention leads may lead to associated long-term memory content that then becomes part of the working memory [24].

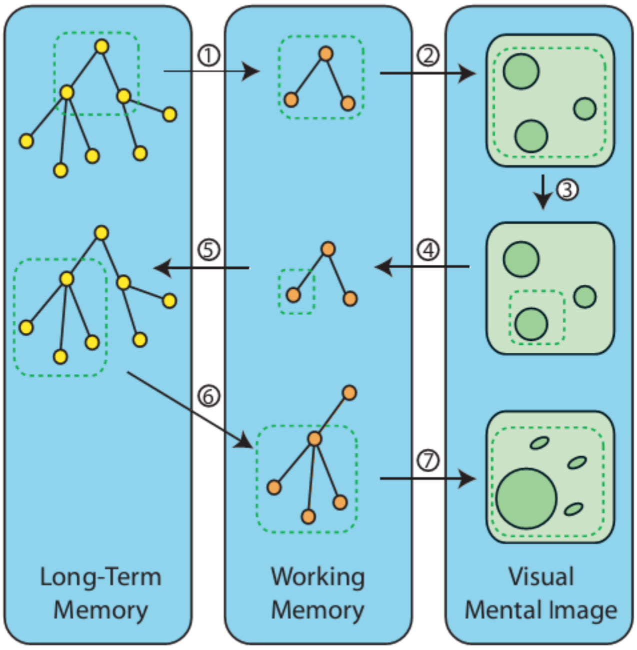


Figure 5.8: Effect of zooming by Engel et al. [24].

One usability issue would be navigation problems while using the interaction technique ”Zooming” when there are no orientation features in high zoom levels any more, called ”Desert Fog”. The viewer then loses the orientation because of missing context, as described in Cockburn et al. [18] ). Smooth zooming helps users preserve their sense of position and context [65].

**Evidence** Cockburn et al. [18] discuss smooth and efficient animation trajectories in pan-zoom space. Pointing to a location and issuing a zooming command by clicking on a mouse button is a very satisfying way to zoom in. Transition speed is important when animation wants to help reconstruct the change of zoom scale. As research suggest the brief period of automatic zooming should last between 0.3 and 1.0 second to show the transition between the state before and after the change.

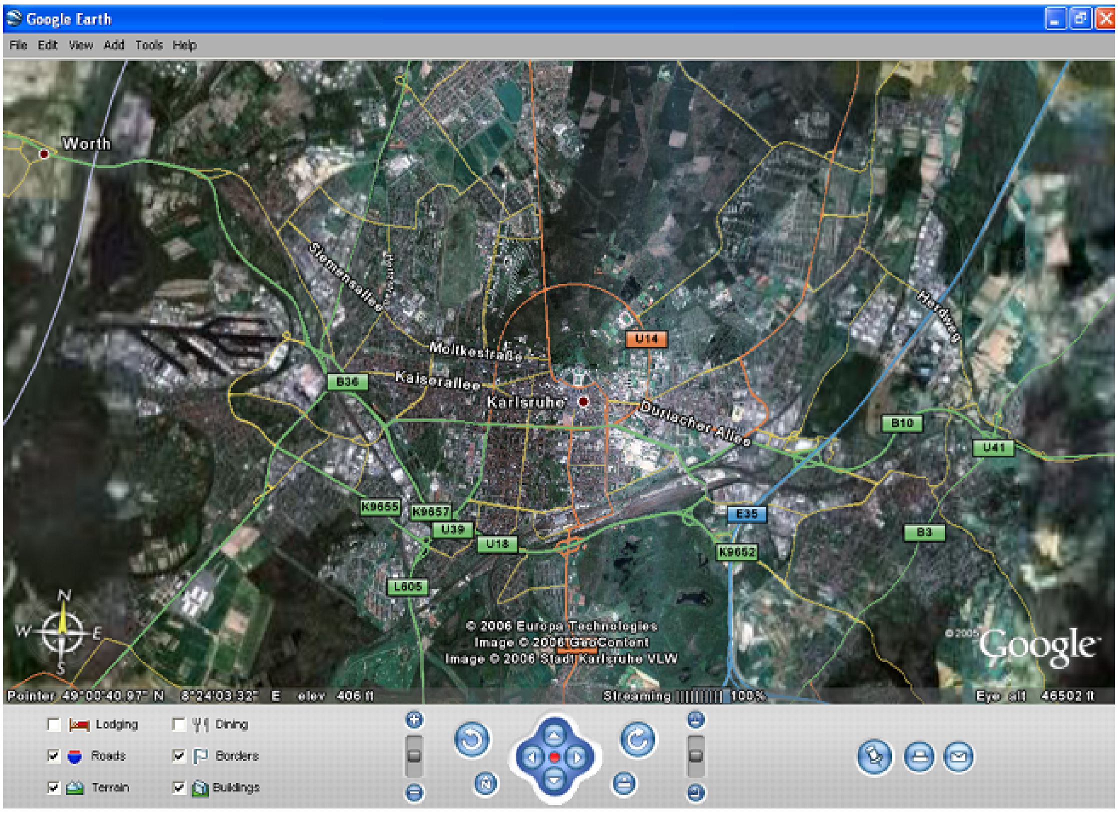
Zooming allows attention to be focused on one spatial region of a figure, keeping unnecessary detail off the screen while providing context. Instead of breaking a diagram into pieces spatially, one can imagine instead slicing along an axis of ”complexity,” separating detail into layers that become visible only as required. A simple animated transition such as a quick fade-in or a small sliding motion can provide a subtle and effective cue for differentiating the layers of information [89].

### Guideline 17: Use the interaction technique ”filtering”. [Interaction - Guidelines for interactive event sequences]

Dynamic queries is a key element in information visualisation. It enables filtering data of interest and with giving the user control of the content, he can quickly focus on his task [65]. Control elements like sliders and buttons only work well if coupled with a rapid update rate of the display (less than 100 milliseconds), even when there are tens of thousands of displayed items.
The interaction technique ”filtering” allows to manage complexity through overlays. A multi-layer design supports universal usability by allowing to choose the level of complexity and enable novice users to get their hands on by reducing functionality in the lower levels [66]. In a screenshot of Google Earth 5.9 the controls are placed in the bottom whereas checkboxes on the left allow to hide or show specific information like roads or borders.

**Evidence** Interactivity brings more accurate results [6]. Reducing information on a display and providing users with the ability to turn components of the visualisation off and on is also suggested by Ware [81]. Tekusova and Kohlhammer [73] pointed out that features like a selection, filter, and search function can be useful for users to highlight specific data which they would like to observe during the animation. Liu et al. [41] introduce a layered indexing method to enable traffic querying on different resolutions. They tested different load shedding techniques to demonstrate the better performance of their solution.
Shneiderman [66] suggests that multi-layer interfaces can assist users raising the level of complexity step by step. Harrower also states that reducing complexity and information overload can be done with letting the users turn data on and off [31].

In the next Chapter, the guidelines are briefly summarised.



☐ Lodging
☑ Roads
☑ Terrain
☐ Dining
☑ Borders
☑ Buildings

Figure 5.9: Example of filtering in Google Earth [51].

## CHAPTER 6

# Catalogue of Design Guidelines

In this chapter the guidelines are summarised to provide a compact catalogue of guidelines. The guidelines are kept brief to enable a good overview of the guidelines. The application context is given to further ease the selection of relevant guidelines. The effect of each guideline is described and the advantages and trade-offs are stated separately. Issues, either positive or negative, that come along with the guideline further inform the designer. With this framework empirical studies have to be the evidence for cognitive theories. The deduction of guidelines was done in all conscience to facilitate the design of TMS. They aim to support designers of complex systems during the design process for static representations, but especially when motion is used for the visualisation of temporal data.

### Guidelines

**Guideline 1:** Choose pre-attentive attributes according to data type.
[Visual perception - Guidelines for static representations]

| | |
|---|---|
| Description | Use visual attributes that are rapidly processed by visual perception (tabular overview of data types can be found in Fig. 5.3) with an upper limit of four distinctions for each attribute. |
| Effect | The unconscious perception of these attributes reduces the cognitive load of a representation and the content can be quickly and effectively comprehended. |
| Upside | Reduction of cognitive load. |
| Downside | Possible combinations are limited. |
| Issues | Colour blindnesses and effects like change blindness or combinational influences of the attributes are to be considered. Another issue is the mapping decision if the data type is not easy to categorise in quantitative, ordinal or categorical data types. |
| Evidence | Mazza [45] combines results of empirical studies and generated a rule of thumb for different data types. |

**Guideline 2:** Group elements to a maximum of five chunks.
[Visual perception - Guidelines for static representations]

| | |
|---|---|
| Description | Avoid overloaded displays and keep the number of important elements in the range that can be attended to. Chunks are built from a grouping effect of spatial structures in the external representation as well as in our working and long-term memory. |
| Effect | We perceive groups of elements fast because organising pieces of information into larger, meaningful units is a universal cognitive principle. |
| Upside | If objects on a display are perceptually salient they can be easily isolated to form a group of similar objects based on the objects attribute. |
| Downside | The amount of data that can be depicted is restricted. |
| Issues | Perceptual properties of motion lead to the perception of groups if there are multiple similar motions, though the perceivable number of chunks reduces with motion. |
| Evidence | Users can access four to five distinct object in a display at the same time [8, 24, 81]. |

**Guideline 3:** Prefer 2D representations over 3D.
[Visual perception - Guidelines for static representations]

| | |
|---|---|
| Description | 2D representations are clearer and more precise than 3D and are to be preferred over 3D representations. |
| Effect | 2D representations can not establish a one-to-one mapping between world spaces and map space and sacrifice the third dimension to get a clearer and more precise visual representation. |
| Upside | • Facility.<br>• Accurate mapping.<br>• No occlusion problem. |
| Downside | Visualisation of data may demand more space and usually contains redundant information. |
| Issues | Interactivity allows the best use of 3D representation and 3D representations can be used if interactivity is possible and overload can be avoided. |
| Evidence | 3D representations increase cognitive load and the user's mental effort to correctly interpret the represented data [45]. |

**Guideline 4:** Use aggregates for the representation of large datasets.
[Geographic data - Guidelines for geographic visualisation]

| | |
|---|---|
| Description | Aggregates represent a group of data points so that fewer markers are needed. |
| Effect | Aggregates simplify a display so that it does not get crowded. |
| Upside | • User gets aware of what is important.<br>• Establish a clear view on the data. |
| Downside | • Occlusion of other information.<br>• Anomalies of data possibly gets hidden. |
| Issues | Appropriate thresholds for the granularity of the generalisation have to be considered. |
| Evidence | Harrower [31] states that effective maps have to be highly generalised so that only the most important trends or feature emerge. |

**Guideline 5:** Prefer small multiples for comparing tasks.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | Prefer small multiples over dynamic representations when the user needs to compare information at specific time points. |
| Effect | Small multiples show moments of important change. |
| Upside | • To have all the information at one time.<br>• Can be explored without a time limit.<br>• Faster response time. |
| Downside | • Space restriction.<br>• Better accuracy achievable with animation. |
| Issues | Faster responses do not automatically worsen accuracy. |
| Evidence | Small multiples should be used for tasks that require the user to read topological information [6] and compare information at specific time points [30]. Animation should only be used if it is impossible to present the data in static form [31]. |

**Guideline 6:** Use animation for transitions.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | Animation is an effective way of presenting transitions as they help to understand the spatial relationship between views and support users to track changes. |
| Effect | Visual transitions establish coherence using visual ties to events occurring in adjacent frames in an animation. |
| Upside | • Show the interrelations among change in space (position), place (attribute) or in time.<br>• Couple perceptual salience with thematic relevance between scenes in an animation. |
| Downside | Some studies show that using animation can be confusing. |
| Issues | Giving the user the possibility to stop the animation and proceed frame-by-frame overcomes potential uncertainties. |
| Evidence | Animation should be used for tasks related to the dynamic evolution of data and is treated in various study fields [6, 17, 31, 88]. |

**Guideline 7:** Reduce visual events to a minimum in a display.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | The number of visual events in a display should be kept small to avoid change blindness. |
| Effect | Reducing the possibility that change blindness occurs for important changes in the display. |
| Upside | Important changes are seen more likely. |
| Downside | It is not possible to influence the number of change events in every application domain. |
| Issues | Change blindness on the other hand can be used to purposely make ”hidden” changes in order to not disturb the observer in his primary task. |
| Evidence | Rensink [57] states that change blindness involves mechanisms central to our visual experience of the world. |

**Guideline 8:** Use dynamic variables to control the animation flow.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | With the use of dynamic variables the temporal dimension can get influenced to control the flow of an animation. Duration and order have a strong impact on the animation's narrative character. |
| Effect | The visualisation of temporal change and its effects can be controlled with dynamic variables. |
| Upside | • Controlling transitions to mitigate or induce the change blindness effect.<br>• Emphasis on location and attributes of temporal phenomena. |
| Downside | Different paces support the identification of certain cluster types. |
| Issues | Characteristics of change are shown in Fig.5.7. |
| Evidence | Fabrikant and Goldsberry [26] investigated the effects on knowledge construction processes using different dynamic variables. Many studies investigate the effects of dynamic visualisation variables [12, 23, 32, 38, 43]. |

**Guideline 9:** Apply the congruence principle.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | Structure and content of the representation should correspond to their internal representation. An effective external visual representation of routes for example, should be based on turns, because routes are conceived as a series of turns |
| Effect | Natural cognitive correspondences in graphics help users form a consistent mental model. |
| Upside | Facilitates comprehension of the content. |
| Downside | - |
| Issues | Understanding a graphics organisation signifies cognitive effort that takes some time. The visual structure should be preserved during animation. |
| Evidence | For effective and efficient display design thematically relevant information should be congruently displayed in a salient manner [29]. |

**Guideline 10:** Apply the apprehension principle.
[Perception of motion - Guidelines for dynamic representations]

| | |
|---|---|
| Description | Consider perceptive limitations in the design of motion in order to accomplish correct apprehension. |
| Effect | Structure and content of external representation gets readily comprehended and accurately perceived. |
| Upside | • Motion gets accurately perceived.<br>• ”Unnecessary” information can be left out (what the user does not apprehend anyway) which leads to performance savings. |
| Downside | - |
| Issues | Perceptual and cognitive limitations in the processing of a changing visual situation are general drawbacks of animation. |
| Evidence | Animations are often too complex or too fast and the motion can not be accurately perceived [77]. |

**Guideline 11:** Use motion as notification element.
[Monitoring tasks - Guidelines for representation of change]

| | |
|---|---|
| Description | Use motion as notification element to enhance the detection of change. |
| Effect | Motion attracts the users attention better than other attributes, especially in the peripheral vision. |
| Upside | Relevant changes are perceived to a higher chance. |
| Downside | Animated elements can get annoying, e.g. high frequent blinking, and may distract the observer in his primary task too much. |
| Issues | • It is unpredictable if a visual change is detected. Designers have to experiment with the media to establish the visual impact of a change because the detection of a visual change depends very much on the nature of the visual media.<br>• Combination with sound or hue have to be tested. |
| Evidence | Unexpected events are rather noticed when they are visually similar to the events they are paying attention to than completely unexpected events [67]. |

**Guideline 12:** Avoid load imbalances with the aggregation of temporal data.
[Monitoring tasks - Guidelines for representation of change]

| | |
|---|---|
| Description | Use temporal aggregates to avoid load imbalance in the processing of voluminous temporal data. |
| Effect | Dropping redundant data in the temporal dimension leads to performance savings. |
| Upside | Applications with large-scale real-time data can process and visualise the data promptly. |
| Downside | Possible loss of temporal patterns. |
| Issues | Temporal aggregation may further be combined with attributive aggregation [4]. |
| Evidence | Phenomena in information are perceived depending on the scale of a representation where the temporal regularity of a phenomenon is of interest [38]. |

**Guideline 13:** Provide interaction possibilities.
[Interaction - Guidelines for interactive event sequences]

| | |
|---|---|
| Description | Provide interaction controls for the users of the information visualisation. |
| Effect | Support cognitive processes in the visual exploration of the content. |
| Upside | • Data apprehension.<br>• Raises interest and curiosity. |
| Downside | Some interaction techniques can overload our cognitive capacities and therefore should be avoided, e.g. scrolling. |
| Issues | Interactions possibilities should support the comprehension of the context when changes happen and when they happen and need to offer control over time and space, so that the user gets a feeling of the data. |
| Evidence | The benefit of user interactions is analysed in several studies with the outcome that interactivity is the key to overcome the difficulties of perception and comprehension in animated visualisations [45,48,77]. |

**Guideline 14:** Use the visual information-seeking mantra.
[Interaction - Guidelines for interactive event sequences]

| | |
|---|---|
| Description | First overview, second zoom and filter, third details-on-demand. |
| Effect | The characterisation of user tasks and adopted sets of activities for problem solving supports the design of GUI. |
| Upside | Support users in the search for information and overall use of an information visualisation. |
| Downside | - |
| Issues | Performance can be improved if overview + detail facilities are combined with zoom. |
| Evidence | Shneiderman [65] describes this guideline for advanced GUIs and other studies prove this concept to be valid [18]. |

**Guideline 15:** Let the user control the presentation speed.
[Interaction - Guidelines for interactive event sequences]

| | |
|---|---|
| Description | Give the user control over the presentation speed. |
| Effect | The presentation speed influences the ability to identify changes in the animation and the user can better create mental models if he has control over the speed. |
| Upside | Improved accuracy of mental models. |
| Downside | If the speed is too fast observer can miss information, if too slow they may not see the motion at all or have problems with the Gestalt grouping. |
| Issues | Longer examination times do not automatically result in better accuracy. |
| Evidence | Studies show that giving the user control over the animation is beneficial and that users get frustrated more easily when they can not control the presentation speed [31, 39, 48, 59]. |

**Guideline 16:** Use the interaction technique ”smooth zooming”.
[Interaction - Guidelines for interactive event sequences]

| | |
|---|---|
| Description | Use a quick fade-in when changing the zoom level and display the current scale level. |
| Effect | Users get a subtle cue to connect the information from one state to the zoomed state and apprehend the effect of the change. The zooming animation should last between 0.3 and 1 second to show the transition. |
| Upside | • Zooming allows to focus on a spatial region while maintaining context.<br>• Animated zooming supports tracking the change of zoom levels. |
| Downside | Orientation problems in different zooming level can occur depending on the data. |
| Issues | Additional processing steps can assure fast switching between different levels and that each level contains enough referencing context. |
| Evidence | Animation supports reconstructing the change of zoom scale [18]. |

**Guideline 17:** Use the interaction technique ”filtering”.
[Interaction - Guidelines for interactive event sequences]

| | |
|---|---|
| Description | Give the user control over the display of the data, so individuals can decide what they like to observe during an animation. |
| Effect | Filtering reduces complexity and avoids an information overload for a better viewing experience. |
| Upside | • Overlays reduce complexity.<br>• Filtering facilitates exploration and raises curiosity.<br>• Users gain confidence in using this interaction technique. |
| Downside | Users may not get additional information if they miss the interaction option. |
| Issues | Not showing all features at first sight is often a problem for technical designers. |
| Evidence | Several studies prove the filtering interaction technique to be beneficial [31, 66, 73, 81] |

CHAPTER 7

# Critical Reflection

The debriefing and interpretation of empirical results is not a straightforward but complex task. Decisions were made with Spence' dogma in mind to form existing knowledge to the use of designers in a simple and clear way. In this thesis the framework of design actions was chosen to accomplish that.

Carpendale states that while there are definitely benefits that come with the use of guidelines, they are based on what is known to be successful and therefore tend not to favour the unusual and the inventive.

> ”In the design world, common advice is that while working without knowledge of guidelines is foolish, following them completely is even worse.”
> Carpendale [15, p.35]

Ward [80] emphasises that design guidelines are never a substitute for rigorous usability studies. To improve a design one should formally test it with potential users of the target audience. Harrower [31] advises to ask the users questions about both the interface and the visualisation itself.

## 7.1 Comparison with related work

Some guidelines are very specific and detailed while others are and abstract. With very specific guidelines the sheer number of guidelines can make it difficult to find the right guideline for any situation. General guidelines are often few in number but they probably need too much interpretation.

Chang summarises gestalt based guidelines in a categorical way to structurally inform designers about existing knowledge. He states that most guidelines are a simple collection of knowledge and that there exist few guidelines for multi-sensory displays as they are relative new [16].

Research in cartography suggests that traditional graphic design principles may only partially transfer into the dynamic realm, and therefore design for animation needs special attention [31].

Animation is discussed in literature since many years now and the community is still at odds with the beneficial use of animation. Because of the lack of specific design guidelines evaluations of animations may have resulted in bad results.

Fabrikant [26] proposes a research agenda and sketches a series of empirical experiments aimed at developing cognitively adequate dynamic map displays to systematically evaluate the effectiveness of interactive and dynamic geographic visualisation displays [32].

Nesbitt's [50] approach of multi-sensory guidelines are categorised in different levels of complexity and abstraction and can be of use for the evaluation of designs.

Tversky et al. [77] are sceptical of many published animation studies, citing problems with incomparable representations and study methodology. In their own studies of use of animation to illustrate or communicate the workings of complex systems, they found no benefit to animation and they doubt effectiveness of animation for trends. However, they acknowledge that the use of animation for transitions may well lead to a benefit [59]. Zongker and Salesin [89] counter Tversky's argument by describing a number of design principles that make animation presentations effective.

# CHAPTER 8

# Summary

This thesis deals with the visualisation of complex, voluminous data and thoroughly analyses empirical studies that evaluated such visualisations to derive guidelines for designers. Chapter 1 introduces the problem statement and motivation of this thesis. The aim was to identify patterns in the results of empirical studies about the effectiveness of visualisations and to form this existing knowledge into guidelines which are applicable by interface designers. Due to the co-operation with the Telecommunications Research Center Vienna (FTW) it was of interest to figure out optimal visualisation techniques for Floating Car Data (FCD) in Traffic Management System (TMS), which visualise highly dynamic spatio-temporal datasets. Therefore the beneficial application of animation for massive amounts of time-oriented data was examined.

Chapter 2 describes the state-of-the-art in the visualisation of FCD as well as existing design principles. FCD are used for accurate traffic assessment, prediction and for related services such as accurate routing and navigation. For the visualisation of travel time maps current systems retrieve FCD from taxi fleets, public transport, private cars and combinations of those. The state-of-the-art analysis further shows that there is a need for new evaluation methods in the field of information visualisation, due to the fast development in this field. Evaluating visualisations and designing appropriate methods is still a strong remaining challenge. There are few evaluation studies on animation for time-oriented data and existing studies rather address the general benefits than specific aspects of animations. More evaluation studies of animated visualisation would result in detailed insights and better design recommendations could be found.

Graphical user interfaces need to be optimised with regard to the principles of human perception. Research indicates that the visual system can only track four to five distinct motion trajectories simultaneously in the same visual field. Consequently, cognitive theories and studies related to information visualisation from different fields are summarised in chapter 3. Characteristics and requirements of TMS were explored in co-operation with the FTW and the results are summarised in chapter 4. Versatile possibilities for the visualisation of large datasets point out the need for design guidelines to construct effective visualisations.

Spence' and De Bruijn's framework for theory-based interaction design was used to employ a compact catalogue of guidelines where empirical results are the foundation rather than experiences of designers. The focus is on animated representations because the guidelines should especially support the effective visualisation of spatio-temporal data in TMS.

Seventeen guidelines were derived from the results of empirical studies, categorised in the context groups: visual perception, geographic data, perception of motion, monitoring tasks and interaction. An in-depth analysis can be found in chapter 5 and a compact catalogue of guidelines is provided in chapter 6.

The guidelines aim to support designers of complex systems during the design process, especially when motion is used for displaying temporal data. Adapted to the perceptual and cognitive limits of the human mind, they lead to an optimal design of graphic displays with comprehensible animations, where the user perceives what was intended in the first place.

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# List of Acronyms

**2D** two-dimensional

**3D** three-dimensional

**CHART** Coordinated Highways Action Response Team

**DSMS** Data Stream Management System

**FCD** Floating Car Data

**FTW** Telecommunications Research Center Vienna

**GPS** Global Positioning System

**HCI** Human Computer Interaction

**TMS** Traffic Management System

**GUI** Graphical User Interface

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