Reducing the information load in map animations as a tool for exploratory analysis

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Abstract

This dissertation investigates the information load that animated maps cause to their viewers, and presents two novel visualisation methods to support the exploratory visual analysis of the animations. Information load consists of the information content of the map and its presentation. The number of objects and their attributes are the unavoidable content, but the visualisation of the objects, the background map, and display settings of an animation have an effect on the information load and experienced complexity of the presentation. Information overload causes a load on human beings' cognitive capacity and working memory. Our brain is capable of processing only a few pieces of information at a time, and if new information is provided faster than it can be moved into the long-term memory, some of the information is lost. Luckily, the information can be segmented into meaningful wholes, mental chunks, to increase the processing capacity.

The aim was to find out, what factors increase the information load in animated maps, how this load could be reduced, and how the formation of mental chunks of an animation can be supported. The most important factors affecting the information load were recognised to be the temporal extent of the dataset, geometry complexity and illogical movement of the data presented, and the user's task. When the temporal extent of the information grew too big for the users, the amount of information was automatically reduced from another aspect. The combination of two datasets, that was designed based on previous knowledge about combination colours, was experienced as being too complex because of the graininess of the dataset and the unexpected behaviour of the phenomena.

The novel visualisation methods presented, temporal equal density transformation and temporal classification, aim to reduce the information load without any loss of the information content; a feature that is important in exploratory analysis where the task is unknown. In the user tests, they were proved to be particularly useful to reveal such spatio-temporal patterns that would have been left unnoticed with traditional animations. They seem to be able to reduce the information load by spreading the information flow equally over the whole period and by segmenting the animation into easily adoptable chunks.

As a conclusion, it can be argued that the designing of map animation sufficient for exploratory analysis should take into account the characteristics of both the spatial and temporal structure of the data, since a task-based visualisation is not possible to define in exploratory use.

Tiivistelmä

Tämä väitöskirja käsittelee kartta-animaatioiden käyttäjälleen aiheuttamaa informaatiokuormaa, sekä esittelee kaksi uutta menetelmää animaatioiden eksploratiivisen analyysin tueksi. Informaatiokuorma koostuu tietosisällöstä ja sen esitystavasta. Objektien määrä ja niiden ominaisuudet ovat välttämätöntä tietosisältöä, kun taas niiden visualisointitapa, taustakartta ja animaation asetukset vaikuttavat informaatiokuormaan ja animaation koettuun kompleksisuuteen. Informaation ylikuormitus rasittaa ihmisen työmuistia ja kognitiivista suorituskykyä. Aivot pystyvät käsittelemään kerrallaan vain muutamaa kohdetta, ja jos uutta informaatiota tulee nopeammin kuin edelliset saadaan siirrettyä säilömuistiin, osa informaatiosta menetetään. Informaatio kuitenkin voidaan ryhmitellä suuremmiksi kokonaisuuksiksi, jolloin säilömuistiin siirtämisen kapasiteetti kasvaa.

Tämä väitöskirja pyrkii selvittämään, mitkä tekijät kasvattavat kartta-animaatioiden aiheuttamaa informaatiokuormaa, kuinka tätä kuormaa voidaan lievittää, ja kuinka käsiteltävien kokonaisuuksien muodostamista animaatioista voidaan tukea. Tärkeimmiksi informaatiokuormaa lisääviksi tekijöiksi tunnistettiin ilmiön ajallinen laajuus, geometrian kompleksisuus ja ilmiön epälooginen käyttäytyminen, sekä käyttäjän tehtävämäärittely. Kun tarkasteltavana aineiston ajallinen laajuus kasvoi liikaa, käyttäjät vähensivät automaattisesti tietosisältöä joltain toiselta akselilta. Kahden aineiston yhdistelmä, joka oli suunniteltu kaksimuuttujaisen visualisoinnin aiempiin tutkimuksiin perustuen, koettiin liian kompleksiseksi. Tämä johtui aineiston geometrisesta rikkonaisuudesta ja aineistojen esittämien ilmiöiden epäloogisesta käyttäytymisestä.

Esitellyt uudet menetelmät, temporaalinen tasavälimuunnos ja temporaalinen luokittelu, pyrkivät vähentämään informaatiokuormaa ilman, että yhtään tietosisältöä häviää. Tämä ominaisuus on tärkeä eksploratiivisessa analyysissa, jossa käyttäjän tavoite ei ole vielä selvillä. Käyttäjätestit osoittivat menetelmät lupaaviksi. Erityisesti ne onnistuivat paljastamaan aineistoista hahmoja, jotka olisivat jääneet huomaamatta perinteisen animaation avulla. Menetelmät vaikuttavat onnistuvan vähentämään informaatiokuormaa tasoittamalla havainnot tasaisesti tarkastelujaksolle ja ryhmittelemällä animaation sisällön helpommin omaksuttaviksi palasiksi.

Yhteenvetona voidaan todeta että eksploratiiviseen käyttöön tarkoitetun kartta-animaation suunnittelussa tulee ottaa huomioon datan spatiaaliset ja temporaaliset ominaispiirteet, koska tehtäväperusteinen suunnittelu ei ole mahdollista.

Acknowledgements

Contents

List of Figures

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their roman numerals.

I. Multimäki, Salla; Seppänen, Hannes; Ahonen-Rainio, Paula. 2010. User Profiling for Maritime Situational Picture. Journal of Location Based Services, vol 4, no. 3-4, pp. 240-252. ISSN: 1748-9725.

II. Multimäki, Salla, Mäkilä, Antti, Korpi, Jari, & Ahonen-Rainio, Paula. 2016. Experiencing bivariate colour scales on animated maps. International Journal of Cartography, vol 2, no. 1, 1-18. ISSN: 2372-9333.

III. Multimäki, Salla; Ahonen-Rainio, Paula. 2015. Assisting the Detection of Spatio-Temporal patterns in Temporally Transformed Map Animation. International Journal on Advances in Systems and Measurements, vol. 8, no. 3 & 4, pp. 168-177. ISSN: 1942-261x.

IV. Multimäki, Salla; Hall, Andreas; Ahonen-Rainio, Paula. 2015. Comparison of Temporally Classified and Unclassified Map Animations. Cartographic Perspecives no. 82 (forthcoming). I74SSN: 1048-9053.

Author's Contribution

Publication 1: The author was mainly responsible for writing the paper, except for subchapters 2.1 and 2.2. For the study, the author designed the questionnaire presented in section 2.3 and analysed the results of the study.

Publication 2: The author was responsible for writing the paper, the literature review of the study, designing the animations, and the design and analysis of the interviews.

Publication 3: The author was responsibe for writing the paper, the literature review, and designing and implementing the test animations, as well as the design of the user test and the analysis of the results.

Publication 4: The author was mainly responsibe for writing the paper, as well as designing the test animations. The design and impelementation of the user test and analysis of the results were done in co-operation with the second author.

1. Introduction

"The wizard looked down at the cat and realized for the first time how odd it looked now. The living often don't appreciate how complicated the world looks when you are dead, because while death frees the mind from the straitjacket of three dimensions it also cuts it away from Time, which is only another dimension. So while the cat that rubbed up against his invisible legs was undoubtedly the same cat that he had seen a few minutes before, it was also quite clearly a tiny kitten and a fat, half-blind old moggy and every stage in between. All at once. Since it had started off small it looked like a white, catshaped carrot, a description that will have to do until people invent proper four-dimensional adjectives."

Terry Pratchett: *Equal Rites*

A map always has a temporal extent. In its simplest form, a map presents the situation in one particular moment of time, and without the knowledge of that time, the map is more or less useless. Presenting any change over time in a static map is a more complex issue. Some surprisingly insightful visualisations about change over time have been created, one good example being Minard's map about Napoleon's infamous campaign to Moscow in 1812. After all these years of technical development, this map, drawn in 1869, is still argued to be the best map ever drawn presenting change over time.

Animations brought a whole new perspective to the spatio-temporal data. Presenting the change over time in an animation is as natural as it is to present spatial information in a map. It uses the very same dimension to visualize the information that was the one producing it. In an animation, which is like a map of time, we could see the temporal phases of the wizard's cat, maybe not at once, but almost.

1.1 Motivation

Ever since increasing computing capacity made it easy to animate the change in spatial data over time, it has been a widely used technique. Studying the use issues of animated maps has an equally long history. Animation is a natural way to present temporal change of the data, because it fulfills the congruence principle (Tversky et al. 2002): the phenomenon in the real world (here: the flow of

time) should, if possible, have a similar correspondence in the presentation. In animations, time presents time, although usually some temporal scaling has to be done if the case is not real-time monitoring.

Animated maps have been proved to be particularly useful in presenting the overall picture of the phenomenon (Harrower & Fabrikant 2008). The potential of animation in studying the development of phenomena is not limited to maps; the use of animations in information visualisation is a growing field of research (Ware 2012) and animations are particularly useful in instructions, manuals, or teaching the working of a mechanical system (Tversky et al. 2008). This potential has made animation a popular technique also in the field of earth sciences (DiBiase et al. 1992). The weakness of animation lies in the same ground as its strength, the overall picture: it is not suitable for look-up tasks (Andrienko & Andrienko 2006) or comparison between the values with two different timestamps.

The usability of animated maps can not be discussed without paying attention to the control tools. The possibility to control the course of animation is almost mandatory, excluding some short information animations showed in public. In addition to basic play, pause, and jump functions, the possibility to adjust the speed of the animation can have a considerable effect on the usefulness and experienced usability of the animation. However, the control tools, too, have their disadvantages. They undoubtly need some attention from the user, and this reduces the level of attention the user can dedicate to the actual information in the animation and cause a split attention effect (Harrower & Fabrikant 2008). The use of control tools can also take some time to learn, and this increases the threshold of starting to use the system.

The user's attention plays a key part, because the information load of an animated map can be practically unlimited. Whilst the speed of the animation can be exhausting and multiple objects with several attributes in a map can constantly appear, disappear, merge and move, the user easily gets lost. Only the congestion and overlapping of the objects make them truly invisible for the user, but in practice, the perception of the human user is much more limited. The user can focus his/her eyes only on one spot at a time, and the more complex the animation gets, the more is missed. There are also limitations on how many different colours or shapes we can distinguish from each other. An even more important limitation is the capacity of the working memory of the brain, capable of handling only a few objects at a time.

If these characteristics of the user and the information load of the animated map are not taken into account, the result can at its worst be a presentation that is confusing, uninformative, and even misleading. This deficiency is not unknown for cartographers, who have for centuries modified maps by generalising, classifying and filtering the data. These traditional cartographic methods, however, face an unexpected disadvantage with the modern use of geospatial data: the process of exploratory analysis, which tries to find the unseen phenomena from the massive amounts of data and is based on the assumption that the user is able to see everything. Generalising or filtering this data can lead to

the disappearance of patterns from the data, and therefore also the detailed level of information should always be available for the user.

This thesis cuts into this problem. It identifies the factors that make map animations too complex for users to cope with.This thesis is searching for methods that, instead of filtering any data out, emphasise the potentially important characteristics of the phenomenon, and if the exact task of the user is ill-defined, this emphasising should be done based on other factors than the task.

1.2   Core concepts

Map animation is are used here to sum up the concept that has been referred to in cartographic literature as e.g. "dynamic representation" (e.g. Slocum et al. 2001), "dynamic map" (e.g. DiBiase et al. 1992), "animated display", "animated map" (Harrower 2003), "temporal cartographic animation" (Kraak et al. 1997), and "map animation" (Harrower & Fabrikant 2008). It is a presentation changing over time and showing the location and attributes of the data objects in different moments of time. It is common that the map animation contains a steady background map on which the data objects, points, lines or areas, are presented. These data objects can have attribute information presented by any of the visual variables (Bertin 1967/83), the most noticable ones being the colour and the size of a point symbol (Wolfe & Horowitz 2004). There are also animated maps that do not contain any change in the objects over time; animated fly-by views are one good example but these types of animations are not considered in this thesis. Here, the terms "map animation" and "animated map" are both used; the first term emphasising animation as a tool to deliver spatial information, and the later term emphasising the map presentation being animated.

The information content of a map, static or animated, comprises all information presented in it; the set of objects and their attributes, as well as all reference information, i.e. the backround map. Spatial distribution of the objects in the map, for example, influences the experienced complexity of the map (Stigmar & Harrie 2011) but is not an aspect of information content. The data content, on the contrary, in this thesis refers only to the number of single data objects presented on the map, not their visualised attributes.

The visual complexity of a map is here used with an emphasis on the user's experience. The complexity of the map has been studied a lot from the viewpoint of visual clutter, but mostly on static maps. Rosenholz et al. (2005) defined the information content and density to cause visual complexity, but van den Berg et al. (2009) identified the spatial congestion of the objects to be more important. In geovisual analytics, the variety and richness of the data might be the most important factor causing complexity experienced by the user (Kraak 2011, Korpi & Ahonen-Rainio 2013).The experience of a complex map does not require high information content and density, but can be caused also for example by the characteristics of an animation.

The information load of a map animation is formed by all the factors that load the presentation, its main factors being the information content, visualisation of the information, and pace of the animation. Two animations presenting the

same information content can therefore have very different information loads. A high information load can be caused for example of visual clutter (Rosenholtz et al. 2005), where information density and information layout prevent an effective performance of a task. Information load is often discussed together with cognitive load, which is explained below. Information load should not be mixed up with toxic information overload, because all displays produce a certain amount of information load.

Cognitive load theory (CLT), brought from cognitive psychology to the field of geography by Bunch & Lloyd (2006), suggests that there is a limit on the amount of information that humans can gather from the surrounding environment. Our working memory is capable of handling only a few chunks of information at a time, after which it takes some time to transfer this information into our long-term memory. This transference process causes cognitive load for a user.

Split attention effect arises when multiple events take place at the same time in different parts of the display. Since this is very common in map animations, split attention has stated to be one of the most important issues that has to be solved when making map animations (Kraak et al. 1997) and is closely related to the information load of a map. Human attention is easily focused by movement and bright colours (Wolfe & Horowitz 2004), and this feature can be used in focusing attention onto important features.

Visual analytics is a field of research that aims to best benefit the computing capacity of computers and the effective visual analysis processes of a human (Roth 2012). Visual analytics is not limited to cartography, but is a wider concept containing the visualisation of all kinds of information.

Exploratory analysis is a data-driven analysis approach. It is empirical investigation of the data, motivated by the analyst's interest but without any specific questions in mind (Andrienko & Andrienko 2006). Exploratory analysis is located in the first phase of the analysis chain, where the questions to be asked are searched for (DiBiase 1990). Exploratory analysis is often an iterative process, moving from holistic investigation to the more specific analysis executed with various tools, including visualisation tools. This iteration is comparable with Shneiderman's (1996) well-known mantra about the information analysis process: "Overview first, zoom and filter, details on demand".

Task in this thesis refers to the mission or question that the user has, and to which he/she has to find the answer by studying the spatio-temporal dataset. Andrienko & Andrienko (2006) presented two types of tasks. Elementary tasks are simple queries which can be answered at their simplest by a single word; for example, "What is the population density at point P at time T?", where two factors of the data are known and the third one is asked. Synoptic tasks concern bigger wholes about the behaviour of the phenomenon, like analysing the trend of a population during a certain period of time.

Pattern in spatio-temporal, point-type dataset can be either purely spatial, purely temporal, or both of them simultaneously. A good example of spatial patterns is a hotspot, where a subset of events is located closer to each other, forming a dense spot. Temporal patterns can be for example a congested period of events followed by a quieter period, or a trend of an increasing number of

events. Spatio-temporal patterns consist of a rich variety of behavioural phenomena of the phenomenon, for example spreading or an increasing trend in an attribute. When studying patterns of spatio-temporal datasets, it must be noted that the variety of possible patterns depends on the nature of the data. Static objects can form different patterns than moving objects, and appearance and disappearance of the objects form different patterns than a steady number of objects. Moreover, area-type datasets have their own variety of patterns. Their geometry varies from smooth-edged polygons to granular raster images, and the areas can also appear, diappear, merge, and split into new areas.

1.3 Scope

This thesis focuses on the information overload of animated maps. The aim is to find out what factors are causing information overload in animations, and to search for methods which can relieve this load and support the visual analysis of map animations in exploratory use. The focus is on animations where the change in the objects is presented over a static background. The effect of the background map for the interpretation of the map animations is discussed but not systematically tested.

  This thesis focuses on datasets that consist of points, with one exception of area-type data. From the point-type datasets, the emphasis is on static objects appearing on the map rather than moving objects. The visualisation of attribute information is not systematically studied in this thesis. In particular, only the location and the timestamp of the objects is shown and all attribute information is removed from most of the point-type datasets.

  The focus is on the animated maps themselves and all discussion about the usability refers to the interpretability of the maps.The effect of control tools and other user interface functions is not studied in this thesis. In some studies, the users had no chance to use the control tools, and if they had, all feedback and comments related to the control tools were left out of the analysis. This limitation was put in place in order to focus on the intrinsic cognitive load of map animations.

Only visual presentations are covered: although haptic (Griffin 2002) or sonic (Krygier 1994) presentations are studied more and more, they are not discussed in this thesis except the discussion about sonic temporal legends in presenting the effect of temporal transformations. The detailed visualisation considerations of the map animations are not covered exept when they are considered in the cases presented in papers. An extensive consideration of cartographic principles such as colours, classification and filtering methods, or symbols, is therefore lacking.

1.4 Objectives and research questions

Because the objectives of this thesis were twofold, as mentioned previously, the research questions were also formulated in two phases. To gain the knowledge

of the cognitive load caused by map animations and the overload they bring to the user, research questions 1, 2 and 3 were formulated:

RQ1: How do the differences in the temporal extent of the data affect the preferred information content in the animated map?

The information content of a map is always a compromise between the essential information and clarity and readability of their presentation. This compromise depends on the user's task and needs. An animated map, showing either real-time or recorded information, increases the complexity of the map display by adding the temporal aspect into the examination. Therefore, to avoid the information load growing too big, it is plausible that the amount of presented data must be decreased from a spatial or thematic aspect.

RQ2: What factors cause the experienced complexity of an animated map combining two area-type datasets?

Combining two area-type datasets is a well-studied topic in cartography. The most important combination methods for animations, including overlapping, juxtaposing and altering images have been compared in previous studies, and the optimal colour combinations for static overlapping layers have been proposed (Brewer 1994). What is missing is the combination of these two factors: colours of overlapping layers in an animated map.

RQ3: Can the information load of map animation, caused by temporally irregular and congested data, be relieved by temporal transformation?

Recorded datasets representing point-type events can have very different temporal structures. There can be long empty periods between events, or the events can be congested temporally and spatially so that the single events are impossible to perceive. Even if the events do not in fact overlap spatially and temporally, the animation presenting such data can be so congested that change blindness (Simons & Levin 1997) prevent the detection of every event. Coping with this kind of congestion simply by slowing down the animation causes the long, empty periods to grow even longer.

On the basis of these questions, two novel methods: temporal equal density transformation and temporal classification, were presented for visualising and highlighting the potentially important patterns in spatio-temporal data. Therefore, research questions 4 and 5 were:

RQ4: How can the recognition of spatio-temporal patterns of point-type events be supported by visualisation, and what are the benefits and limitations of the tested methods?

Exploratory visual analysis of spatio-temporal data does not contain any clear tasks or questions, but aims at finding something potentially important. Visual analysis software typically has a set of different ways to explore the data; for example, parallel coordinate plots, scatter plot matrices, and linked views of the

different methods. In this thesis, new ways of visualising the map animation, without reducing its data content by filtering or generalisation, were highlighted in order to help the user to find spatio-temporal patterns that would stay hidden with traditional animation.

RQ5: How does the viewing order of temporally classified and unclassified animations effect the analysis?
In visual analysis, the user can either freely select which tools are used and in which order, or the analysis can be driven by some pre-defined process. If the course of the spatial analysis process is pre-defined, the usage order of the tools must be selected carefully to achieve the best possible results. Shneiderman (1996) advised offering the overview first before a more detailed examination. Here, two presentations with the same data content, but with different visual emphases, were studied. The aim was to find out, whether this principle of overview and details works when the differences are on visual presentation alone.

1.5   Structure of the dissertation

This thesis consists of the summary part and four publications. The summary first covers theoretical foundations of the field in question in Chapter 2. Chapter 3 presents the materials and methods used, and Chapter 4 presents the results that are significant for this thesis from all included publications. These results and their contribution to the existing knowledge of the field are discussed in Chapter 5 and Chapter 6 concludes the dissertation. The four publications are appended in the latter part of the thesis.

2. Related Work and Theoretical Foundations

Map animations pass information to their viewers with visual stimulus that change over time. The effectiveness and efficiency of the animations vary greatly and are dependent on the data and the user's task. Animations are nowadays easy to produce with computational methods, but their efficiency is limited by the users' capacity to adopt information. To raise this capacity, usability and visualisation of the animation should be designed to correspond to the user's goals and tasks.

In this section, spatial, temporal, and spatio-temporal variables of the data being presented in the map animations are introduced, followed by static and dynamic visual variables that can be used to present them. After that, the advantages and possibilities, and correspondingly challenges and shortcomings, of map animations are discussed, followed by the cognitive psychology theories behind these pros and cons. The exploratory analysis, its process, techniques, and users are covered, and finally, the usability study methods that are used in this dissertation are introduced.

2.1 Visual variables in maps and map animations

Maps have traditionally presented the phenomena of the real, three-dimensioned world on a smaller scale, and mostly in only two dimensions on paper or screen. Vector geometry objects on a map can be points, lines, or closed polygons i.e. areas. A group of topological relationships, e.g. intersection, overlapping, or touching, can be defined between the objects.

Bertin (1967/83) defined seven visual variables used in maps to present thematic information. These variables (size, shape, lightness, colour, orientation, texture, and location) are applicable for point and line symbols as well as for polygons. When technological advances made it possible to create maps with computers and visualize them on screens, new visual variables were suggested by MacEachren (1995): arrangement, crispness, resolution, and transparency. Slocum et al. (2010) expanded the definition of variables into a third dimension with spacing and perspective height. Brewer (1994) has conducted more detailed research about the use of the components of colour (hue, saturation, and value) in cartographic visualisation. Appropriate colour combinations for different types of data and for bivariate data combinations has been defined by Harrower & Brewer (2003). Wolfe & Horowitz (2004) stated colour, size, motion, and orientation to be undoubted guiders of visual attention. Garlandini &

Fabrikant (2009) tested certain visual variables and found that size was the most, and orientation least, efficient and effective.

Over time, objects (usually called events) can either have a single timestamp or duration, and corresponding to the spatial objects, they can have relationships such as: before, during, or overlapping (Peuquet 1994). Vasiliev (1997) formed five categories about the use of time in cartography: moments, duration, structured time (comparable to Peuquet's temporal relationships), distance, and space as a clock. If the object exists in both, time and space, it can either be static or moving when its location in 2- or 3-dimensional space changes over time. Blok (2000) suggested five concepts characterising the behaviour of spatio-temporal phenomena: moment in time, pace, duration, sequence, and frequency.

The possibility to visualise change over time in an animation raised a need to define dynamic visual variables that form the experienced flow of animation. According to DiBiase et al. (1992), these variables are: rate of change, speed, and duration. MacEachren (1995) added three more: display rate, frequency, and synchronisation. Later Blok (2005) stated that two of these; rate of change and synchronization, are not actually variables, but effects. Andrienko et al. (2003) approached the same topic by defining a set of variables that can be potentially controlled in an animation: speed, direction, extent, moments/intervals, and smoothness.

A similar definition of variables has been given for haptic (Griffin 2002) and sonic (Krygier 1994) maps. The main objective in these has been to find correspondents for visual variables, and later researches of haptic and sonic maps are mainly aimed to benefit users with visual impairment.

2.2 Characteristics of map animations

Animation, when not presenting real-time data, usually compresses the events of some time period into a shorter presentation. Therefore, animation has a temporal scale in a similar way than any map has a spatial scale (Andrienko et al. 2010), and like a spatial scale, this temporal scale affects the suitable degree of generalisation and sample density. While a spatial scale is typically presented as numbers, a temporal scale seems for some reason to be of less interest to users, and the only visible number can be the total length of an animation. A temporal legend can be a time slider that shows the current moment of real-world time and animation time, and simultaneously acts as a control tool (Kraak et al. 1997).

Animations cannot be studied without taking into account the effect of user control. It is common to offer the user at least the possibility to pause an animation and play it again (Harrower & Fabrikant 2008). Jumping into any scene of an animation is nowdays a more common tool than fast-forwarding, although the possibility to adjust the speed of the animation could be very useful. While the control tools help the user to study the phenomenon, they also always occupy part of users' attention and raise the cognitive load (Harrower & Fabrikant

2008). Pausing animation also wastes the best advantage of the animation: smooth change that gives an overview of the phenomenon's behaviour.

2.2.1 Benefits of natural presentation and quick overview

Dynamic visual variables, the flow of time, and the need for user control make an animation a much more complex presentation than a static map (Tversky et al. 2002). Why is it still such a popular and widely used tool? The most important reason is its naturalness; animation uses time to present time, and is therefore as easy to understand as possible. It fulfils the congruence principle presented by Tversky et al. (2002) saying that "the structure and content of the external representation should correspond to the desired structure and content of the internal representation". Tversky et al. did not study geographic animations but a series of user instructions of a device, but there is no reason to assume that this principle would not apply to map animations as well.

Animation is particularly useful in the early phase of the analysis process, offering an overview of the phenomenon (Harrower & Fabrikant 2008). Moellering (1976) studied early computer graphics and stated that animations are particularly suitable for recognising spatio-temporal patterns. Dransch (2000) stated that animations can support the formation of mental models of time-related spatial patterns, and mental models can work as "chunks" of information that take up one place in the working memory, even though they can be formed from several objects.

Studying the superiority between static and animated maps has been a common interest as long as the production of animations has been possible. Koussoulakou & Kraak (1992) found out that there was no difference in the performance's correctness, but patterns were perceived faster from animations than from static maps. Tversky et al. (2002) stated that more important than the animation's movement is its ability to interact with the user or contain simply more information than a static presentation. This disparity of static and animated presentations makes their comparison difficult, and therefore Fabrikant et al. (2008) suggest the concept "inference affordance" to represent both the equivalences of information content and design quality between different displays.

Lobben (2008) showed that animations are better than static presentations for time-related tasks, but also found some evidence that static maps could work better with location-related tasks. Griffin et al. (2006) proved that users answered more quickly and found more patterns and spatio-temporal clusters when they used animated presentations, in comparison to small multiple maps. Lowe (2014) reminded us that when the phenomenon presented is complex and unfamiliar to the viewer, the risk of cognitive overload is the weakness of animations.

2.2.2 Challenges of information overload and visual complexity

According to Lowe (1999), there are several aspects to an animation that can cause overload of the user's working memory: a) the amount of information, b)

the limited viewing time for each frame, c) split attention caused by simultaneous changes, and d) the requirement to remember the previous frames. Map animations are identified as often offering too complex information (Tversky et al. 2002). Rensink (2002a) stated that the attention span can only cope with 4-5 items with a few properties at the same time. While animation (particularly one of those without the user's possibility to interact with the system) is played at a constant speed, the user has to process the old information and simultaneously adopt the new information, and there is a risk that the user can't keep up with the speed (Hegarty 2004). Hegarty et al. (2003) proved that learning from static diagrams can be supported by mentally animating the diagrams. Earlier Hegarty (1992) had proved that mental animations are formed for smaller units, not for the whole process at once, indicating the limited capacity of human thinking. Correspondingly, Bogacz & Trafton (2005) found evidence that meteorology experts even form the mental "animations", or dynamic models about the phenomenon, in their minds based on a series of static images. The fact that they favoured static presentations over the ready-made animations suggest that the information load of each scene was too big to be adopted from animations. This assumption was supported by Maggi et al. (2016), who studied the effect of one visual variable, scene frequency (i.e. frame rate per second) on the speed change recognition of an object in an animated display. They found out that this effect was two-fold: continuous animations are realistic and fulfil the congruence principle, but simultaneously they load the working memory more than semi-static animations of very low scene frequency. Correspondingly, Lowe (2014) reminded us about the danger that animation can give the viewer a false impression of comprehension because they seem so natural and self-explanatory.

Information overload is closely related to visual complexity or visual clutter. Rosenholz et al. (2005) defined visual clutter as a state where performance of some tasks worsen because of the number of objects, or their visualisation or placement. Van den Berg et al. (2009) suggested that this clutter is caused by the information density or its layout. The difference between these definitions is that while Rosenholz et al. (2005) spoke about the number of objects (corresponding to information content), van den Berg et al. (2009) identified the congestion of the objects to be more important. Both of the above definitions also attempt to measure this complexity with computational methods, (Li & Huang 2002, Rosenholtz et al. 2007, Stigmar & Harrie 2011) all focus on static presentations.

Li & Huang (2002) evaluated the earlier measures of quantitative map information and found out that those measures did not consider spatial distribution. Therefore they suggested a new set of measures: metric, topological, and thematic measures. Rosenholtz et al. (2007) reminded that the number of objects does not always increase the complexity: they stated that some patterns are easier to recognize when there are more objects indicating the pattern. They also tested three measures of visual clutter: feature congestion, subband entropy, and edge density, against numerous criteria, and found that among the tested measures the feature congestion was superior. Later, Stigmar & Harrie (2011)

12 evaluated three measures of map legibility: the amount of information, spatial distribution, and object complexity. Based on the user tests and expert evaluation, they concluded that the amount of information and spatial distribution are usable measures for the legibility of a map. The third measure, object complexity, was not found to have any effect on map legibility evaluated by the users, but the authors stated that this might have been a consequence of the generalisation already made in the test maps.

2.3 Cognition and perception

MacEachren and Kraak (2001) listed "to develop cognitive theory to support, and assess usability of, methods for geovisualisation that take advantage of advances in dynamic (animated or highly interactive) displays" as one of the challenges related to cognition and usability. Cognitive psychology was suggested to have potential in visualizing geographical databases (Mennis et al. 2000). Bunch & Lloyd (2006) contributed to this agenda by applying the knowledge of cognitive load into the field of geographic information, and Harrower (2007) searched its links for animated maps. In this subchapter, the cognitive load and principles of human perception and attention are presented, and methods to guide attention and relieve cognitive load are discussed.

2.3.1 Cognitive load

Cognitive load theory (Sweller 1994) is based on the co-operation of the limited working memory and the (almost) unlimited capacity of the long-term memory. The working memory can handle only a few simple chunks of information at the same time: 7+-2 is a number of objects originally given by Miller (1956), but later the number has been suggested to be smaller, not more than 4 (Renskink 2002, Cowan 2010). These few objects must be processed and stored in the long-time memory before new objects can be detected. If information is offered faster than we can process it, a cognitive overload is formed.

In practice, the cognitive load is eased by the automatic processes in the human brain. Gestalt laws (Wolfe 2012) help us to structure our surroundings and form meaningful wholes from the pieces of information we see. Therefore they increase the amount of information that can be handled at the same time, by increasing the content of mental chunks in which the information is processed in the working memory. Gestalt laws, first introduced by a group of German psychologists, are a set of laws or principles, based on which the human brain sorts objects into different groups. These laws can be organised into five categories: proximity, similarity, continuity, closure, and connectedness. They are applicable for static as well as moving objects, while some of them, such as "the law of common faith" particularly concern moving objects.

According to Paas et al. (2003), cognitive load can be divided into three types: intrinsic, extraneous, and germane cognitive loads. The intrinsic cognitive load is caused by the amount of information, the extraneous cognitive load is the unnecessary load caused by, for example, poorly designed visualisation or a user interface containing unimportant information, and the germane cognitive load

forms from the presentation of the task and even the motivation of the user to fulfil the task. Simultaneously with Paas et al. (2003), Mayer & Moreno (2003) introduced different information channels that can be overloaded, and presented nine factors causing cognitive load on these channels as well as possible solutions for them. Five of these factors are applicable for maps:

1) overload in visual channel (solution: part of the information via an audio channel, for example read out loud)

2) overload in all channels (solution: segmentation)

3) overload caused by unnecessary information (solution: remove the unnecessary information or direct the user's attention to important)

4) important information is presented in a way that confuses the user (solution: better presentation)

5) the user must keep in mind the important information (solution: keep the critical information visible).

The last point on this list, keeping the critical information visible, is comparable to the usability heuristic "recognition rather than recall" presented by Nielsen (1994), who stated that drop-down menus are superior to the text input, because in the first case the user doesn't have to keep in mind all the options, but only recognise the right one from the list. Atkinson & Mayer (2004) spoke about the "toxicity of overload" in the context of PowerPoint presentations, and presented five principles to avoid it, from which two are comparable to the factors of Mayer & Moreno: segmenting is identical to the overload in all channels (second point of the list above) and modality to the overload in visual channel (first point).

Paas and Tuovinen (2003, Tuovinen & Paas 2004) carried out research on the measurability of the cognitive load. They suggested that if the mental effort and performance of the user are put on the axes of a diagram, cognitive load can be measured as the distance from the diagonal of that diagram. The third, temporal axis of that diagram could be, for example, reaction time or the relationship between the learning time and the time that was needed to fulfil the task. Vidulich & Tsang (2012) suggested that there are three measurable variables to evaluate the mental workload (a term that can be compared to cognitive load): performance, subjective ratings, and psychophysiological measurements.

Harrower (2007) stated that the methods that have been used in order to relieve the cognitive load of animated maps can be divided into two approaches: increasing the amount of user control, and building more structure to the animations. The suggestion of structuring is closely related to the idea of mental chunks of an animation (Harrower & Fabrikant 2008) and to the solution of the point two (segmentation) in the above list of Mayer & Moreno (2003). Chunking the data into temporal periods supports the working memory in moving objects into the long-term memory. According to Block & Zakay (1996), a human perceives time by chunking it into meaningful periods, which are started by some external stimulus. A period is accumulated until it is experienced to be ended. This model of how a human perceives time is called the attentional-gate model. What is remarkable about this model is that the chunks, time periods, do not have to have equal length but they are determined by external stimuli. From this

point of view, the temporal mental chunks of an animation could as well have various lengths, instead of regular limits, such as seconds, hours or days. This was supported by the findings of Höffler & Schwartz (2011) who proved selfpacing viewing of an animation to result in better learning than system-paced viewing.

2.3.2 Perception

Before any cognitive load can be formed, overloading the user's capacity or not, the actual detection of the phenomenon must be done. Even though the visual system of the human eyes and brain is not covered in this thesis, there are some special issues in perception that must be discussed in this context: attentional blink and repetition blindness that deal with RSVP (rapid serial visual presentation), change blindness, and the split attention effect.

Attentional blink (Shapiro 1994) is a moment when the brain is temporally locking out any new stimulus because the older one is being processed. This should not be mixed up with cognitive overload, which is caused by the information processing between the working memory and the long-term memory, although the effect of the phenomenon is somewhat similar. Attentional blink happens particularly if we are actively searching for some particular piece from a continuous information flow. When that piece is found, recognizing it takes 200-300 ms and during that time a new stimulus with similar relevance is missed. On the contrary, repetition blindness occurs, when two identical stimuli are presented temporally too close to each other. In that case, the latter one can be missed, whether the stimuli are verbal or visual (Chun 1997).

Change blindness (Simons & Levin 1997) refers to a human's inability to detect changes in different presentations. It occurs with static displays as well as with animations, and even with real-life events. Its probability increases when the visualisation is complex (for example a detailed photograph) or when the user's attention is directed to some certain detail. If we look at a static picture and one detail of it is changed, we can detect that change only because it causes an inevitable blink. If a short gap is added between the screens, relatively large parts of it can be changed without us noticing it (Rensink 2002 b). This phenomenon is known as "flicker paradigm". With the gap, focused attention is needed to see change, and even then, an eye saccade is enough to cause change blindness (Simons & Levin 1997). Change blindness has a great effect on the visual analysis of animated maps, and the fact that users tend to overestimate their capability of detecting changes (Fish et al. 2011) worsens the situation. Goldsberry and Battersby (2009) suggested that there are three different levels of change detection that can be applied to dynamic maps: in level 1 the reader only notices that a change happens, in level 2 the reader identifies an increase or decrease in the phenomenon, and in level 3 the reader fully detects and understands the change and its meaning.

The Split attention effect is suggested as being one of the most important issues that need special attention when designing animated maps (Kraak et al. 1997), and Harrower (2007) stated that it involves both, static and animated graphics. Split attention is a risk whenever the user's attention has to be divided

between multiple objects in an interface. Viewing the animation and simultaneously using the time slider, either for manipulating the timestep or simply reading it as a temporal legend, is a typical example of this. Kraak et al. (1997) suggested that embedded legends, like changing the brightness of the background (simulating the alternation of day and night), or using an audio legend, could ease the split attention caused by the legend. Later, Midtbo (2001) presented more embedded legends, for example the map itself moving along the time slider or the clock circle.

Hegarty (2011) suggested that animation always causes more split attention than static visualisation, because a static display acts as an external extension of the working memory and more capacity is left to process the important information.

2.3.3   Attention guiding by cueing and filtering

Motion is a perceptually salient feature that easily grabs attention (Wolfe & Horowitz 2004). Opach et al. (2014) tested how users focus their attention, when there are multiple components in dynamic cartograhic displays. They found that the size and motion of a component are the most important factors guiding our attention, and that this guidance happens intuitively and the user's task or goal does not affect this. Fabrikant & Goldsberry (2005) highlighted that visual attention is both bottom-up and top-down driven, so that the attention can be simultaneously guided by perceptual salience and thematic relevance of the map. To study the relationship between these two, Steelman et al. (2011) presented the NSEEV (Nothing-Salience, Expectancy, Effort, and Value) attention behaviour model that highlights movement as an attention-capturer. This model has later been used to study particularly demanding real-time monitoring tasks (e.g. traffic control (Imbert et al. 2014), air traffic control (Maggi et al. 2016) and airline flight decks (Weibel et al. 2012).

Bertancourt (2005) stated that cueing, such as highlighting or other signalling of the important elements, can prevent cognitive overload of the animation by guiding our attention to important elements on a map. Robinson (2011) suggested a set of new highlighting methods apart from traditional visual variables: leader lines, style reduction, and contouring. Moreover, he presented simple criteria to evaluate the use of different highlighting methods in the geovisualisation environment. De Koning et al. (2007) tested cueing (highlighting a part of the animation by darkening the rest) as an attention guider, and found out that it did not only improve the users' learning about the highlighted part, but also other parts of the animation. This finding was remarkable, because according to De Koning et al. (2007), Lowe (1999) suggested that cueing only small elements can diverge attention away from other relevant elements and therefore increases the extraneous cognitive load. Nevertheless, Amandieu et al. (2011) proved that guiding attention with cueing did reduce extraneous cognitive load in an animation presenting neurobiological phenomenon occurring in synapsis. Cueing also supported mental modelling. Boucheix & Lowe (2010) used colour as a cue to target the attention in complex animations and found out that it produced better results than arrows as cues, or the animation with no cues at all.

The successful use of cues as attention guiders supports the theory of attention being mostly a bottom-up process, and so does the fact that even when attention is guided by some top-down task, it can be captured by a sudden motion or other unexpected visual stimulus (Franconeri et al. 2005). Griffin & Robinson (2015) advised using leaderlines, instead of colour encodings, as attention-guiders between the elements that belong together, since no difference between these two highlighting methods was found in efficiency nor in effectiveness. They suggest that colour therefore stays reserved for attribute data visualisation. Korpi et al. (2014) tested three highlighting methods: style reduction (where only important objects retained their colour while others were reduced to greyscale), style propagation (where the important objects grew bigger and got a red circle around them), and leader lines. They found no significant difference between the style reduction and style propagation methods, but leaderlines were proved to be slower to detect. Although Korpi et al. (2014) tested static displays, the longer response times are an important factor when considering attention-guiding in animated maps.

On the contrary to highlighting, filtering can be used to guide users' attention into desired elements. Filtering can be done based on attribute information, location, or time window but more sophisticated methods are also proposed. Swienty et al. (2008) tested relevance-based filtering, where the relevance of objects was defined for example by spatial or temporal proximity to the user, or by viewshed analysis. Nishida et al. (2003) categorised the strategies of information reduction in emergency management into three groups: cognitive filtering (the user's interest), social filtering (relationships berween the users), and economic filtering (cost-profit-analysis of the information). Ellis & Dix (2007) created a taxonomy for methods aiming to reduce clutter that causes information overload. They divided the existing methods into appearance, spatial distortion, and temporal categories. Appearance includes e.g. filtering and clustering, spatial distortion includes e.g. displacement and space-filling, and the temporal category includes only animation. That is to say, Ellis & Dix (2007) considered animation as a tool to cope with information overload.

Instead of the plain, inflexible addition of single cues to enhance the user's experience, a broader approach to cueing is focus + context techniques, which present a part of the information with a higher level of detail but keeps the rest of the information as a reference. This focus of information can be spatial or thematical (Schumann & Tominski 2011) and the technique has also been used to visually emphasise a subset of a timeline (Krüger et al. 2013).

2.4 Exploratory visual analysis in cartography

Cartography as a science is no longer in isolation, but closely connected to other fields of science, such as human–computer interaction, information visualisation, and visual analytics (Roth 2012). Visual analytics aims at the co-operation of humans and machines by combining effective automated data processing with the understanding of users (Keim et al. 2008). The opportunities that this

co-operation between humans and computers brought to cartography were already identified by Knapp (1995). The fact that the analysis process is userdriven can, according to Keim et al. (2008), actually change the threat of information overload into opportunity. Exploratory analysis is used particularly in the first phase of the analysis, where the questions to be asked are searched (DiBiase 1990). Dykes & Mountain (2003) stated that exploratory analysis is suitable for large datasets with unknown structures.

2.4.1 Explorative use demand interaction

Exploration of unknown dataset imposes high demands on the user interface and map visualisation. The design of effective visualisation is highly dependent on the map theme, map purpose, and map audience (Fabrikant & Goldsberry 2005), and in explorative use, not any of these are necessarily yet known. When the task is ill-defined, the evaluation and, therefore, development of effective software is difficult and the border between the map visualisation and the user interface is narrow (Fuhrmann et al. 2005). Issues concerning the user interface of the animation are excluded here in order to best focus on the maps themselves and their visualisation.

   This limitation is somewhat artificial since the interaction between the user and the system via a user interface and control tools has a remarkable role in the exploratory analysis process. In fact, Andrienko & Andrienko (1999) stated that presentations used in exploratory data analysis should never be static, and Monmonier (1990) suggested a set of tools with relevant information instead of searching for one, optimal map visualisation. Passive viewing of an animation is only suitable for the early observatory stage of exploratory analysis (Harrower & Fabrikant 2008), but getting an overview is an essential part of the analysis (Schneiderman 2006), and the knowledge gained from the analysis is impossible to incorporate into the big picture without getting a thorough overview of the whole data.

2.4.2 Exploratory analysis process and tools

Exploratory analysis can be defined as a process, in its simplest form by the following steps: display the data, identify salient features and interpret salient features (de Mast & Kemper 2009). More typical is an iterative process, with a set of tasks and operations that aim to meet the goal (Andrienko & Andrienko 2005). Koua et al. (2006) categorised these operations as follows: identification of clusters and relationships, comparison of values, relation of attributes of identified object, and analysis of the relevance. They stated that these operations are often facilitated by various functions such as scaling, querying, and filtering the data. They also visualized the iterative process of exploration as a series of steps (Figure 1). This iterative process is a part of bigger analysis process as it communicates with representational spaces, such as maps, by tasks or operations. It also produces patterns with visual data mining techniques, and, correspondingly, uses visual data mining to import knowledge from the patterns back into the exploration process.
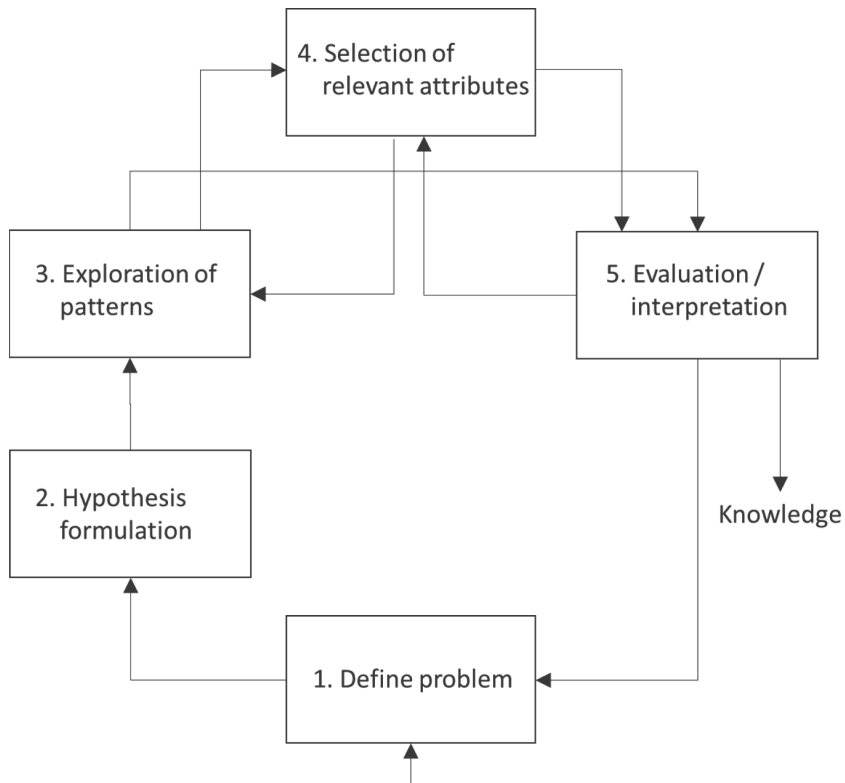
Figure 1. Exploration steps (after Koua et al. 2006).

2.4.3 Tools for exploratory analysis

All operations used to interact with a cartographic presentation can be categorised taxonomically; Roth (2012) reviewed various taxonomies for cartographic interaction primitives and divided them into three approaches that are used in different phases of iterative exploratory analysis: objective-based for forming the intention, operator-based for specifying an action, and operand-based in between the stages of executing an action and perceiving the state of the system.

Andrienko et al. (2003) systematically listed visualisation methods that are suitable for different kind of tasks and data during the exploratory process. Some methods (including map animation) are mentioned as being suitable for all kinds of data, while some others are only suitable for changes in existence, location, or attributes. These three change types are closely related to three aspects, or dimensions, of any data. While change always happens over time, the only definable change in the time itself is existence; whether the object exists in some particular moment of time, or it doesn't.

Aigner et al. (2011) surveyed visualisation of any time-oriented data and presented in total over 100 visualisation methods, from which 17 are suitable for spatial data. These 17 methods are categorised to suit either uni- or multivariable data, linear or cyclic time, instant or interval time primitives, and to be either static or dynamic and 2D- or 3D- presentations. This categorisation differs from

the one used by Andrienko et al. (2003) because it is data-driven and does not take into account the users' tasks, or actual suitability or usability of the methods for those tasks. It only lists all methods feasible for different kinds of data.

2.4.4 Exploratory analysis cases, tasks, and techniques

From the field of exploratory analysis, there are some analysis cases that demand further examination. Combining two dynamic datasets with the same spatial and temporal extent for comparison and relationship seeking is a typical task for visual analysis. The analyst can be interested in finding correlation or causality between these data, or examing their total effect. When there is a temporal lag between the two phenomena that are supposed to have spatial correlation (for example, rainfall and vegetation growth), synchronization of the datasets is suggested to support the analysis (Blok et al. 1999). With synchronisation, the assumed lag can be removed and a more detailed study of the precision of the correlation is possible.

Blok et al. (1999) also studied potential methods to combine two spatio-temporal datasets. Three main methods are identified: juxtaposing images (with common control tools), overlapping transparent images, and alternating the images of two datasets. Gleicher et al. (2011) discussed the use of different information channels for combining visualisations, and stated that these methods use different mechanisms to relay the information about the relationships of the datasets: an overlay uses the visual channel of the user, juxtaposing loads the user's memory, and difference maps (explicit encodings) use the computer's capacity to calculate the information. They also present hybrid methods combining these three categories.

Shipley et al. (2013) discussed animated displays of moving objects and stated that their movement should be studied in cooperation with other objects or events: for example causal relationships between a predator and the prey have an affect on the movement of both of these. They did not give any suggestions about how these kinds of relationships should be visualised, but pointed out that Gestalt laws make the detection of the commonalities in the movement easier. Correspondingly, Dykes & Mountain (2003) discussed how more information can be gained for the analysis with additional data, which can be, in its simplest form, a background map. Moreover, Turkay et al. (2014) stated how many geoinformation phenomena are influenced by geographical features such as coastlines or mountains, or political borders, and that these should be possible to take into account when analysing such phenomena.

2.5 Studying the users and usability of explorative analysis

The effect of user groups, particularly experts and novices, has been a widely studied topic in the usability studies of map animations. The differences between these two groups seems to be a result of two factors: experts' previous knowledge about the domain, and their experience in performing certain kinds of tasks in certain environments. Therefore, the domain experts (e.g. biologists)

and the method experts (GIS professionals) should be studied separately. Compieta et al. (2007) suggested that the best analysis results would be achieved when these two expert types work together in close co-operation. Another problem with defining the experts is that nowdays geovisualisation applications can be used by anyone online, not a certain group of scientists (Slocum et al. 2001). When the users are assumed not to be professionals, tutorial videos or other introductions to the use of the system is essential, and simultaneously challenging (Andrienko et al. 2002).

Despite these difficulties in defining experts and novices, it is clear that these groups behave differently when interpreting maps, which are complex systems of signs and symbols (Montello 2009). Novices tend to choose the elements of the maps based on their perceptual salience rather than thematic relevance (Lowe 1999). Andrienko et al. (2002) suggested that expertise in geovisualisation helps the users to adopt new visualisation ideas and techniques more easily. Harrower et al. (2000) found that additional tools (temporal brushing and focusing) did benefit the expert users, but could even worsen the results of the novices that were confused by the tools. It also seems that when the users can define the amount of information visible in the map, the users with lower spatial ability tend to overload the visualisation with data that is not actually relevant to the task (Smallman & Hegarty 2007). Ooms et al. (2012) studied the differences in response times and eye fixations between expert and novice users in the context of interactive and dynamic maps, and found that the most significant difference between these groups was that experts performed more quickly.

Usability is defined in an ISO standard 9841-11 as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use". Despite its generality, this standard also succeeded in providing guidelines for developing and evaluating the usability of cartographic products and software. It defines the usability of the product for specified users, with specified goals, in specified contexts. Fabrikant and Goldsberry (2005) repeated these guidelines by stating that three pillars of map design (which naturally aims for good usability) are its theme, purpose, and audience. Fabrikant et al. (2010) suggested that these priciples have a more important role than the user's expertise level. Nielsen (1994) measured usability with five attributes: learnability, efficiency, memorability, errors, and satisfaction. This is more of an overall approach and aims at the entire using process of the product, while cartographers like Fabrikant and Goldsberry had more specific targets with maps relaying their information to the users.

When the overall usability of a system and the usability of map presentation are so close to each other, it is natural to use the methods of usability studies to evaluate them (Slocum et al. 2001). Like any software or equipment, a map aims for the effective, efficient, and satisfying relaying of information, and correspondingly, the realisation of these aims can be measurable with the same tools (Slocum et al. 2001). When evaluating existing geovisualisation tools, the emphasis is often on summative evaluation, not formative (Nielsen 1994) although Fuhrmann et al. (2005) recognise this as being problematic. In usability studies, the research methods can be divided into qualitative and quantitative methods.

Quantitative methods include all measurable indicators such as the correctness of the answers, the reaction time, the number of eye fixations, etc. while qualitative methods concentrate on features which can be studied by feedback from the users describing their satisfaction.

The method to evaluate the usability of a map animation should be selected to suit the purpose of the evaluation (Fuhrmann et al. 2005). Combining different evaluation methods in one study enables more thorough analysis (e.g. Hegary 1992, Koua et al. 2006). Quantitative methods can quickly produce great amounts of easily processable data from user tests and online surveys. Eyetracking method have quickly become popular in geovisualisation studies, because it reveals where the user's attention is focused and what are the most salient features in the visualisation. Qualitative methods, on the contrary, are typically applied to smaller groups of users and can include interviews of individuals or gropus, or observation of use. The data produced by qualitative methods needs much more pre-processing, for example verbal protocol analysis (MacEachren et al. 1998, McGuinness &Ross 2003), before it can be analysed.

All methods, quantitative and qualitative, can contain possible sources of errors. The distribution of test users can be biased or the test users can misunderstand the task they are about to perform. Montello (2009) stated that using students as research subjects is problematic because they can lack the real motivation to understand the display being tested.

The most important problem, particularly with interviews, is that the user's intuition about the usability of the system does not necessarily match its real usability (Andre & Wickens 1995, Hegarty 2011). A more geovisualisation-specified problem is that, as stated above, studying the quality of the map visualisation or usability of the system is very task-oriented. In exploratory use there are no specific elementary tasks, but more complex, ill-defined goals, and therefore testing the usability of such systems is difficult (Fuhrmann et al. 2005). Van Wijk (2005) called for a numeric method where the value of visualisation is determined by its effectiveness and efficiency, but did not propose how those should be measured. Another factor affecting the usability evaluation of systems used for exploration is that interaction between users and the system, multiple views, and map manipulation are neccessary (Andrienko & Andrienko 1999). This is a problem when testing a single visualisation method, because the usability of the software and the effectiveness of the visualisation method are easily mixed up.

3. Materials and Methods

Different research methods, many of the familiar ones from the field of usability studies, were used in this thesis. Four independent studies were included, and these studies utilised different types of datasets as materials for the user tests.

3.1 Materials

Geometry type, temporal extent, attribute information and other factors of the datatsets used in different studies are presented in Table 1.

The study in Paper I concerned the user profiling of maritime situational pictures. Three different user groups of the same situational picture software participated in this study. A maritime situational picture is a real-time visualisation of the vessel traffic in the Gulf of Finland used by authorities. It allows the user to select visible elements on the background map, like depth, navigable routes, and sea marks, according to the user's tasks and preferences. All vessels with an AIS (Automatic Identification System) are shown on a map as point symbols, and additional information such as the name of the vessel and its movement vector can be displayed as well. In the system, it is possible to visualise the predicted movement of the vessels based on their current direction and speed. The visualisation of the background map has separate day- and night-modes. Figure 2 shows a screenshot from the situational picture.

Table 1. A summary about the characteristics of the datasets used in studies.

Data \ Paper	I	II	III	IV
Geometry	point	area	point	point
Movement	yes	yes	no	no
Continuity	yes	yes	no	no
Temporal extent	real-time	1 day	3.5 / 100 days	365 days
Attribute information	yes	yes	no	no
Classification of attribute information	no	yes	-	-

Paper II presents a study of visualising two area-type datasets in a single animation. Two different combinations from four datasets were used in this study.

The first visualisation combined the predicted rainfall (a subset from the global dispersion model SILAM) and radar observations of realised rainfall from the Finnish Meteorological Institute (FMI) from the same period of time. The second animation, shown in Figure 3, combined two subsets from SILAM: relative air humidity and birch pollen concentration. Both combinations were formed from three separate 24-hour period datasets from May 2015.

Twitter messages, also known as tweets, were the dataset used in the test animations in Paper III. Coordinates and time stamps of the tweets were collected from Port-au-Prince, Haiti, after the earthquake in 2010, but no attribute information was recorded. From the massive amount of tweets, two smaller datasets of equal size were selected. The first dataset contained the very first days after the earthquake, and its temporal structure was irregular because of the electricity problems in Haiti causing 12-hour gaps with no tweets in the nighttime. The second dataset was formed by picking every 10th tweet from a period of four months after the earthquake. In that dataset, the density of the events was biggest on the first days and weeks after the earthquake, and decreased smoothly after that.

The last dataset used as material in this study was voluntary-based bird observations. All observations about grey and true geese from a one-year period inside Finland were included. This dataset was provided by the open global biodiversity database (gbif.org). No attribute information about the exact species of the birds was included in the study, only the locations and time stamps of the observations.

Figure 2. A screenshot from a maritime situational picture system. Vessels are visualised as triangles with the name tag on the upper-right corner. Squares are temporary obstacles.
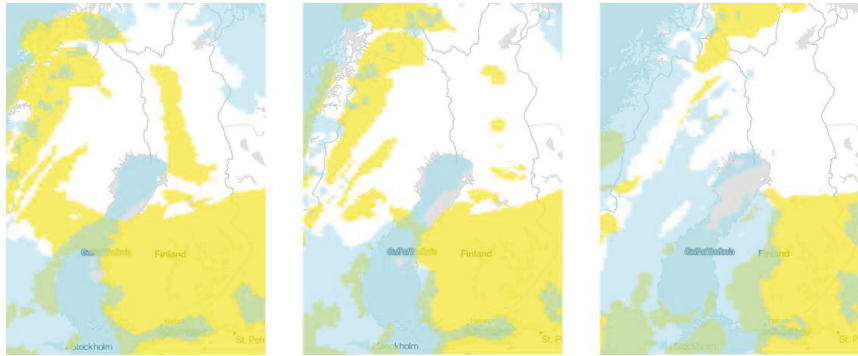
Figure 3. Three screenshots showing the movement of high relative humidity (blue layer) and birch pollen concentration (yellow layer) during the day. The combination of these layers forms green areas.

3.2   Methods

The studies of this thesis draw their research methods mostly from the field of usability studies. Two different user tests and interviews were carried out, observation of use was conducted in two studies, and questionnaires were delivered to the users. Table 2 shows an overview of research methods used to answer each research question.

Table 2. Research methods that each paper used to answer their allocated research question(s).

Paper	Research questions	User test	Observation of use	Interview	Questionnaire
I:User Profiling for Maritime Situational Picture	1		X		X
II: Experiencing Bivariate Colour Scales on Animated maps	2			X	
III: Assisting the Detection of Spatio-Temporal patterns in Temporally Transformed Map Animation	3, 4	X	X	X	
IV: Comparison of temporally classified and unclassified map animations	4, 5	X			X

RQ 1 was answered by first observing the users of the maritime situational picture while they were performing their tasks. The users presented three different user groups from two different organisations. To complete the findings of the observation, a questionnaire about the data elements that the users kept visible in the system while using it was delivered to the users in the later phase of the study. In total, 26 users answered the questionnaire.

   The answers from the questionnaire were processed by forming bar diagrams from each group, showing the number of times when the subjects had marked

each map element to be used "always or most of the time", "sometimes", "never", or whether the subject didn't recognise the map element in question. Then these diagrams were analysed by first comparing the answers inside one, biggest group to ensure the reliability of the results. Then, answers from two groups inside the same organisation (the Navy) were compared against each other, and finally the answers from these two groups were combined and compared against the other organisation.

This comparison was visualised in a data cube, where the amount of information was presented in three axes: the spatial, temporal and thematic aspects. The differencies between the user groups in the data cube answered RQ 1.

RQ 2 was answered by an experimental study combining two datasets with group interviews. Group interviews were selected for the research methods, because the study was a part of a project studying the potential use of openly accessible meteorological data, and specific use tasks were not defined. Two example visualisations with similar background maps and other details of the animations were created, both visualising two datasets related to each other by transparent layers. To examine the clarity and comprehensabilty of these animated bivariate visualisations, three group interviews were carried out. Each group contained 4-5 participants, and the groups had different backgrounds and levels of expertise. These group interviews were audio recorded and transliterated. From this material, those aspects concerning the complexity of the animation that arose from all three groups, and the aspects that were mentioned in two groups without the third group presenting an opposite opinion, were selected for the analysis. The analysis revealed the most important factors that increase the experienced complexity of map animations with two datasets.

The study presented in Paper III answered research questions 3 and 4 and presented a novel visualisation method that equalised the timesteps between two consequent events in an animation. This equal density transformation was conducted for two datasets, and from both datasets, two animations were produced; the original one and the transformed one. The success of the transformation was studied with user tests, and the users' throughts about the transformation and its usefulness were studied through interviews. In the user test, the number of times that the users viewed each animation, was calculated by observing the use. A screenshot from the test arrangement is shown in Figure 4. Also, the statistics about how many times each animation was viewed as a whole or interrupted (paused, fast-forwarded or jumped) were compiled. The users were also interviewed while they were viewing the animations and performing the tasks, and the rest of the interview questions were covered afterwards. The experienced information load of the animations and its difference between the original and transformed animations were evaluated from these results. The benefits and limitations of this method (RQ4) were studied by analysing the results from the user test. In the test, subjects could give their answers to the questions either orally, when they were written down by the interviewer, or by typing them into the text box of the test page. From these answers the subjects' ability to recognise spatio-temporal patterns from the datasets were studied. The answers that the subjects gave orally to the interview were also written down by

the interviewer. From these answers, the potential application areas and the most important weaknesses of the tested method were documented.
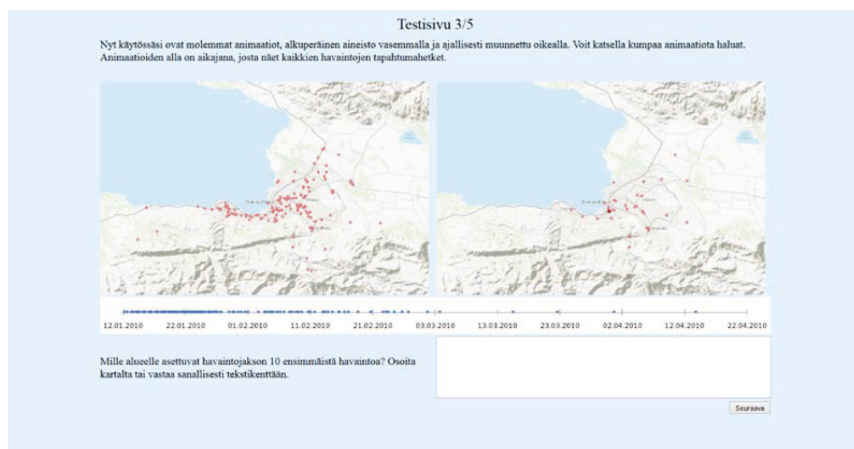
Figure 4. A screenshot from the user test of paper 3. An animation of the original dataset is shown on the left, and an animation of the transformed dataset is on the right. Under the animations is a timeline presenting the original dataset. At the bottom is the test question and a text box for answering.

Another visualisation method, temporal classification, was presented and tested in Paper IV. To test the benefits and limitations of visualising the periods of increasing, decreasing and steady number of events in the data with different colours, a user test was carried out with two animations; temporally classified and another, more traditional one that presented the flow of time with smoothly changing colours of the events. The test was implemented over the Internet in order to reach the domain experts of the visualised phenomenon. 45 participants were divided into two groups of which one saw temporally classified animation first and the traditional version of the same data after that, and the other group in the reverse order. Figure 5 shows screenshots from temporally classified animationand traditional animation from the same moments in time. To answer RQ 4, the users were asked to describe the phenomenon they saw on the animation in their own words, and a protocol analysis and word count were conducted for this material. Also the users' preferences between the two animations and free feedback were requested from the users. The results from the protocol analysis and word count were analysed by comparing the results from the two groups and from the two animations. This analysis revealed the usefulness of the temporal classification method and the importance of the viewing order of the animations, which was researched in RQ5.
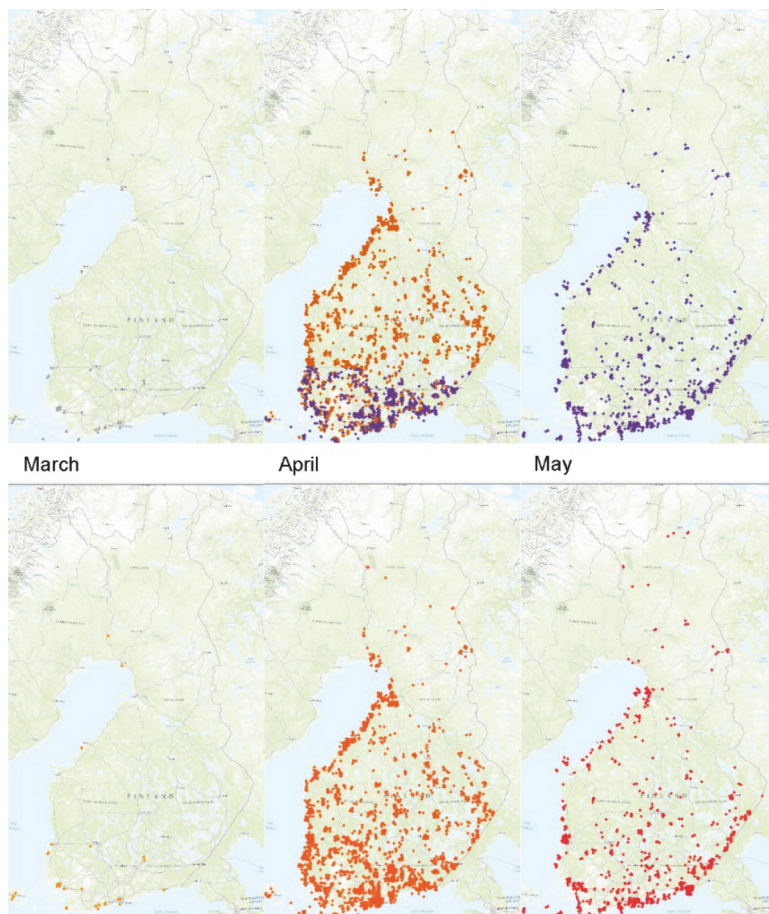
Figure 5. Screenshots from a temporally classified animation (above) and the traditional animation as a comparison (below). In April, the number of events per day is already decreasing in southern Finland, while it is still increasing in the northern parts of Finland. This change is not visible in the lower screenshot.

4. Results

The results answering research questions 1, 2, and 3, concerning the information load of a map animation, are presented in Chapter 4.1. Results answering research questions 4 and 5 about the design and validation of the novel visualisation methods are presented in Chapter 4.2.

4.1 Controlling the information load of a map animation

The information load of a map animation was studied in Papers I, II, and III. The effect that temporal extent and experienced complexity have to the information load, and the possible methods to relieve that load, are presented below.

4.1.1 The effect of temporal extent

In the study presented in Paper I, the users had almost unlimited possibilities to modify the information content that was visible in the maritime situational picture. Observation of use revealed some differences in the number and nature of visible data elements.

The quantitative analysis of the answers for the questionnaires revealed a high level of conformity within the group, which suggests that the research method was reliable. Between user groups 2 and 3 within the same organisation, the task analysis conducted in the same study revealed differences in the user groups' tasks, and the results from the questionnaire followed these differences. The biggest difference between these groups from the same organisation was the number of different map elements needed. The operators of the maritime control centre, which act as lower-level operators and therefore handle smaller spatial areas and shorter time periods, chose "always or most of the time" for more map elements than the supervisors of the situational centre. The elements that the higher-level supervisors had marked as the ones they used most were all also on the operators' lists. This suggests that the difference was particularly in the total amount of information content instead of choosing different elements.

A comparison between the two organisations showed that there were some elements that were among the "top ten" for one group, but among the ten least used ones for the other. In addition to the differences in the type of the elements, there were also differences in the number of data elements. VTS officers (group 1) usually had more information visible in their situational picture; this was naturally caused by their main task of securing maritime safety, which requires more information about e.g. the sea routes and depth information.

The most important result is the differences in the information content be-tween groups 2 (Maritime control centre) and 3 (situational centre), visualised in Figure 6.These groups were both from the navy, and therefore internal stand-ards defined the visualisation of certain elements. Supervisors from the situa-tional centre (group 3) had larger operational areas and longer time periods in their responsibility. The difference in the spatial extent of the responsible areas of these groups was much smaller than in the temporal extent; while operators of maritime control centre (group 2) acted almost real-time, the supervisors in group 3 typically had a time period of several weeks in their reports. Therefore it can be assumed that differences in the information load between these groups was mostly caused by the temporal extent. However, based on these results the effect of differences in these groups' tasks can not be ruled out. In the interviews, supervisors also stated that they need the situational picture system very rarely in their work, and that most of their reporting was done with other systems.
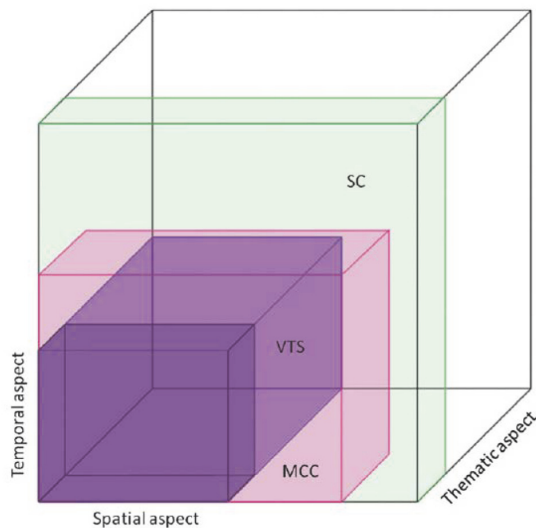
Figure 6. The data cube presenting the differences in spatial, temporal and thematic aspects of the information content between the user groups of the maritime situational picture.

Another significant result is the behaviour of the users in group 1, discovered while observing the use of the system. Groups 1 and 2 both acted mostly realtime, but they had operational areas of different sizes. While VTS operators in Group 1 could not reduce the number of visible elements because of safety reasons, and neither could they reduce the temporal extent from real-time, they had adopted a way to reduce the information load from the spatial aspect by opening multiple separate windows with close-ups of certain areas. This method returned the total information load of each view to an acceptable level. Watching several windows simultaneously was not a problem because VTS operators al-ways work in pairs. Group 2, on the other hand, had simpler tasks, and therefore they could reduce the number of visible data elements suitable for their opera-tional area.

From these results, a conclusion can be drawn that the temporal extent of the data in an animated situational picture had a remarkable influence on how the users in this study limited the amount of data visualised on the map. This limitation can be done either by filtering the data by its types or by cropping the spatial extent under examination at once.

4.1.2 Experienced complexity of animated map

The user's task played a key role in the results of Paper II which studied the experienced complexity of the visualisation of two area-type phenomena in a single map animation. Visualising two (or even more) datasets with transparent layers of different colours is a common method with static maps. The assumption for RQ 2 was that the movement of the phenomena is the greatest factor causing increased information load when animating two datasets.

To study the factors that cause the experienced complexity of an animated combination of two datasets, two different data combinations from different meteorological datasets were visualised. The first combination presented the predictions and observations of the same data (rainfall), visualizing the areas and/or time periods when the observations do not meet the prediction. The second combination presented two separate phenomena: relative air humidity and the birch pollen concentration of the air, to study their supposed correlation.

These two animations were presented to the users from different backgrounds. In the group interviews that were carried out after presenting the animations, the most important discussions concerned the target users and the tasks of the visualisations. The interviewees were also asked to give their opinions about the selected colours and classification of the data combinations.

The interviewees in all groups agreed that the level of task definition (finding anomalies and studying correlations) was not sufficient. They called for more detailed information about the potential users and the message that the visualisation was supposed to deliver. In particular, the users from the meteorology professionals group stated that the optimal visualisation is strongly dependent on the level of expertise of the users, and that differences in this expertise would have an affect on colours, classification, and even the transparency levels of the data layers. These results indicate, that the experienced complexity of animated maps is not dependent only on the geometry and movement of the phenomena. The selected visualisation of the data can increase or decrease the experienced compelxity, depending on the user's task. However, the usefulness of this kind of analysis tool was clear since the interviewees from the meteorology professionals group said that combining a modelled prediction and observations of the same phenomenon was not possible with their current tools, and that it would be useful in their work.

When viewing the air humidity + pollen visualisation (see Figure 2), interviewees stated that the green combination of blue and yellow layers did not look like a combination, but rather its own, separate layer. This might have been caused by the unpredictable, illogical movement of the datasets and their combination. The blue humidity layer did not affect the pollen concentrations as expected. With another example, combining a rain prediction (visualised with yellowish

green) and rain radar images (visualised with purple), the interviewees were
most confused by the various colour shades of combinations. While the layer
colours were selected so that their combination forms a neutral grey it created
a three-step classification of both layers, a situation where the areas of greenish
or purplish grey were mixed with neutral grey. This effect was strengthened by
the dappled structure of the radar images, which can be seen in Figure 7, and,
moreover, the movement of these images.

To sum up the answer to RQ 2, the geometrical complexity in this case caused
by the dappled raster images, and unpredictable behaviour of the phenomena
were the greatest factors confusing the users. However, the exploratory use of
the map must be taken into account at a more detailed level than was done in
this study, and without it, no reliable evaluation of experienced complexity can
be achieved.
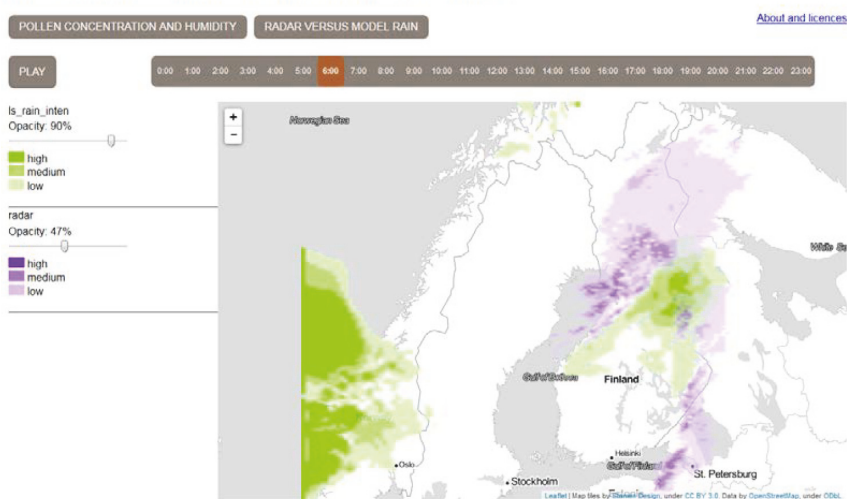
Figure 7. A screenshot from the test visualisation shows that a rain prediction form the disper-
sion model (green) forms continuous areas, while the rain radar image (purple) is more dap-
pled.

4.1.3   Relieving the information load of map animations

A way to cope with information load of map animations, caused by irregularity
in the temporal structure of the data, was examined in Paper III. A point-type
dataset was processed with a novel method called temporal equal density trans-
formation, and animations of both original and temporally equalised datasets,
were created. The users' interpretation of the phenomenon, based on the ani-
mations they saw, and their opinions about the animations were analysed.

The users told that the original animation and equalised animation revealed
different patterns from the data, and made the same data look different. They
also stated that the equalised animation was useful, or even essential, for some
tasks conducted in the test. Moreover, a mention was made that the original

animation was so fast that it was not possible to notice all the events and it had inefficient empty periods.

The quantitative results from the study showed that when the users had a chance to choose between the animations, temporally equalised animation gained more viewings and it was more often viewed as a whole, without interrupting the flow of time by pausing or jumping, than the original animation. However, these differences were too small to be statistically significant with a sample of nine test users. These results suggest that temporal equal density transformation of point-type events seems to reduce the experienced information load by offering a continuous, predictable change and by giving each event equal significance. When the users have less need to interrupt the equalised animation by pausing or jumping, the viewing is smoother and more overall, which is one of the strengths of the animated displays.

The key results answering research questions 1, 2, and 3 can be concluded as follows: When the temporal extent, of which the users have to be aware at the time, get longer, the information load on the users increases and makes the users to limit the amount of information in some other dimensions. They either filter the number of data types visible on the map, or, if this is not possible, crop the spatial extent in a single view. Geometrical complexity, meaning the scattered images with holes and unconnected pixels, and the unpredictable, illogical movement of the areas had the greatest influence on the experienced complexity of the animation with area-type data. However, in both cases, the task definition had a remarkable role, and the influence of these tasks should be studied further.

In the third study, the tasks were defined more clearly, and the excessive information load was clearly caused by the temporal congestion of the data. Removing this congestion by temporal equal density transformation helped the users to examine every event of the data and helped them to gain different impressions of the same dataset.

4.2 Novel visualisation methods and the viewing order of the animations

In addition to the transformation discussed above, another visualisation technique for map animations were presented in Paper IV. The benefits and limitations of these two methods were studied with user tests. The results answering research questions 4 and 5 are presented below.

4.2.1 Benefits and limitations of the novel visualisation methods

The users of temporal equal density transformation had a slight tendency to favour the equalised animation over the original one, especially when conducting simple elementary tasks, but this difference was too small to be statistically significant. The most important proof of the usefulness of method was a spontaneous detection of a pattern, which could not be done with the original animation, but which was mentioned by seven users out of nine after viewing the equalised animation. The users reported that they noticed a spot on a map in which several

consecutive events took place. This pattern was not noticed in the original animation because the consecutive events followed each other too rapidly.

However, the equalised animation did not have only advantages. The majority of the verbal feedback about the equalised animation was positive, saying that the equalised animation was "easier to watch" and "nicer". However, two out of nine test users mentioned that the equalised animation was "exhausting" or "tiring", but they also agreed that the equalised animation was useful in some cases. In the interviews, the users called for a clearer temporal legend showing the effect of the transformation. This could have helped the users to interpret the data correctly; now there were several cases where the users' interpretation of the phenomenon varied between the original and equalised animation, despite the fact that the data was actually the same. There were also few clear misinterpretations of the data based on the equalised animation, because the user was not aware of the true flow of time during the equalised animation. This drawback could possibly be relieved with a proper temporal legend.

The need of both original and transformed animation, and also the importance of their viewing order, was found to be even stronger in the study presented in Paper IV. In this study, the verbal protocol analysis was conducted to analyse the descriptions that the users wrote based on the animations they saw. In addition to the word count of the verbal protocol analysis, the user test showed some interesting results from the descriptions themselves. They suggest that when viewing the traditional animation, the users leant more on their previous knowledge about the phenomenon, and used the animation only as a confirmation. However, when viewing the temporally classified animation, several users described the phenomenon as behaving against their expectations. In particular, after the classified animation, nine out of 22 test users said that they saw the first marks of the autumn migration in the northwest shore. This is against the common conception that the main route of the autumn migration should move via the eastern border of Finland, a mention that was made in several descriptions based on the traditional animation. This finding suggests that the temporal classification method can support the visual analysis of the phenomena more than traditionally coloured animations, even though the actual behaviour of the phenomenon was the same with both animations. Therefore, as was found in RQ 4, this kind of visualisation method can support the recognition of a spatio-temporal pattern that would stay hidden with more traditional visualisations.

4.2.2 Viewing order of the animations

The limitation of temporal classification method is that the best benefit can be reached if a temporally classified animation is viewed together with a more traditional visualisation, and that the order of these animations do matter. The word count analysis showed that the length of the descriptions was about the same in both groups after the first animation. However, the group who saw a temporally classified animation first, wrote shorter descriptions after the second, traditional animation. This suggests that they did not get any new infor-

mation from the second animation. The other group instead, who saw the traditional animation first, wrote even longer descriptions after the second, temporally classified animation.

In verbal protocol analysis, nine different protocols were identified from the descriptions. The analysis revealed statistically significant differences both between the animations and between two user groups in Table 3. The classified animation produced more mentions about relative time and, particularly in Group 2, about the number of events. Between the user groups, the most significant differences were in the mentions about the location of the events and in absolute time. The results suggest that while temporally classified animation can be said to be an effective tool for visual analysis, it is not irrelevant how and when it is viewed. The best benefits are gained when the traditional animation is viewed first and the classified animation after that. This is in line with Schneidermann's (1996) well-known recommendation for analysts: "Overview first, zoom and filter, details on demand". These results were also supported by the feedback the users gave: classified animation was preferred and considered to be insightful and easy to understand more often than the traditional animation, but these tendencies were stronger among Group 2.

Table 3. The numbers show, how many times each protocol was mentioned by both user groups after both animations.

Category	Existence			Movement			Time			Word count
Protocol	appearance / disappearance	number	location	direction	route	duration / speed	relative	absolute	animation	
Group 1 Traditional	8	28	31	4	1	4	9	42	0	291
Group 1 Classified	10	37	33	7	2	2	31	32	4	431
Group 2 Traditional	8	34	64	3	5	3	11	45	0	426
Group 2 Classified	7	73	80	8	2	7	34	59	3	612
Traditional animation total	16	62	95	7	6	7	20	87	0	717
Classified animation total	17	110	113	15	4	9	65	91	7	1043
Group 1 total	18	65	64	11	3	6	40	74	4	722
Group 2 total	15	107	144	11	7	10	45	104	3	1038

To sum up the results answering research questions 4 and 5, both tested methods can be said to be valuable and effective for recognising spatio-temporal patterns. Their limitations are similar; the flow of time and important landmarks for certain moments of time should be clearly visible for the user. They both also benefit from the original version of the dataset presented together or before the modified version. In particular, in Paper IV the traditional animation viewed first raised the advantage gained from the temporally classified one.

5. Discussion

The results from this thesis have been divided into theoretical and practical implications. In this chapter, they are discussed separately, followed by the evaluation of reliability, validity, and the generalisability of the results. Finally, suggestions for future research topics are made.

5.1 Theoretical implications

The aim of this thesis was to contribute to the theory of exploratory visual analysis of geographic data by studying the factors that cause and increase the cognitive load caused by animated maps. Moreover, new methods were presented in order to relieve this load and support the exploratory visual analysis process of the user, particularly the recognition of spatio-temporal patterns. The findings and their contribution to the existing knowledge about the exploratory analysis are discussed.

5.1.1 Temporal extent of the data

When screening real-time data, temporal change in a map presentation is bound to the changes in the real world. Therefore, if the events on a map happen too rapidly, the user has no chance to slow down the animation and the only option to limit the information stream is to reduce the information content from other data dimensions, i.e. spatial or thematic. In the study presented in Paper I, the users did this either by reducing the number of different data elements, or, if this was not possible because of safety reasons, divided their area of inspection into smaller pieces. This compares to the economical filtering proposed by Nishida et al. (2003), where the cost-profit analysis is conducted between the visual load of the element in the map and the information gained from it. Traditional methods for reducing the information load by generalising or filtering were not possible because of the safety demands and real-timeness of the system, and therefore only cutting the information content was possible. These methods were uniform inside the user groups and different between them, which suggests that the decision was task-driven rather than personal. The differences between the user groups suggest that the user's task and motivation has an effect on the germane cognitive load, as stated by Paas et al. (2003).

5.1.2 Experienced complexity

Map animations combining two area-type datasets might sound like a simpler-case than it actually is. Combination visualisations of two datasets have been studied in a static environment and recommendations for suitable colour combinations for bivariate data have been made (Brewer 1994). Similarly, suggestions about how to combine two datasets into an animation have been made (Blok et al. 1999, Gleicher et al. 2011). What has been lacking is the research about the use of bivariate colour visualisation in combining two datasets in an animation. Given the fact that the tested visualisations in Paper II were based on existing knowledge about visualisation and colour theories, the success was not as good as expected. Change over time in map presentations, together with geometrically complex, discontinuous data and the classification of the data visualised by different lightness of hues made the combination visualisations too complex for the users to understand properly. Based on the feedback collected from the interviewees, is is assumed that slowing down the animation would not have affected the results, although it would have decreased the information load.

The existing literature concerning the complexity of maps focuses on the measures of the number, variety, and spatial distribution of objects in a static map (Li & Huang 2002, Stigmar & Harrie 2011). Based on the results of Paper II, the concept of the experienced complexity of animated maps seems to be a much more complicated issue. In the example featured in this study, confusion among the users was caused by the illogical movement of the areas that did not follow the viewers' expectations about the behaviour of the phenomena. These kinds of situations caused by the characteristics of the data are hard to avoid without a priori knowledge of the data we are about to analyse, which is typical in the beginning of the exploratory analysis process. Also, a finding was made that visualising the data in three different classes made the perception of the actual hue difficult to perceive. This was caused by the transparency of the la ers, which together with a greyscale background map produced too many combinations. A better performance would require either spatial generalisation of geometrically grainy data, eliminating the classification and presenting the areas with only one shade, or both. The suitability of these methods depends on the task and the purpose of the map as well as the geometrical and behavioural characteristics of the data.

Moreover, the perception of the colours was distracted by the neighbouring colours and the afterimage effect. This could have been partly avoided by using a white background map with only black contour lines or other localising elements. That is an easy and simple way to reduce the information on a map, and equally suitable for static and animated maps.

5.1.3 Information load of temporally uneven dataset

Animating a dataset that consists of congested and uneventful periods is meaningful only when we want to get a rough overview of the data and its temporal

distribution. More detailed analysis of the events from such animation is impossible, if the events overlap spatially and/or their temporal distance is too small for the viewer to cope with because of the change blindness or time required by the eye saccades. However, if we simply slow down the animation so that every event is detectable, we simultaneously lengthen the distance of sparse events, an influence that is unwanted. This thesis offers a solution to this problem by presenting a temporal transformation that is loaning from the spatial, equal density transformation. Equalising the temporal distance between the two consequent events in an animation solves both problems; temporal congestion and inefficient empty periods. The results indicate that this kind of a transformation is useful for certain kinds of analysis tasks. Its strength lies in the equal importance it gives to every event, and in the continuous, predictable change that is easy to follow due to steady information load. It is known that map animation with excessive information load can easily overcome the cognitive capacity of the viewer (Harrower & Fabrikant 2008) and leave the viewer unaware or confused. With animation, the user has only a short time to examine the details (Harrower 2003). Based on the results presented in this thesis, the temporal equalisation transformation can be stated to relieve the information overload and therefore adds additional value to the visual analysis toolkit. However, the results remind us that ensuring the viewer's awareness about the real flow of time is important. This could be done with a well designed temporal legend with two timelines, one for the animation time and the other for the real-world time. This kind of legend could simultaneously show the strength of the transformation at different moments of time. Another option would be to include builtin pauses for meaningful time periods, which would offer a natural way to show the flow of time and, simultaneously, form temporal chunks to handle the time (Harrower & Fabrikant 2008).

5.1.4 Novel visualisation methods supporting the recognition of spatio-temporal patterns

The benefit of the temporal equal density transformation was two-fold. In addition to relieving information overload as discussed above, it supported the recognition of certain spatio-temporal patterns. The results of the user test show that this method is capable of revealing a pattern (several consequent events in the same location) that was not seen in an original animation. The observation of this pattern from the original animation was impossible because of repetition blindness (Chen 1997). In other words, the temporal equal density transformation emphasised the order of the events and made the detection of every single event possible. It also prevents the users to be aware of the actual flow of time. This suggests that both animations, the original and temporally equalised, should always be available for the user, and that the first overview of the data should be presented with non-transformed animation to avoid misinterpretations.

The second visualisation method was temporal classification, which visualises the events with different colours according to the temporal behaviour of the phenomenon at the time. The area of examination was divided into zones, and

the daily number of events in each zone was either increasing, decreasing or steady. This method was inspired by the requirement of "segmenting" (Harrower 2007) and "temporal chunking" (Harrower & Fabrikant 2008) which should help the user to cope with the continuous information load of an animation. According to the user tests, temporal classification helped the test users to detect the starting point of a spreading phenomenon, and it also made the users produce longer and more detailed analysis of the phenomenon. Thus, the results support previous studies of cueing (De Koning et al. 2007, Boucheix & Lowe 2010). Additional element (here colour), can work as a visual cue and thus better the performance despite the fact that it actually increases the information content of the animation.

5.1.5 Viewing order of the animations

Simultaneously with the benefits and limitations of the temporal classification method, the effect of the viewing order of the animations was studied. The hypothesis was that as Schneiderman (1996) suggested, an overview should be presented to the users first, before more detailed examination. In the study presented in Paper IV, however, the actual information content was practically the same in both animations. The events, their number, location and timestamps, were identical, as well as temporal and spatial extent of the animations. The only difference was that in the temporally classified animation, the events got different colours according to the temporal behaviour of the phenomenon, while in the comparison animation the colour of the events changed smoothly through the year. Therefore, the results showing the superiority of the group who saw the traditional animation first and the classified after that, were sligthly suprising. They indicate clearly that, in addition to the importance of offering various ways to examine the data, a pre-defined process can be useful as a part of iterative exploratory analysis. During the iteration there can be several pre-defined processes like the one described above, and the user can move freely between them.

5.2 Practical implications

The users' tendency to limit the information load of the animated visualisation was a clear finding in the study presented in Paper I. In that study, a suggestion was made that the maritime situational picture system could benefit from pre-configurations designed separately for different user groups based on their profiling. This is an approach that could be useful for a wider audience. If the same system is used by several user groups with different tasks and different emphasis of the data, the performance and learning of the users could be supported by configurations that take into account those characteristics. A similar approach was presented e.g. by Boulos et al. (2011) in a precision information environment for emergency management professionals.

Also the study about the experienced complexity of combining two datasets considers the topic of the user's needs and tasks. The results from the group

interviews indicate strongly that the task should be considered at a more detailed level than was the case in this sudy. Task definitions "finding anomalies" and "studying correlation" were not clear enough, or they were not explained to the users explicitly enough. This fact should be taken into account when designing openly accessible web pages; when the users and their needs are not known, inadequately designed data visualisations can lead to misunderstandings and confusion.

More detailed task definition could be used when defining the appropriate classification, and presenting areas with only one hue results in a much less complicated view. The results indicate that the geometries of the radar images should be generalised, or too detailed variation of the shades of the compound colours will occur. Moreover, a finding was made that greyscale background maps can cause confusion for the users when interpreting colours. Thus, the assumption is that greyscale should be avoided when possible and strive for using black contour lines with white as the background map.

As stated earlier, temporal equal density transformation of a map could be useful when the temporal structure is very uneven or when the task concerns detecting single events from the data. The limitation of the proposed method is that it is mostly suitable for relatively small datasets. Suggestions for several application areas, in which this kind of presentation relieving the information load could be useful, were recorded, for example traffic planning, crowd movement analysis, environmental analysis, and oil destruction activities. However, these applications would not be possible without more detailed research about the temporal legend communicating the flow of time.

The test results indicated that temporal classification with colours would be a powerful tool supporting the analysis of spatio-temporal behaviour of pointtype events. If the analyst could freely test different spatial zone divisions and temporal resolutions, change the cumulativeness of the events and number of classes, and form every time new animations of the data, very different emphases of the data could be presented. The increase and decrease periods in the phenomenon's intensity could possibly be presented with point size instead of colour, or those periods could be indicated with smooth change, not by classes at all. Although, in that case the idea of temporal segmenting, one of the advantages of the method, would be lost.

5.3   Reliability and validity

The reliability and generalisation of the results presented in this thesis mostly depend on two factors: the research methods and confirmation of the collected results, and the characteristics and visualisation methods of the datasets used in the tests.

The profiling of the user groups, based on the results presented in Paper I, was implemented in the Finnish Navy after the results were published. This suggests that the results were found credible and useful among the users. However, a systematic testing of the resulting profiles was left undone, and therefore the

reliability of these results can not be evaluated. Also, the theory about the maximum information content visualised at the time, and the role of temporal extent, were not verified.

When studying the complexity of the visualisations of two area-type datasets in the same animation, the method used was collecting opinions from the participants of the group interviews. This kind of intuitive feedback does not necessarily correspond to the actual efficiency of the system (Hegarty 2011, Andre & Wickens 1995). However, the goal in this study was to find out, what kind of experience the users got from these visualisations, and therefore the selected method can be considered suitable. The result that an animated presentation of two phenomena should be simpler (either by geometry or by classification) than a static presentation, is logical and understandable, and can be suggested to be generalisable also for other kinds of data outside meteorology.

The visualisation of static point-type events is always a compromise. When the events don't have any duration which could be scaled to the animation, a selection must be made as to whether the points stay visible forever after once having appeared or disappear after some artificially defined time. Cumulativity can quickly cause a congested presentation where all events are no longer detectable, and the appearance of the new ones is missed. On the other hand, if every point disappears before the next one appears, the resulting visualisation can be gleaming and make the detection of movement patterns difficult. In this thesis, the test animations of temporal equal density transformation were implemented by fading the colour of the old events so that the newest one was always detectable with a brighter colour. In the other test, temporally classified animation and its comparison animation utilised a partial cumulation of the events. One can argue that in both of these tests, the results could have been different if the cumulation was implemented with different settings. However, with these conditions, the results from both of these studies were promising, and support the idea of these methods to be at least worthy of further research concerning their applicability in practice.

5.4   Needs for future research

Below, possible future research topics and directions are listed, first for each included study separately, and then for the whole thesis.

The maximum information load of the map animation is a topic that has been often discussed recently, but the actual studies aiming to measure this information load are few. In this thesis, some progress has been made by proving that this kind of limit for users' capacity clearly exists, because the users tended to reduce information by different methods, even though the information visible in the situational picture did not overlap spatially or temporally. The first step for a deeper understanding of this topic could be to thoroughly study whether this reduction was conducted because the temporal extent of the data grew too long, or because of the differences in the tasks. Lots of useful knowledge about human perception and cognition has been adopted from the field of psychology

for example by Harrower (2007), and these kind of interdisciplinary studies should be continued.

The complexity of map animations experienced is another fruitful topic for future research, not only for those combining two datasets, but as a whole. The consistency or scatteredness of the geometry and the continuity of the movement have great effects on the end result of the visualisation. In cases where spatial generalisation of the data is not possible, other methods to reduce this complexity should be looked for. It is possible that the suitability of the methods is dependent on the user's task, as the results from the interviews suggest.

The novel visualisation methods presented, temporal equal density transformation and temporal classification, were both found to be promising methods still needing a considerable amount of further study. Computational methods to create them, as well as their effect on the datasets with different spatial or temporal structures, are subjects that have to be solved before they are applicable for use. The effects of cumulativeness or visibility time windows of the events is an important factor when animating any event-type data. More specifically, equalisation transformation could benefit from an animated temporal legend, and the potential of different spatial zoning methods in temporal classification should be tested.

To conclude the future research agenda based on this thesis, the information load of the animated map, and the factors that increase it, is an important topic to study. Without the knowledge of these factors, the methods relieving that load are impossible to design. Different methods are suitable for different tasks and different data, and therefore searching for new methods can be assumed to be a neverending story.

6. Conclusions

Map animations are intuitive and easily adoptable presentations of spatial datasets with change over time. They can effectively relay large amounts of information, and they execute the congruence principle of similarity between the data being presented and the method of presentation. However, when these animations are created with high computational capacity, the last bottleneck may not be taken into account: the cognitive capacity of a human being. Continuous change, movement, and the appearance of new objects in various locations simultaneously is cognitively very demanding for the user. There is a concrete risk that viewing such animations does not increase the user's knowledge about the phenomenon but leaves the user uncertain or misled.

In this thesis, the information overload of animated maps was recognised to be dependent primarily on the temporal extent in those cases where the users did not have the possibility to control the animation time. The users modified the view suitable for their tasks, and the differences in the views between the user groups were mostly affected by time: when the examination time period grew longer, the users limited the amount of information from the thematic aspect, and if this was not possible, by cropping the spatial dimension into smaller views. The important effect of temporal dimension was also found in the other study: the experienced complexity of map animations was significantly higher than expected. Since the visualisations of those maps were designed based on previous knowledge about bivariate visualisation of static maps, it can be argued that it was the temporal dimension that increased the complexity so much.

These findings are assumed to originate from the cognitive overload that map animations caused to the users' working memory. To avoid excessive information load, cartographers have traditionally used generalisation, classification, filtering, and other methods that reduce the information content of a map. This procedure can be problematic in the exploratory visual analysis process, where the user's task is ill-defined and information reduction can lead to the disappearance of important features of the data. In this thesis, two novel visualisation methods are introduced that simultaneously preserve the high information content and ease the information load of map animations. They are designed for computational-based pre-processing of the data, aiming for better recognition of spatio-temporal patterns by the user. This kind of a procedure is promoting exploratory visual analysis of unknown datasets.

The exploratory analysis process is iterative and undefined. A rich variety of visualisation tools support the effective exploration process, and the user should have the freedom to choose the course of the analysis process. The findings of

this thesis prove, however, that gently guiding the user from the overview phase into a deeper examination of the phenomenon is useful. The full benefit of the developed visualisation methods is reached when the user first familiarises with the data using a more generic method.

Designing new, insightful methods to support effective visual analysis of spatio-temporal data needs more knowledge of what actually causes cognitive load for the user. In the quest for seeking this knowledge, this dissertation suggests that the total amount of the data in spatial, temporal, and thematic aspects, the experienced complexity of animated maps, and temporal chunking by visual cues are possible paths to follow.

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