# THE TIME WAVE IN TIME SPACE

A VISUAL EXPLORATION ENVIRONMENT FOR
SPATIO-TEMPORAL DATA

Xia Li

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DISSERTATION

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Xia Li

born in Shaanxi Province, China
on May 28, 1977

This thesis is approved by

| | |
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| **Prof. Dr. M.J. Kraak** | promotor |
| **Prof. Z. Ma** | assistant promoter |

*For my parents*

*Qingjun Li and Ruixian Wang*

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# Chapter 1 Introduction

Many of the most important challenges our society is facing today, such as global climate changes, economic crises and infectious diseases depend on the analysis of spatio-temporal data to detect and quantify changes and trends to support solving the problems. Current data collection techniques offer a wide variety of thematic data in many different spatial and temporal resolutions. The challenge is how to search, explore, manage, and apply these continuous streams of data to support problem-solving and decision-making. The application of graphic representations in a dynamic and interactive geovisualization environment is part of finding solutions.

Geovisualization integrates approaches from disciplines like cartography with those from scientific visualization, image analysis, information visualization, exploratory data analysis and GIScience (Dykes et al., 2005). The graphic representations, mostly maps, are used to stimulate visual thinking about geospatial patterns, relationships, and trends. This is strengthened by looking at the data in a number of alternative ways. Playing with the data using these multiple representations without constraints (or traditions) will trigger the user's thinking and help lead to new knowledge. This will significantly improve our understanding of spatial data, but not necessarily of temporal data. This is partly because most methods and techniques approach geo-problems from either a locational or attribute perspective.

In GIScience, the time perspective is given renewed attention, because new Earth observation techniques provide data with temporal resolutions varying from weeks, days, hours or even minutes. It offers the user the possibility to explore the data at more detailed temporal levels, which is very useful since most problems require an understanding of the changes and their impact. Within this framework, a visual approach to this research is discussed from a temporal perspective.

## *1.1 Background and problem description*

Never before has data been collected, stored, processed and presented at such high volumes as it is today. Geographic data is also being collected continuously, at high volumes and by all kinds of sensors. At the same time, extensive archives of old maps and photos are being digitized. In addition, data that has traditionally been non-spatial is now being geo-referenced because almost all information can be spatially located in some way. Altogether, these trends are resulting in a huge number of highly complex datasets. This is creating its own problems because searching, exploring and analyzing such data becomes even more difficult due to its temporal complexity. For example, within hours a certain place on Earth will be scanned several times by different sensors in different satellites, yielding a large amount of remote sensing data.

When a user wants to analyze the changes in a certain area on the Earth using spatio-temporal data, they will investigate what spatial and temporal resolution and distribution are needed for achieving their goal. For example, to study the geological change of a mountain, the temporal resolution of the data could be hundreds of years; if there is a question about urbanization, the temporal resolution needed is a decade, while if they are dealing with crop growth, the temporal resolution of data could be months. Even if the same phenomena are studied, different temporal resolutions might be required due to the geographic or thematic characteristics. For instance, sand dunes along the coast might behave differently on a particular time scale to dunes in the desert.

Thus, due to the temporal complexity of geo-datasets and the different application requirements, it is necessary to find a relevant geo-dataset from the temporal perspective. To analyze and explore these data to support problem-solving, it is also important to focus on the time perspective. Almost all geographic phenomena are dynamic and require specific studies. The key issues in detecting changes are the temporal characteristics, temporal relationships, and temporal regularities or patterns of phenomena or objects. This leads to the following statement of the problem:

Does the use of visualization methods during the exploration of spatio-temporal data contribute to a better understanding of the data if their temporal characteristics are also considered?

## *1.2 Research aim, research questions and methods*

***Research objective***

Based on the above statement of the problem, the main aim of this research was to develop a time-based interactive environment (namely time-space) which applies visualization principles to exploring the temporal characteristics of geo-data, with the aim of helping the user to access and understand the data. 'Space' in time-space does not refer to geo-space, but is the temporal equivalent to location space and attribute space. Time-space is the concept of a temporal visualization environment which is based on time study and visualization theories. This concept emphasizes the exploration of spatio-temporal data from a temporal perspective. In order to build a suitable time space, six research questions need to be addressed:

1. What is the nature of time and specifically the time in GIScience?
2. What are the existing visualization options to explore time?
3. Based on visualization theory, how can time-space be structured?
4. What graphic representation can be used and how can this be realized (i.e. develop a prototype)?
5. How can time space be used to explore spatio-temporal data (perform a case study)?
6. Does the concept of time-space and the new graphic representation work (usability testing)?

These questions led to the structure of the research project, as shown in Figure 1-1. Starting with a literature review on time and visualization theories, existing temporal visualization methods are discussed. Following that, the requirements for temporal representation and temporal interactive functions are summarized and a time theory for designing time-space formulated. Then a new graphic representation, called a time wave and based on the timeline and time wheel, is introduced as a major part of time-space. The interactive environment which combines time-space with location space and attribute space closely is also discussed. Based on a conceptual design of time-space, a prototype of the time wave was developed to test the validity of the concepts. The operational ability of the prototype was evaluated by users working on a case study. This thesis ends with the conclusions from our study and suggestions for further research.

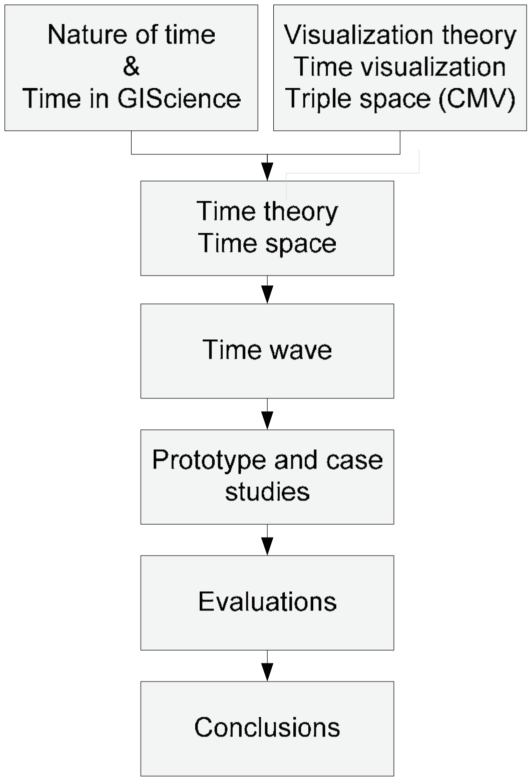



**Figure 1-1. Research structure.**

## 1.3 Key factors

The key factors in this research were:

**Time space and triple space** Time space is a concept that aims to explore spatio-temporal data from a time perspective, without neglecting the location and attribute perspectives. To structure time-space, the graphic representations should allow the user to represent the temporal data according to different time views (e.g. linear or cyclic), and they should allow for interaction of the user. Triple space structures the data, the visualizations and user interaction in an efficient way. It supports the user's thinking process to find answers to their questions. Triple space is implemented according to the Coordinated Multiple View (CMV) principle and, as such, it supports exploration as an interactive and iterative process. The exploratory activities are guided by the visual information-seeking mantra of Shneiderman (1996). Depending on the task, the user can switch from one space to another, and into any of the information-seeking modes (overview, zoom/filter, or details on demand). It is claimed that the optimal solution space from a temporal perspective is time-space interactively linked with location and attribute space. This allows the user to tackle the problem flexibly from many different perspectives.

**Temporal visualization concept** This concept was developed to take a closer look at the integration of several visualization theories accepted in GIScience and information visualization and extended with a specific temporal component. From a time perspective, several views on time, such as linear/cyclic, relative/absolute are used to discuss temporal data. A temporal task space (TTS) is structured for the temporal user task, by combining change typology, reading level and temporal query. Temporal data and temporal user tasks work together in selecting a temporal visualization. This concept was also studied from a user application perspective. It can therefore bridge the gap between visualization theories and user applications. The TTS is potentially a kind of knowledge system which will allow users to select the most suitable temporal visualization.

**Time wave** The time wave is introduced here as the main element of time-space. It allows access to, and exploration of, large amounts of spatio-temporal data. The time wave not only combines linear and cyclic time, but also temporal data representations and interaction. It further allows a limited representation of attribute and location data. It can be used as a temporal reference, a temporal data representation system, and a temporal interaction tool. It can be used to answer important time-related questions and, in combination with graphic representations in location and attribute space, most of the complex questions related to temporal geodata; as such it supports the user in the task at hand in discovering spatio-temporal patterns and relations. The time wave is a good example of how an alternative view on the data may reveal patterns not always evident in traditional graphic representations.

**Using the time wave in time-space**: a prototype of the time wave was implemented to assess the above ideas. The time wave in time-space was coordinated with maps in location space and with graphs in attribute space. In this environment, temporal representation and temporal interactive tools can be closely combined to support the exploratory process. Extensive usability evaluations have been performed to judge the validity of the new concepts and graphic representation.

## *1.4 Thesis outline*

Working from the earlier statement of the problem, the main aim and the research questions, this thesis is accordingly structured in eight chapters. Parts of this work have already been published in the papers shown in Table 1.

**Chapter 1 Introduction**: introduces the research background, defines the problem and the research aim, lists the main research questions listed, and outlines the structure of the thesis.

**Chapter 2 Time**: discusses time from different perspectives, including philosophy, cognition and GIScience, to understand what temporal elements are required in time-space.

**Chapter 3 Visualization**: reviews several visualization theories based on a common approach for problem-solving with visualization. Discusses the state-of-the-art in time visualization in order to understand existing temporal visualization and to discover how it should be improved. Explores spatio-temporal data from a time perspective supported by the Coordinated Multiple View (CMV) technique, and introduces the triple space concept as a visualization environment.

**Chapter 4 Time-space**: describes the design of a temporal visualization concept for time-space by combining time studies with visualization theories.

**Chapter 5 Time wave**: introduces the time wave, a new graphic representation, as a basic element of time-space based on the discussions above and a combination of the timeline and time wheel.

**Chapter 6 Prototype**: describes the design and implementation of a prototype to verify the new concepts introduced. Reports on a case study to explain the working environment.

**Chapter 7 Evaluation**: evaluates the effectiveness, efficiency and satisfaction of the new approach and assesses the usability of the time wave and its visual environment.

**Chapter 8 Conclusions**: summarizes the results of this research, discusses the conclusions and makes suggestions for future work.

| | Paper | Related Chapters |
|---|---|---|
| **1** | Li, X. and M.-J. Kraak (2008). The time wave. a new method of visual exploration of geo-data in time–space. The Cartographic Journal **45**(3): 1-9. | 3, 4, 5 |
| **2** | Li, X., M.-J. Kraak, et al. (2007). Towards a visual representations to express uncertainty in temporal geodata. Proceedings of the 23rd International Cartographic Conference (ICC), Moscow. | 3, 4 |
| **3** | Li, X. and M.-J. Kraak (2009). Temporal links in the coordinated multiple view environments applied in location space, attribute space and time-space. ICC 2009: Proceedings of the 24th International Cartographic Conference (ICC) Santiago, Chile: The world's geo-spatial solutions. | 3, 4 |
| **4** | Li, X. and M.-J. Kraak (2010). A temporal visualization concept: a new theoretical analytical approach for the visualization of multivariable spatio-temporal data. Proceedings of Geoinformatics 2010, IEEE. (accepted for publication) | 2, 3, 4 |
| **5** | Li, X. and M.-J. Kraak (2010). Explore multivariable spatio-temporal data with the time wave: case study on meteorological data. Proceedings of ISPRS. (accepted for publication) | 6 |
| **6** | Li, X., A. Coltekin, et al. (2010). Visual exploration of eye movement data using the Space-Time-Cube. Sixth International GIScience 2010, Zurich, Switzerland, LNCS, Springer. (accepted for publication) | 7 |

**Table 1-1. The thesis chapters and how they relate to published/accepted papers.**

# Chapter 2 Time

## 2.1 Introduction

Time has been being a major subject of study in philosophy, art, poetry and science. People try to understand the essence of time and search for answers to questions such as: Does the past still exist? Where is the past? Can we travel to the past? Does the future already exist and is it waiting to meet us? In the field of science, time is discussed in the domains of physics, geometry and perception, among others.

Providing an overview of different views of time without judgment and defining the scope of this research in the context of time is the aim of this chapter. The scope is delineated firstly through a definition of time and an overview of time research in the different disciplines, such as philosophy, cognition and perception. This provides a general view of time in man's mind. The role which time plays in GIScience will also be discussed. Finally, a commonly accepted view on time, based on previous work in GIScience, will be summarized. This view will be the starting point for a discussion of temporal data, temporal user tasks, and temporal visualization, which are the core to this research.

## 2.2 Nature of time

**What is time?**

Time has been studied by scientists and philosophers for more than 2,500 years. The question 'what is time' has been asked over and over again and still confuses people today.

In Webster's Twentieth Century Dictionary, second edition (Webster, 2003), time is defined as:

1. the system of those sequential relations that any event has to any other, as past, present, or future; indefinite and continuous duration regarded as that in which events succeed one another.
2. the period between two events or duration or during which something exists, happens, or acts: measured or measurable interval.
3. a period of history, characterized by a given social structure, set of customs, etc.; as, medieval time.
4. a precise instant, second, minute, hour, day, week, month, or year, determined by a clock or calendar; as the time of the accident.
5. Indefinite, unlimited duration in which things are considered as happening in the past, present, or future; every moment there has ever been or ever will be.

Webster's gives 29 definitions, and in the New Oxford Dictionary of English there are even 128 entries listed, with the main ones being:

1. the indefinite continued progress of existence and events in the past, present, and future, regarded as a whole;
2. a point of time as measured in hours and minutes past midnight or noon;
3. an instance of something happening or being done;

5. time as allotted, available, or used;
6. an instance of something happening or being done; an occasion.

Furthermore, depending on the discipline, there are widely divergent views about the meanings of the various definitions.

These definitions of time show the persistent efforts of man in studying time. Time is a strange notion still. It is everywhere and is always running. Everyone feels it, but nobody can touch it. Everyone must manage his or her own time, but nobody can stop it. Hence it is difficult to provide an uncontroversial definition of time. St. Augustine, who was a famous philosopher and theologian, said: "*If nobody asks me, I know what time is, but if I am asked then I am at a loss what to say*" (Augustine, 398). St. Augustine's (c. 354–430 AD) eloquent prose about the mystery of time, which is perhaps the most quoted, is given **towards the beginning of this chapter**.

Time may be motion.

– Aristotle, 322 BC (philosopher)

Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time …

– Isaac Newton, 1687 (mathematician and physicist)

Temporal dimensions can be altered (or "warped") by high-speed motion.

– Albert Einstein, 1921 (physicist)

Time is as such nothing. It is a concept.

– Walter Isard, 1970 (economist)

Time is not a substance or object but rather a special system of relations among instantaneous events. Time is a linear continuum of instants and is a distinguished one-dimensional sub-space of space-time.

– Adolf Grünbaum 1973 (philosopher of science)

Time is a fascinating "thing". It has no synonym; it is the ultimate in basic-level objects.

– Eleanor Rosch, 1978 (cognitive scientist)

In the theory of relativity, the concept of time begins with the Big Bang the same way as parallels of latitude begin at the North Pole. You cannot go further north than the North Pole.

**–** Kari Enqvist, 1997 (cosmologist)

As shown above, it is impossible to define time clearly, but since time is the major topic in this research, at least a working definition of time is needed. The first definition of time in the New Oxford Dictionary of English will be used in this research: time is the indefinite continued progress of existence and events in the past, present, and future, regarded as a whole. Time is regarded as one of the few fundamental quantities.

Understanding how people perceive time and how they study time in different disciplines is more important than a crisp definition of time, because the aim of this research is to design an understandable and usable temporal exploration environment. A brief review of time research in philosophy, cognition and perception, and physics follows.

**Time in philosophy**

In philosophy, one distinguishes the observed world and the existing world. The observed world is related to epistemology, empiricism, idealism, mentalism, immaterialism, spiritualism, subjectivity, measurement, etc. The existing world is related to ontology, naturalism, materialism, physical entity, and existence (Ma, 2003). The observed world is a subset of the existing world. Time has both observed (measured) and existing (duration) characteristics. People use different units (year, month, day, etc.) and tools (clock, calendar) to measure time (observed view). However, time would not stop even if all the measurements should stop (existing view). In this study, the scope is limited to observed time.

In the Eastern world, the earliest text about time appears in the *Vedas* around 2000 BC. It recorded that ancient Hindu cosmology upheld the idea that the universe goes through repeated cycles of creation, destruction and rebirth, with each cycle lasting 4,320,000 years. A similar concept of time is found in Buddhism as well, with the *samsara,* the endless cycle of birth, death and rebirth. This view of circular time is typical of the thoughts on time accepted by most early Asian people. A similar situation, in which religion influences the concept of time supported by philosophy, is found in the Western world. Christianity believes time was created by God, resulting in time being conceived as directional, advancing and non-repetitive (Helman, 2005). These are the rudiments of two important views on time as conceived by modern people: linear and cyclic time.

The Greek philosophers also contributed considerably in shaping today's view on time. Parmenides (early 5th century BC) and Heraclitus (c. 535–475 BC), who are regarded as pre-Socratic Greek philosophers, wrote essays on the nature of time. Parmenides thought change was impossible, being subjective and relative, and that existence is timeless, uniform and unchanging. This line of thought defines his view on time: time does not exist independently; it exists in the world of appearances (Reichenbach, 1999). Heraclitus emphasized the 'Becoming' (objectivity and absolute). Heraclitus said "*time is an orderly motion, with measures and limits and periods. Of these the sun is overseer and guardian, defining and arbitrating and revealing and illuminating the change and* *the seasons which bring all things.*"

Democritus (c. 460–370 BC) was convinced of the objectivity of time. He thought time was objective, timeless and untreatable. Plato (c. 428–348 BC), who was influenced by Parmenides and Heraclitus, strongly disagreed with Democritus' thinking. He distinguished time in reality and in human understanding. He combined being and becoming as: "*the world of Becoming is an instantiation or manifestation of the more primary world of Being."* Time, in other words, is an essential part of the process of manifestation (McFarlane, 1998). With his words in *Timaeus: "time is a moving image of eternity,"* he negates the objectivity of time. Plato's views dominated the golden age of Greek thinking, around 400 BC and his thoughts were later extended in Newton's system (Peuquet, 2002).

Aristotle (c. 384–322 BC), who was a student of Plato, provided a systematic study on the fundamental properties of time, establishing the first complete theory. He also insisted on the objectivity of time and defined time as "*the counting of movement with respect to the before and after."* Time does not exist independently of the events that occur in time. His theory of time had an important influence on the development of ancient and modern physics and on philosophy.

The other discussion on time from a philosophic perspective comes from Plotinus (c. 204–270 AD) who followed Plato's view on time and criticized Aristotle's conception of time. St. Augustine's (c. 354–430 AD) eloquent prose about the mystery of time, which is perhaps the most quoted, is given at the beginning of this chapter. This discussion of time in philosophy provides a basic view of human ideas on time, which have resulted in several views that are widely accepted, such as its linear and cyclic nature, objective and subjective time, and relative and absolute of time. These will all be incorporated into this research.

**Time in cognition and perception**

Time, as experienced by humans, is the topic of this section, which focuses on time cognition (the process of thinking about time) and time perception (the understanding of time). Although the notion of time is not associated with a specific sensory system, the work of psychologists and neuroscientists indicates that our brains do have a system governing the perception of time (Marphetia, 2001). Research on time is important in the field of cognitive science, where one studies neural mechanisms that account for the human experience of time's flow (Damasio, 2006; Marphetia, 2001), and for man's ability to place events in a proper temporal order (Jones, 2004; Wearden, 2007).

People can visit or re-visit a place, touch an object, and feel temperature. For time this is different, when people say 'now', that 'now' has passed and never comes back. It seems that change is the key to knowing about the existence of time, (Vasiliev, 1997). Trying to understand change is one of the driving forces for studying time.

When a person is asked what time it is, most answers will be based on a calendar or clock. Calendars and clocks are not only the tools which are used to ‘control’ time, but are also typical symbols for representing time (Figure 2-1). Both the calendar and clock are representations of cyclic time. Linear time is often represented by a timeline, such as the control bar in multimedia players. These solutions are familiar representations for time supported by spatialization.


**Figure 2-1. The typical symbols that represent time: clock (left) and calendar (right).**

In a study about consciousness in the human brain, it became apparent that time could be thought of as a region in the mind in which the past, present and future has a particular spatial location (Jaynes, 1976). There are many results from research supporting the general idea that space is often used cognitively to convey meaning (Lakoff, 1980; Scaife, 1996; Zarks, 1999). Memory, reasoning, and cognitive processing in general can be facilitated by visio-spatial representations (Larkin, 1987; Scaife, 1996; Stenning, 1995; Tversky, 1995). All the representations in the visualization domain are based on spatialization of abstraction. In this point of view, spatial information is represented in a most direct way, comparable with attribute and time. More recent studies address the question of how such an abstract concept as time is represented by the cognitive system. Van Sommers (1984) asked test participants to draw a visual representation of time; most of them drew a horizontal timeline from left to right. Antonion et al. (2008) did a series of experiments based on this study and concluded that temporal information is cognitively represented through left-to-right spatial coordinates, as had already been shown for other ordered sequences (e.g. numbers).

**Time in physics**

The perception of time can be considered as private time. Physical time is public time, the time that clocks are designed to measure and disseminate (Dowden, 2009). Until the 20th century, most people followed Galileo and Newton and thought time was the same for everyone, everywhere. Our modern conception of time is based on Einstein’s theory of relativity, in which rates of time run differently depending on relative motion. These are the two most influential theories on time in the history of science.

In 1687, Newton proposed the concept of absolute time in his publication *'Philosophiae Naturalis Principia Mathematica'*. He said '*Absolute, true, and mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year*.' Linear time, first proposed by Newton as the formulation for the treatment of time on the basis of mathematical physics, became a general concept.

In 1905, Albert Einstein doubted the classic theory about the notion of absolute time and could only formulate a definition of synchronization for clocks that marked a linear flow in his *'Special Relativity'*: '*The time lapse between two events is not invariant from one observer to another, but is dependent on the relative speeds of the observers' reference frames.*' In his theory, space and time merged into space-time, where we live on a world line rather than a timeline, and thus, four-dimensional space-time form a container for our world.

Space and time are inseparable. Space is still time, while time is space in motion. Peuquet (2003) wrote: '*The two taken together constitute the totality of the ordered relationships characterizing objects and their displacements.'* Newton though time and space formed a container for events, which was as real as the objects it contained. In contrast, Leibniz (1646-1716) insisted that time and space were a conceptual apparatus describing the interrelations between events. Prior to Albert Einstein's relativistic physics, space and time had been treated as distinct dimensions, but Einstein linked time and space into space-time. An extensive discussion on the nature of time and space can be found in the literature discussing the relativity and the quantum theories (Hawking, 2001; Hoover, 2003; Morriston, 1999; Myrvold, 2003; Butterfield 2003).

The above research on time has gradually improved our understanding of time, but still leads to different views about time, such as existing/observed time, absolute/relative time, continuous/discrete time, linear/cyclic time, etc. Peuquet (1994) designed a diagram showing the varying views of reality including time and space. These different views are shown in Figure 2-2, which is based on her ideas. Because only observed time is being considered in this research, views on existing/observed time have not been included in this diagram. Absolute and relative views, continuous and discrete views, and linear and cyclic views of time are complementary and interdependent, and they are basic views on time for this research.

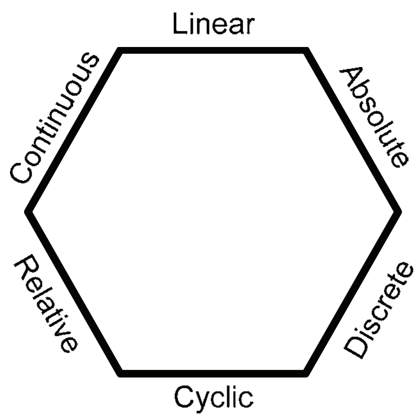



**Figure 2-2. Different views on time that are complementary and interdependent (based on Peuquet's work).**

## *2.3 Time in GIScience*

From the late 1960s, time has been analyzed in geography (Isard, 1970; Daly, 1972; Norton 1984). These works describe the role that different types of time play in different geographies (Vasiliev, 1997). Another prominent geographer was Torsten Hägerstrand (1970), who introduced the concept of time-geography (or time-space geography); he stressed the importance of the temporal factor in spatial human activities. Hägerstrand said: *"We need to understand better what it means for a location to have not only space coordinates but also time coordinates."* In other words, he saw time as a measurement of human activity and tried to answer questions like 'what did people do and how long did it take?'. Typical map representations of this approach are isochrone maps, the space-time-cube, and time cartograms, but also certain flow maps – of which Charles Joseph Minard's diagram of Napoleon's 1812 campaign into Russia is a good example (Figure 2-3). It is well described in Tufte (1983). This map not only shows the time spent on the route, but also the situation of some attributes that varied over time, such as the temperature (weather) and size of the army. His work is regarded as the first to provide detailed temporal information.

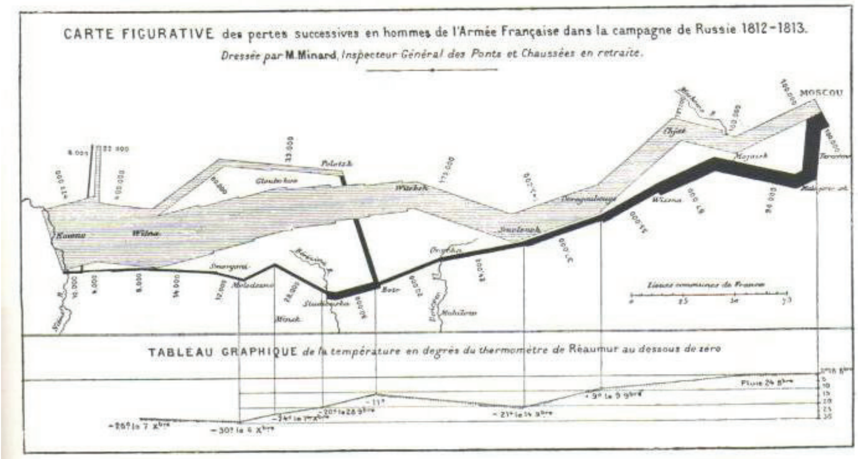



**Figure 2-3. Napoleon's 1812 campaign into Russia.**

Recently, the study of time in GIScience has been stimulated by the need to analyze how spatial patterns change over time, in order to obtain a better understanding of processes. This has coincided with the evolution of modern technologies, such as the computer and internet, and with the abundance of data collected via remote sensing techniques, for instance. Adding the time dimension in applications is now possible and one can detect changes, find anomalies over time, forecast trends, and support decisions. Animations are another example used to represent temporal data in an efficient way.

The emphasis on time in GIScience has a natural fit with emerging perspectives that view time as a scarce commodity in the information economy and accelerating modern lifestyle (Gleick, 1999; Goldhaber, 1997). Furthermore, with the development of satellite surveying technology, researchers in GIScience began to use multi-temporal data instead of time series data in their research topics (Xavier, 2006; Ning, 2006). This gives researchers the ability to examine variations in many processes on Earth, not only over months and years, but also over days, or even hours.

Examples of time-related research in GIScience are both theoretical studies (Yattaw, 1999; Raper, 2005; Butterfield, 2003; Langran, 1992; Frank, 1994) and application studies (Liu, 2006; Morris, 2000;). With the aim of this research in mind, the following sections will discuss two aspects of time in GIScience. First, the modeling of time and different classifications will be discussed, because these models are necessary to determine how temporal information can be represented, and the temporal and spatio-temporal reasoning methods (Frank, 1994). Second, based on these models and classifications of time, temporal visualization methods will be discussed.

**Modeling of time**

In GIScience, the notion that space and time are considered inseparable leads to specific space-time models. Modeling time is therefore closely linked to models that structure space (Frank, 1994). Raper (2000) argued that a four-dimensional space-time approach offered the most complete and versatile framework for the construction of geo-phenomena. Time can be considered as the fourth dimension, whereas the spatial dimensions are usually considered as 2D (for planimetric) and 2.5D or 3D (for the complete three-dimensional representation of spatial objects) (Morris, 2000).

For time issues in spatial databases, ‘world’ time and ‘database’ time are distinguished. Langran (1992) provided a general review of time in GISs (Geographic Information Systems) from time modeling in databases to implementation. She classified three types of temporal relational databases:

- Relation-level versioning: temporality creates and stores a new snapshot of a table when it’s attributes change, e.g. (database time, feature, exist?, X, Y, world time);
- Tuple-level versioning: temporality permits better temporal resolution than the relation-based approach, e.g. (feature, X, time from, time to);
- Attribute-level versioning: requires variable-length fields of complex domain to hold lists of time-stamped attribute versions, e.g. ((feature, time from, time to); (x, time from, time to); (feature, time from, time to)).

Frank (1994) used time modeling to distinguish different types of time, because time models are applied to different applications, with users choosing the model most suitable for the problem at hand. He indicated that the notion of the types of time in GISs is related to the scales of measurement and descriptive models. He listed a number of examples of time concepts, such as: single experience (totally ordered) model versus partially ordered models; continuous discrete, or solely ordered models of time; cyclic versus linear time models; branched time in the past or in the future; and multi-perspective models of time. A complex lattice structure among time types is shown in Table 2-1 from Frank (1994).

<table>
<tr><th></th><th></th><th>Total order</th><th>Partial order</th><th>Branching</th><th>Multiple perspectives</th></tr>
<tr><td rowspan="2">Linear</td><td>Ordinal</td><td>Single experience</td><td>Multiple experiences</td><td rowspan="4">Branching Time</td><td rowspan="4">Time with multiple perspectives</td></tr>
<tr><td>Continuous</td><td colspan="2">Continuous time</td></tr>
<tr><td rowspan="2">Cyclic</td><td>Ordinal</td><td colspan="2" rowspan="2">Cyclic time</td></tr>
<tr><td>Continuous</td></tr>
</table>

**Table 2-1. Lattice structure among time types in GISs (Frank, 1994).**

Another influential researcher is Peuquet (1998). She has distinguished two aspects in time studies, namely, the world state and the changes. She summarized three approaches for representing spatial-temporal data in GISs:

location-based, entity-based, and time-based representations, and for each she defined three types of temporal relationships (1994):

- the association between elements within a given temporal distribution at a given temporal scale;
- the combination of elements from different temporal distributions;
- the transformation between temporal scales.

She pointed out that the selective retrieval and manipulation of data on the basis of these basic temporal relationships is particularly important from an analytical perspective because it allows the examination and derivation of cause and effect, as well as observations of overall temporal patterns (i.e. temporal cyclic and rhythms).

Goralwalla (1998) proposed an object-oriented framework for temporal data models with explicit types and properties to model the diverse features of time (see figure 2-4).

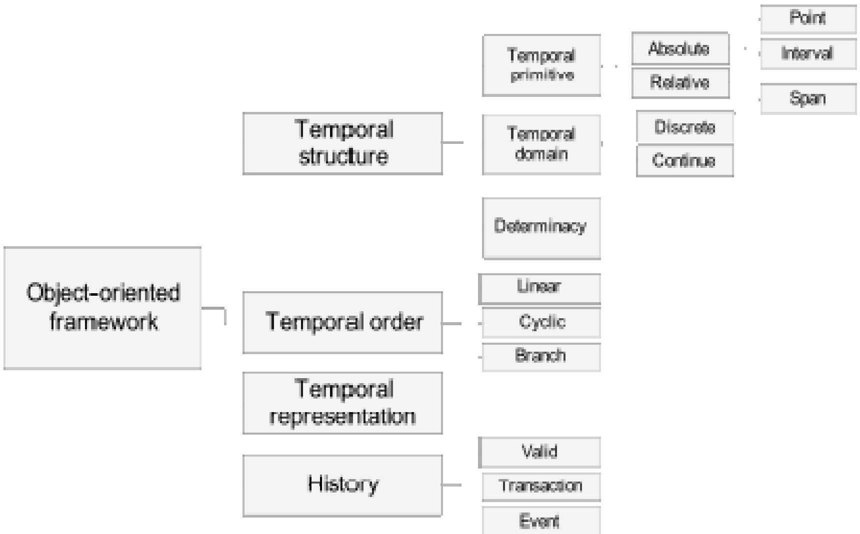



**Figure 2-4. Overview of time modeling approach proposed by Goralwalla (1998).**

**Time visualization**

Based on the data modeling, Langran (1992) reviewed a few, well-known time visualizations:

- Space-time-cube (Hagerstrand, 1970): this combines time and space in a natural way, with time represented as continuous or discrete. The units along the Z-axis can be years, days, hours, etc. The X and Y axes indicate the 2D space.
- Sequence of snapshots: the nature of each time slice is recorded as a snapshot, to inform users about the situation at each time slice in the sequence.
- Base state with amendments: a description of change with a fundamental component of cartographic time.

- Space-time composite: differences in the time dimension are shown as new spatial dimensions.

In the literature on spatio-temporal visualization, most of the techniques are based on three cartographic depiction modes: a single-state map, multiple static maps, or an animation map (Kraak, 1996) (Figure 2-5). Langran's work could in some ways correspond to these three cartographic depiction modes. Obviously, the space-time cube and space-time composite are kinds of single-state map, whereas the sequence of snapshots and the base state with amendments belong to the multiple static maps group.

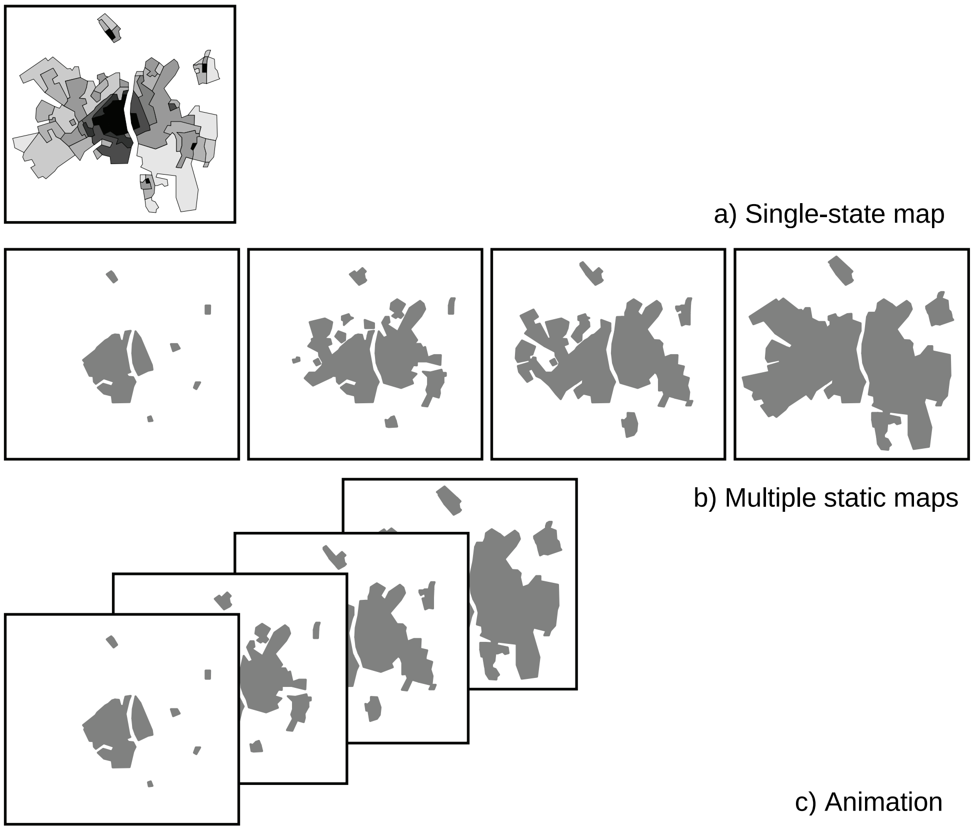



**Figure 2-5. Three cartographic modes: single-state map, multiple static maps and animation map.**

In the classic approach to single-state maps, visual variables, as defined by Bertin, are used to show time in the context of the map. Because time is considered as an ordered variable in most approaches, a value (Figure 2-5a) and texture are often used. A 3D representation can be used to show time-space as well, and the space-time cube is an example of this.

Other solutions for time-space representation are supported by interactive and dynamic techniques which allow users to explore their data in a more flexible way. In this situation, it is possible to combine single-state maps, multiple static maps and animation together. Users could intercept frames of an animation and show them as multiple static maps to detect change, or overlap the multiple static maps as a single state map to further comparison (see figure 2-6). With the interactive timeline, it is possible to move to a snapshot which shows the situation of the city at a certain time, while the animation as a whole shows the trend of urban change.

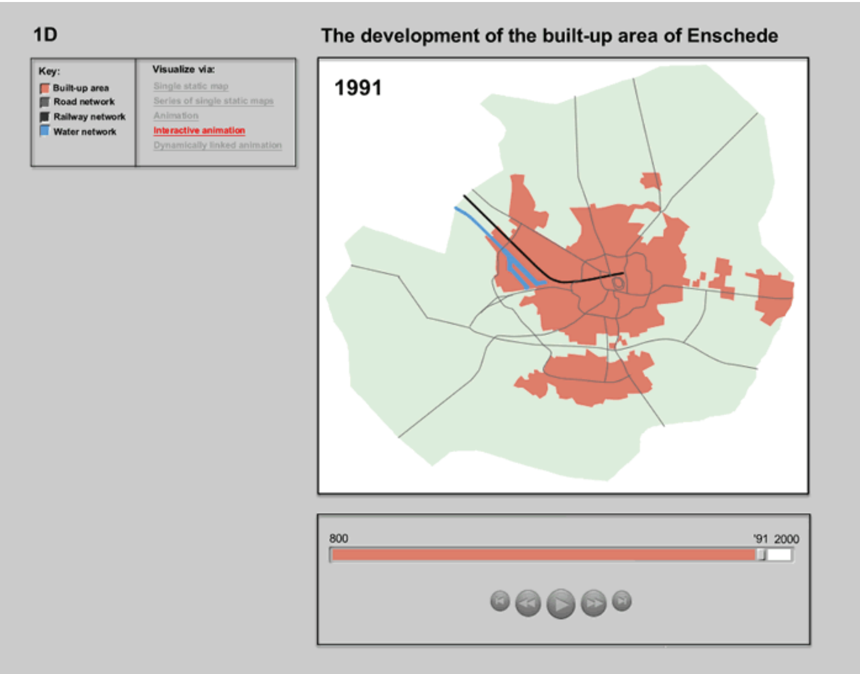



**Figure 2-6. Example of a timeline used to interact with the animation.**

In an interactive and dynamic environment, time visualization can be combined with other visualizations, such as maps and graphs, supported by coordinated multiple views (CMV) (Roberts, 2005; 2008). Data or information can be represented in either temporal order along a timeline (according to temporal location), or as distinct events (temporal objects) (Peuquet, 2002 ), and they can be coordinated with each other (see figure 2-7). This shows an interactive time-series graph dynamically linked to a map. Users can select a time point and see the situation at that time in both a map and a graph. They can also define the animation interval to show the change by animation in a map view.

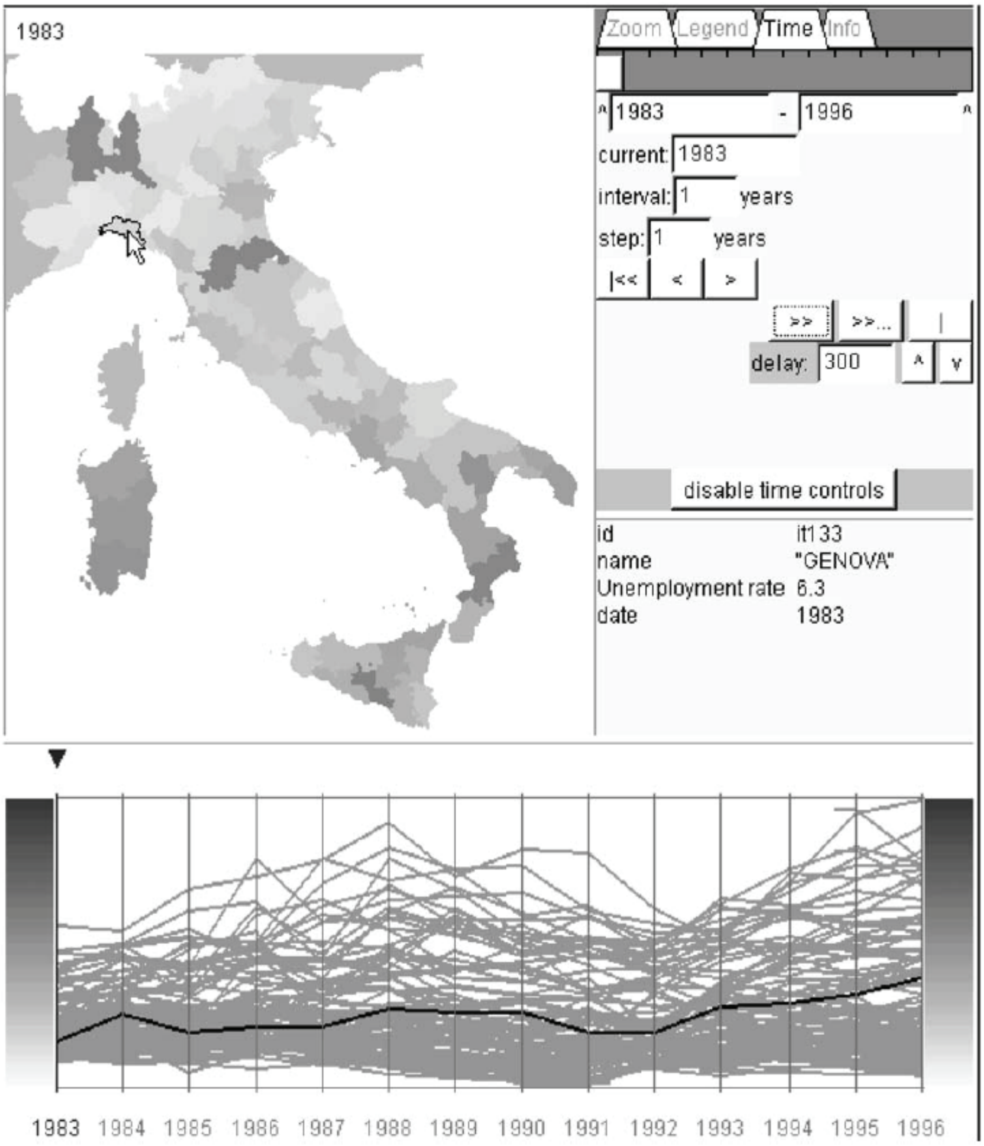



**Figure 2-7. An example which links a time-series graph with a map (Source: http://borneo.gmd.de/and/time/italy.html).**

## *2.4 Views of time in GIScience versus time visualization*

The above discussions on both the nature of time and visualization of time in GIScience are examples of different perspectives on time, each with particular applications in mind. However, there are notable similarities, particular the notions of linear and cyclic time, discrete and continuous time, and absolute time and relative time. These notions are taken into consideration in the time visualization environment when answering different temporal questions, because these notions describe the nature of time and are closely linked to human cognition of time. How these different views on time work in time visualization will be discussed below.

**Discrete and continuous time**

As stated at the beginning of this chapter, time passes continuously, but it is observed and measured at discrete points or in intervals. This distinction can also be recognized in the visual temporal representation. Figure 2-8a shows a discrete approach, while a continuous approach is shown in Figure 2-8b.

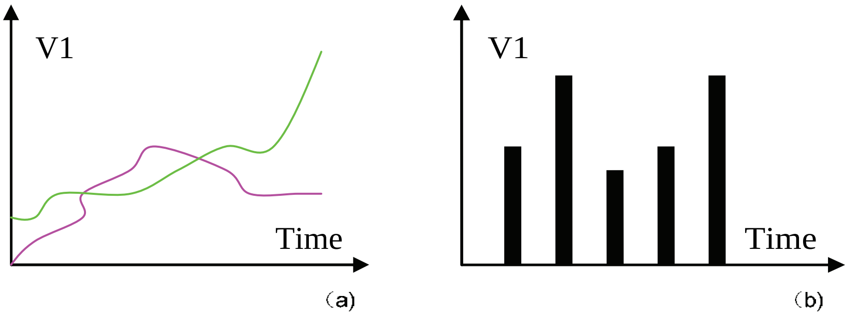



**Figure 2-8. Discrete approach and continuous approach in time visualization.**

**Relative and absolute time**

Time can also be considered as relative (e.g. last week) or absolute (e.g. May 27th). Although Einstein's Theory of Relativity changed the way humans think of space and time, in GIScience, time is approached according to the simple Newtonian concept of non-interacting space and time (Langran, 1992).

In this research, the absolute Newtonian concept of time is followed, which distinguishes absolute time and relative time. Absolute time means that temporal data are based on the measurements on a certain scale, whereas relative time has a reference object. This reference object could be classified as a relative instant or relative interval. For example, in the sentence 'two minutes before 22:00', the '22:00' is the instant reference. In the sentence 'half-way through event A, event B started', event A is the interval reference. Most time visualizations are based on absolute time, which is limited to regular time units.

**Linear and cyclic time**

The continuous nature of time makes it linear (before, after), but it obviously has cyclic characteristics as well (day, season). The *granularity of time* is defined by the different units in which time is expressed, and it can be used to define the scale of time. Granularities include both linear and cyclic characteristics. The regularities or irregularities of a phenomena or an object can be detected in both cyclic time and linear time. For example, 'the speed of the car was faster and faster' is a linear regularity, while 'the speed of this car was faster during the afternoon than in the morning' is a cyclic linear regularity. The frequent occurrence of a cyclic view of time seems to be a reflection of its close association to nature and the natural rhythms in the everyday life of early culture (Peuquet, 2003). Not only different phenomena or objects follow different cycles, but also a single object can show different cyclic characteristics. Most phenomena show both the linear and cyclic characteristics. The timeline (Figure 2-9a) is used most to represented linear time, while the time wheel (Figure 2-9b) is used to show cyclic time. Based on this classification, Figure 2-10 shows examples in the literature based on the timeline, and Figure 2-11 show examples based on the time wheel.

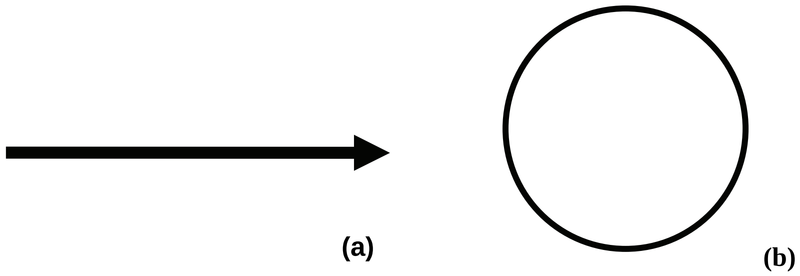



**Figure 2-9. Timeline for linear time and time wheel for cyclic time.**

These classifications are based on different views of time only. To further discuss the time visualizations, a systematic view on time visualization referring to visualization theory will be presented in Chapter 3.

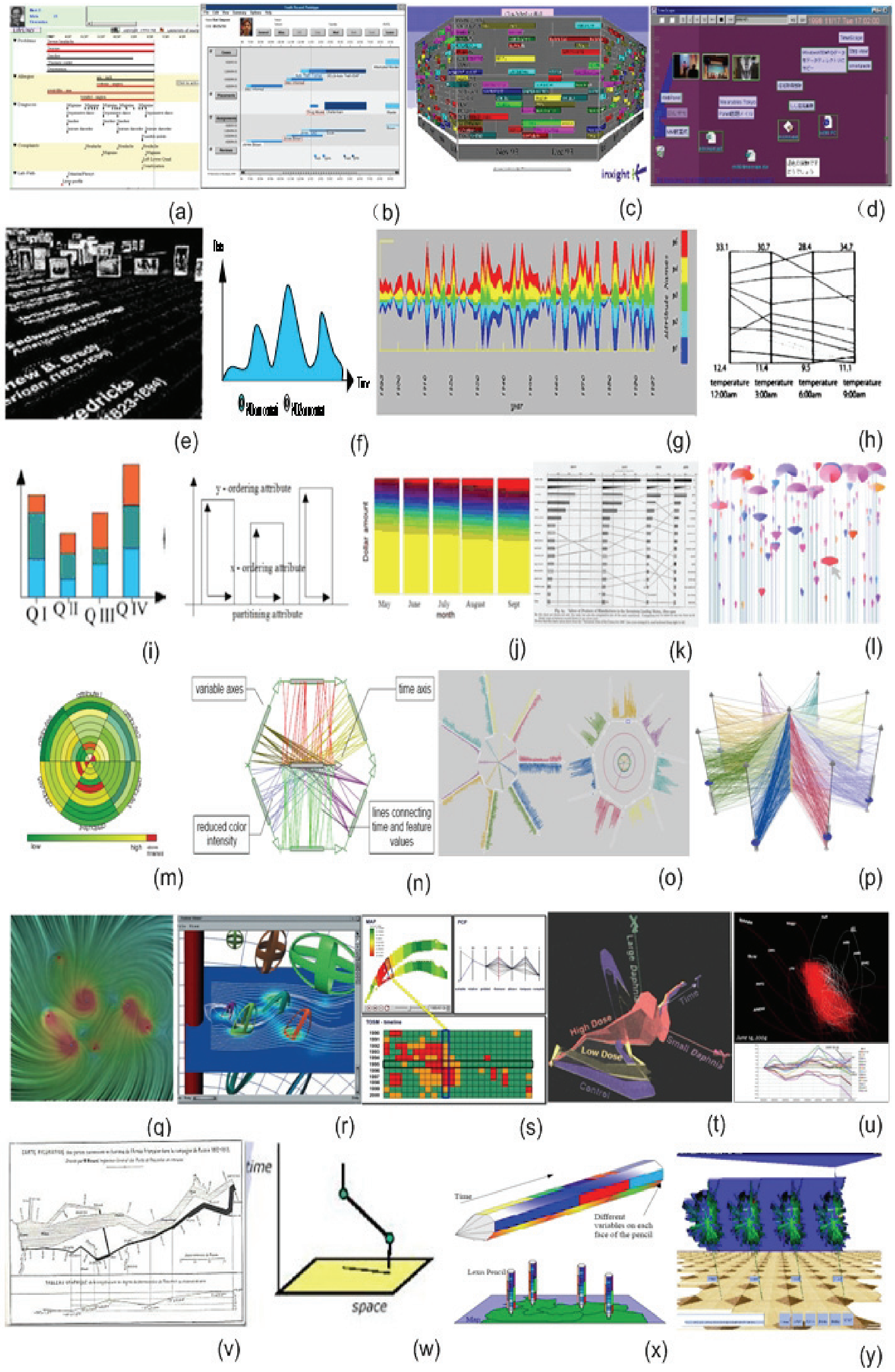


Figure 2-10. Visualizations for linear time.

2-10a TmViewer tool, a prototype implementation of the ITER model (Kumar, 1998). 2-10b Lifelines (Plaisant, 1996); http://www.csdl.tamu.edu/~vijayk/timelines.html). 2-10c Perspective wall, http://www.parc.xerox.com/istl/projects/uir/images/. 2-10d TimeScape (Rekimoto, 1999). 2-10e Dynamic timeline (Kullberg, 1995). 2-10f Curve representation. 2-10g Theme river (Havre, 2000). 2-10h Typical axis value designation hides temporal trends (Edsall, 2003). 2-10i Stacked bar charts (Harris, 1999). 2-10j Pixel bar charts (Keim, 2002). 2-10k Parallel coordinates for the visualization of time-dependent data (Garnett 1903, taken from Brinton 1919). 2-10l People's garden (Xiong, 1999). 2-10m Circle view (Keim, 2003). 2-10n Time wheel (Tominski et al. 2003a, 2003b). 2-10o Two views of different data sets visualized with multi-combs. Left: Time axes extend from the center; an aggregation view and mirrored plots are provided. Right: Variable axes extending from the center and circularly arranged time axis. 2-10p 3D time wheel (Tominski, 2003). 2-10q Image based flow visualization (IBFV) (Wijk, 2002). 2-10r Feature- and event-based flow visualization (Reinders, 2001). 2-10s Temporal ordered space matrix (TOSM) (Vlag, 2006). 2-10t Worm plot (Treinish et al. 1997). 2-10u Flocking boids (Moere, 2004). 2-10v Minard's classical visualization of the fate of Napoleon's army on the campaign against Russia (Minard 1844-70, from Tufte 1983). 2-10w Space-time cube (Hagerstrand, 1970). 2-10x The Lexis Pencils technique (Brian et al. 1997). 2-10y Time tube (Chi, 1998).

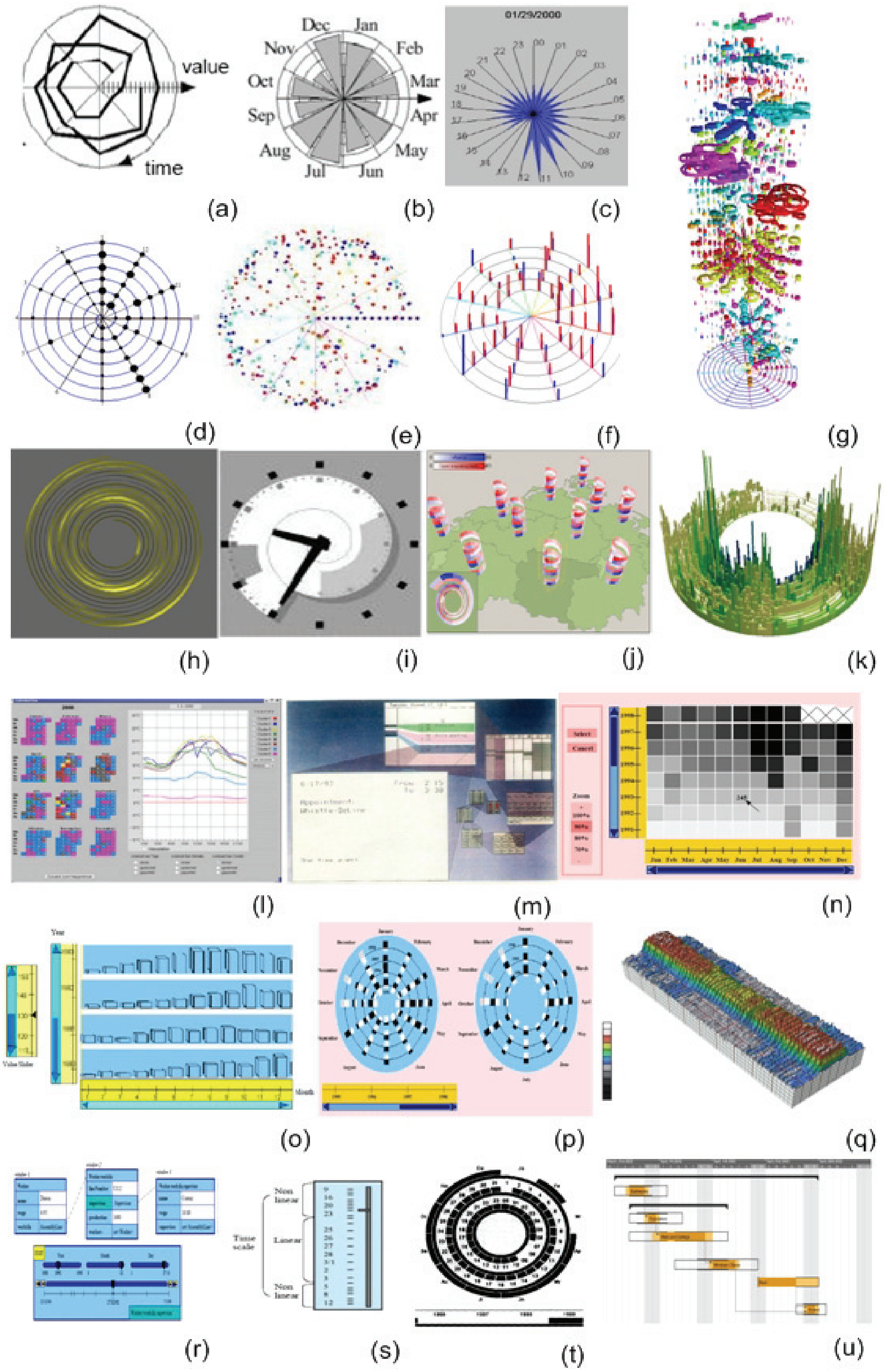



**Figure 2-11. Visualizations for cyclic time.**

2-11a Circle graph (Harris, 1999). 2-11b Sector graph (Harris, 1999). 2-11c Star representation technique (SRT) (Daassi, 2004). 2-11d-g Spiral graph visualization (Carlis et al. 1998). 2-11h Spiral visualization (Weber, 2001). 2-11i SpiraClock (Dragicevic, 2002). 2-11j Helix icons with map (Tominski, 2005). 2-11k Ringmaps (Zhao, 2008). 2-11l Calendar view (Wijk, 1999). 2-11m Calendar visualization (Mackinlay, 1994). 2-11n Agenda technique (Daassiyz, 2000). 2-11o Superposed histograms technique (SHT) (Daassi, 2002). 2-11p The concentric circles technique (CCT) (Daassi, 2002). 2-11q Fingerprints (Wijk, 1999). 2-11r Pointwise temporal object browser (Daassiyz, 2000). 2-11s Time slider (Koike, 1997). 2-11t Cyclic and linear temporal query controls (Brewer, 2000). 2-11u Planning line Glyph (Aigner, 2005).

**Summary**

In this chapter, time is studied from the viewpoint of several disciplines, such as philosophy, cognition and perception, and in a physical way, to better understand how people perceive and gain insight into time. There have always been studies on time and gradually our understanding of time has improved, but we still have many different views of time, such as existing/observed time, absolute/relative time, continuous/ discrete time, linear/cyclic time, etc. These different views of time are widely accepted by most of disciplines and they influence time studies in GIScience, from data modeling to time visualization. They should also be considered when temporal visualization methods are investigated further.

# Chapter 3 State-of-the-art in geo-visualization

## 3.1 Introduction

Geovisualization draws upon approaches from many disciplines, including cartography, scientific visualization, image analysis, information visualization, exploratory data analysis (EDA) and GIScience to provide theory, methods and tools for the visual exploration, analysis, synthesis and presentation of data that contains geographic information (Dykes et al., 2005). Its objective is to visualize phenomena or objects to find regularities/irregularities, detect trends, and to support decision-making. This chapter reviews the development of (cartographic) visualization theory and looks at how to use visualization methods for analyzing the data, to support problem solving. At the end of the chapter I focus on the time perspective, by looking at existing time visualization methods in relation to visualization theories.

## 3.2 Problem solving based on visualization theories

A common approach to support problem solving with visualization is shown in Figure 3-1. A problem is converted into a set of tasks; these are executed in an appropriate visualization environment by translating them into questions with the suitable data at hand. Three keywords are of importance: user tasks, data framework, and visualization framework. The visualization framework includes the graphic representation and functional tools to 'play' with the graphics.

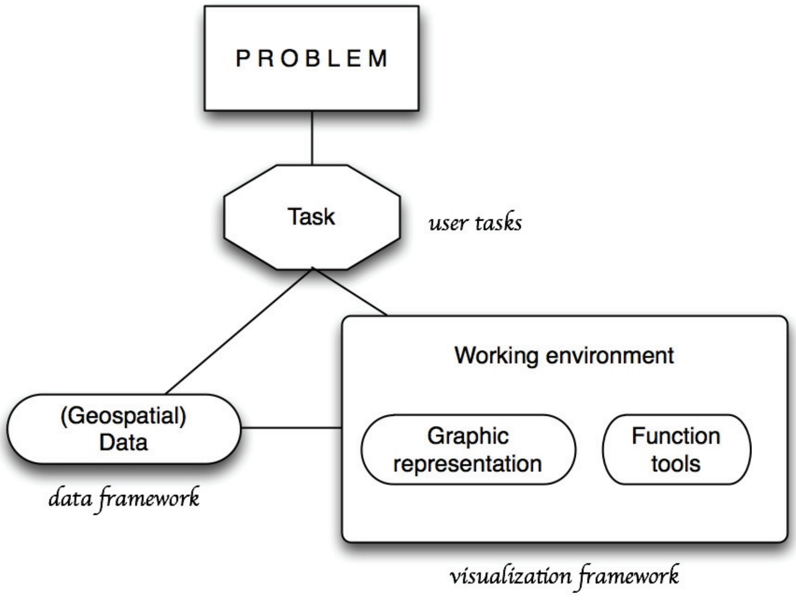



**Figure 3-1. An approach to visual problem solving involving user tasks, a data framework, and a visualization framework.**

It is relevant to ask: How can users formulate, questions based on the data framework? How can the data be addressed in a visualization environment? How can users decide on the best or correct graphic representation(s) and what functions are required to answer the questions? Existing cartographic and geovisualization theories, as proposed by Bertin, Peuquet, MacEachren and Andrienko, can be studied by looking at the inter-relationships of these tightly linked aspects. It should be realized that most of these theories mutually influence each other and that they concentrate on different aspects, as illustrated in Figure 3-2. The figure shows how the different theories relate to the visual problem-solving diagram in Figure 3-1 and distinguishes between paper and digital map distributions of different theories in the common approach. In Figure 3-2b, the theories are plotted along the information processing process and a timeline.

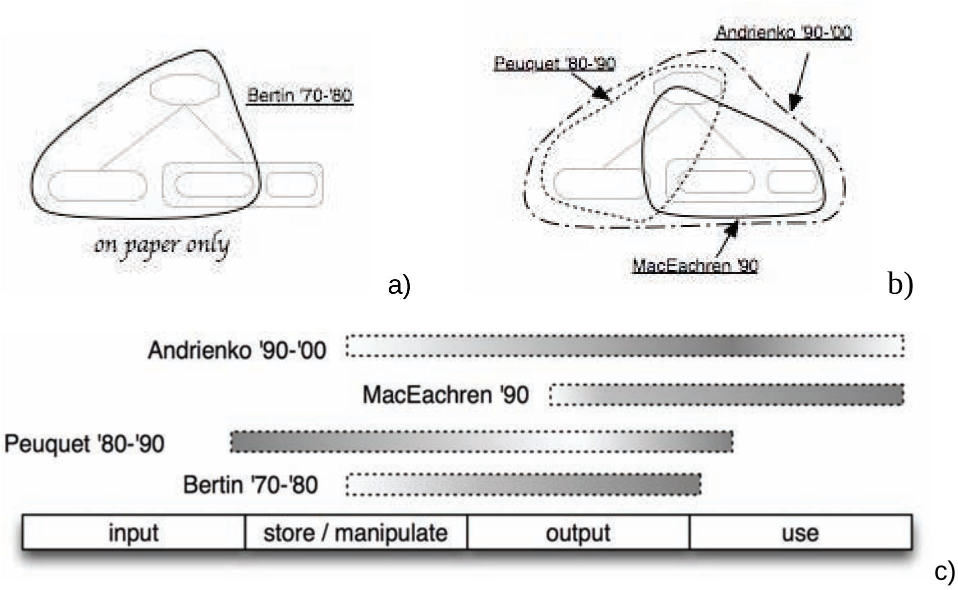



**Figure 3-2. Existing cartographic and geovisualization theories as proposed by Bertin, Peuquet, MacEachren and Andrienko, related to visual problem solving elements: a) distribution of theories in the context of three keywords; b) the theories are plotted along an information processing process and a timeline.**

Bertin's (1967) theory aimed to find the single, best graphic representation for the data at hand. At that time, he was restricted to static graphic representations on paper. With the arrival and development of computers, attention was given to questions like how to structure spatio-temporal data in databases in relation to user tasks. This was studied by Peuquet (1984; 2002) among others. Furthermore, with support from computer- and internet technologies, visualization now not only involves representation, but also interaction. Human-map interactions, cognitive and semiotic issues in spatial representation were discussed by MacEachren (1995). Andrienko (2006) managed to integrate existing visualization theories and focused on exploration analysis.

In the next section, based on Figure 3-1, the data framework, user tasks and visualization aspects are elaborated and these will be extended with a specific temporal component in Chapter 4.

### 3.2.1 Data framework

Never before has data been collected, stored, processed and presented at such high volumes as today. To analyze the huge amounts of data, different frameworks are used to structure and abstract data. In Bertin's data framework (1967), each variable was considered to be a component with a length (units or possible values) and level of organization (qualitative/ quantitative). It is important that each component is transcribed by a graphic variable having at least a corresponding length and level.

Peuquet (1984) specifically distinguished three components in spatio-temporal data which are also used to structure the spatio-temporal questions: location (related to the 'Where?' question), attribute (related to 'What?') and time (related to 'When?') (Figure 3-3a). This 'triad' concept was further extended to a 'pyramid' model, in which 'object' is considered to be a knowledge component on a higher level (Mennis et al., 2000) (Figure 3-3b). This approach is the basis for most research on spatio-temporal data, because phenomena can be described using these three components and the relationships between them.

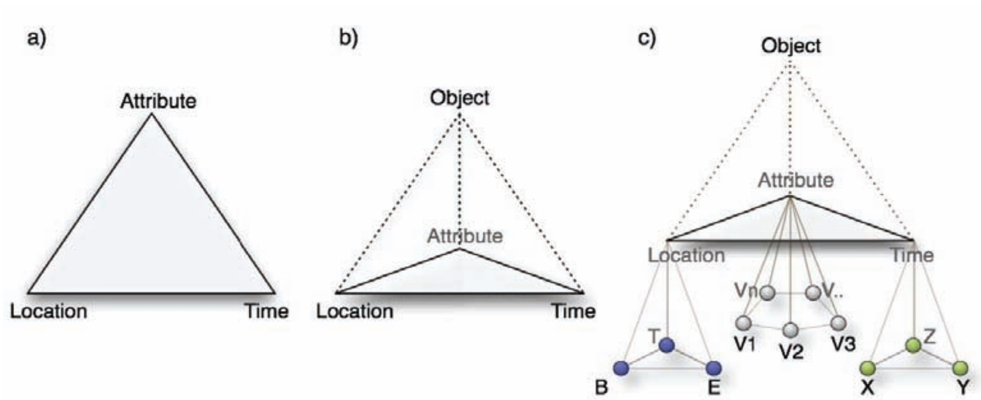



**Figure 3-3. The generic model of spatio-temporal data based on Peuquet: a) the triad; b) the pyramid; c) the pyramid extended with sub-components.**

The pyramid can be considered to be a hierarchical model in which each of the elements can be split into multiple sub-elements. As seen in Figure 3-3c, 'location' is defined by X, Y and Z, 'attribute' includes multi-variables (V1 to Vn,) and 'time' lists different temporal characteristics (here they are observation time, event time and transaction time). The sub-elements correspond to the components of Bertin's framework and each holds the different characteristics discussed by Bertin, such as its length and the level of organization.

Andrienko and Andrienko (2006) further differentiated Bertin's components into referrer and attribute. The referrer defines a context of the attribute, whereas the attribute represents the result of measurements and/or observations. There are three kinds of referrers that coincide with Peuquet's elements of spatio-temporal data: time, location and population. The term 'population' is used in an abstract sense to represent a group of any items.

Based on the above discussion, all the data could be simplified into components holding a length (units or possible values) and a level of organization. The data could be further classified into one of three types: time, location or attribute. In Bertin's work, location was considered to be a special component. Time is a naturally ordered component, on which innumerable comparisons can be based. These could be quantitative, since day, year, etc. are recognized as units. Table 3-1 shows the characteristics of components as they are classified by Peuquet in relation to Bertin's approach.

| | | Bertin | |
|---|---|---|---|
| | | **Length** | **Level of organization** |
| **Peuquet** | Location (X, Y, Z) | $-180^{o} \rightarrow +180^{o}$ <br> $-90^{o} \rightarrow +90^{o}$ | Ordered (could be quantitative) |
| | Time (t) | Infinity | Ordered (could be quantitative) |
| | Attribute (V1, V2 … Vn) | Various | Ordered, qualitative, quantitative |

**Table 3-1. The relation between Bertin's and Peuquet's approach to data.**

### 3.2.2 User tasks framework

User tasks are derived from the problem and are closely related to the data framework at hand. The tasks are transformed into questions.

Based on the components distinguished (the bottom layer in Figure 3-2c), Bertin worked with question types and reading levels to deal with user tasks. There are as many types of questions as components. For example, when temperature changes over time are studied, two components can be distinguished: time and temperature. This leads to two kinds of questions:

- At a given time, what is the temperature?
- For a given temperature, at what time was it observed?

For each question type, there are three reading levels: elementary, intermediate and overall. This approach structures the user tasks based on a systematic analysis of the data.

Andrienko and Andrienko (2006) built on Bertin's question types and reading levels and introduced a user tasks typology. They distinguished a target (what information needs to be obtained) and constraints (what conditions does this information need to fulfill) in the task. In relation to their data framework, it is noted that both the referrers and attributes could be either the target or one of the constraints.

Peuquet linked the questions directly to the three data elements: ‘Where?’ (related to location), ‘What?’ (related to attribute) and ‘When?’ (related to time). Most of the user tasks can be described based on these three elements and the relations between them. Furthermore, with the introduction of the object in Peuquet’s pyramid model, one additional question could be considered: ‘whether?’ (identifying the existence of the object). Accordingly, several generic questions can be defined based on the relation between these four elements, for example:

| | |
|---|---|
| What + where + when ➔ Whether | Describes the existence of an object in a certain situation, e.g. ‘Did it rain more than 20 mm at the mountain top at noon?’ |
| Where + what + whether ➔ When | Describes the time of an event, e.g. ‘When did it rain more than 20 mm at the mountain top?’ |
| What + whether + when ➔ Where | Describes the location of an event, e.g. ‘Where did the amount of rainfall exceed 20 mm at noon?’ |
| When + where + whether ➔ What | Describes the character of an event, e.g. ‘What is the amount of rainfall observed at the mountain top at noon?’ |

In Andrienko’s terminology: the above arrows indicate the ‘direction’ of the questions, with the constrains on the left and the targets on the right. In general, the user tasks are defined by what kinds of data components are involved and their reading level and direction.

In the above example the user tasks can be represented by questions and as such they can also be summarized in the pyramid model (Figure 3-3b). The nature of the questions will determine how the pyramid is approached. This could be from the ‘object’ perspective, or by ‘rotating’ the pyramid to the ‘what’, ‘where’, or ‘when’ perspective. For example, with the town as an ‘object’ on the top (Figure 3-4a), the question: where, when and what is the name of the town could be discussed. With a focus on location (Figure 3-4b), questions can relate to when, what kind of structure, and whether the town was at that location? With attribute on top (Figure 3-4c), the questions will change to where, when and whether the town was at that moment? With time on top (figure 3-4d), a similar approach can be followed referring to a specific moment in time.

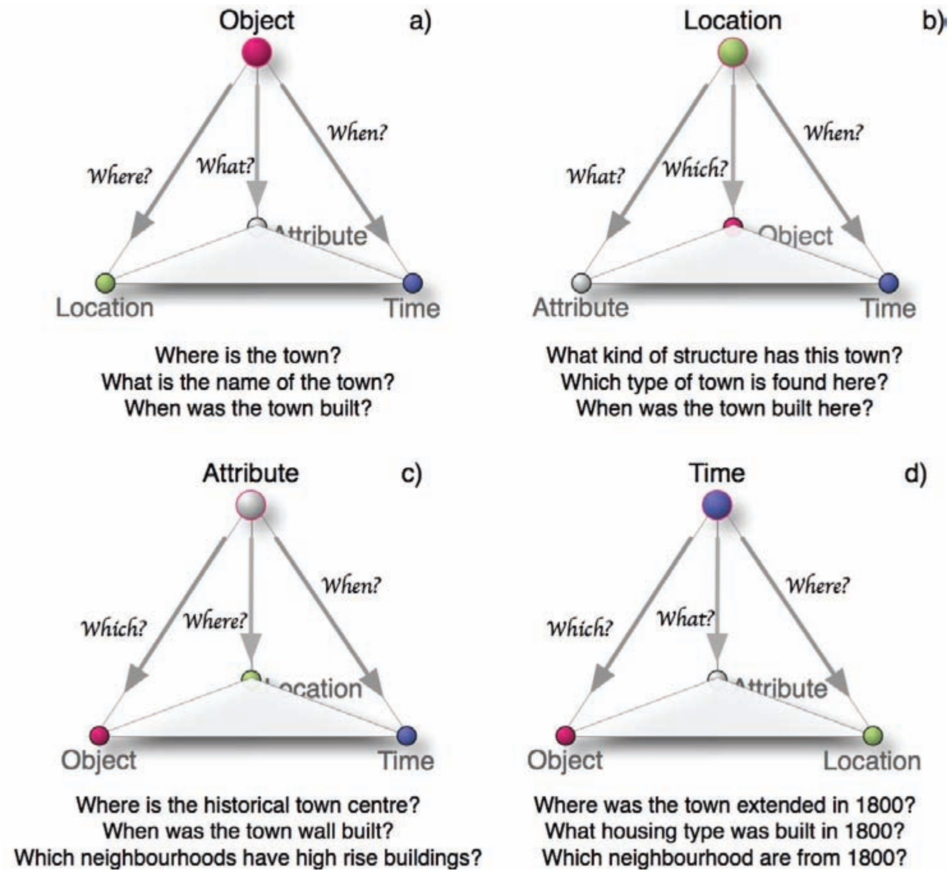



**Figure 3-4. The pyramid perspective, answering questions from an object (a), location (b), attribute (c), or time (d) point of view.**

Only simple examples are listed above, and it is easy to create more complicated questions based on combinations of 'whether', 'where', 'what' and 'when'. At the end all these complicated questions can be broken down into two or more simple questions, and the user tasks can be analyzed and linked to visual representations based on the simple questions.

### 3.2.3 Visualization framework

To support the user tasks, the data can be represented by different visualizations. Each of these representations has its own 'capability' to answer the questions asked. Based on the data framework and user tasks, the visualization can be approached from three perspectives: location-space, attribute-space and time-space. Here the notion 'space' is an abstract notion, not to be confused with geographic space (see figure 3-5):

- Location-space: to represent location and answer the 'where'-related questions, such as what is the spatial distribution of the precipitation? Maps are the typical visual representation in this category.

- Attribute-space: to represent attributes and answer the ‘what’-related questions, such as what kind of precipitation is it? Diagrams such as a pie chart or parallel coordinate plots are typical representations.
- Time-space: to represent time and answer the temporal questions, such as what is the temporal distribution of precipitation per month, season or year? Traditionally represented by graphics with a timeline or time wheel.

In location-space the focus is on the spatial distribution, in attribute-space the focus is on the distribution of the variables, and time-space focuses on the temporal distribution (instance e.g. via a timeline). For all spaces one has to consider the graphic representation of the data and interactive tools to query and manipulate the graphics. Of course, there are also visualization methods that combine two or three ‘spaces’, and these are capable of handling complicated questions.

### 3.2.4 Representation

A suitable graphic representation is found based on the character of the data and the requirement of user tasks. These could, for instance, be different types of maps and diagrams. In these graphics the visual variables, e.g. two dimensions of a plane and 6 further variables (size, value, texture, color, orientation and shape) as proposed by Bertin, are used to represent the character of the data and to allow the user to find answers to the questions. Bertin’s approach was originally limited to static representations but over time it has been extended to dynamic environments as well. These introduced new or derived variables as defined by Green (1988) and MacEachren (1995). In figure 3-5, a combination graphic representation is shown with the link line of spaces, for example, a typical combination of location-space and attribute-space results in thematic maps; a combination of attribute-space and time-space in diagrams, and a combination of location-space and time-space in space-time cubes.

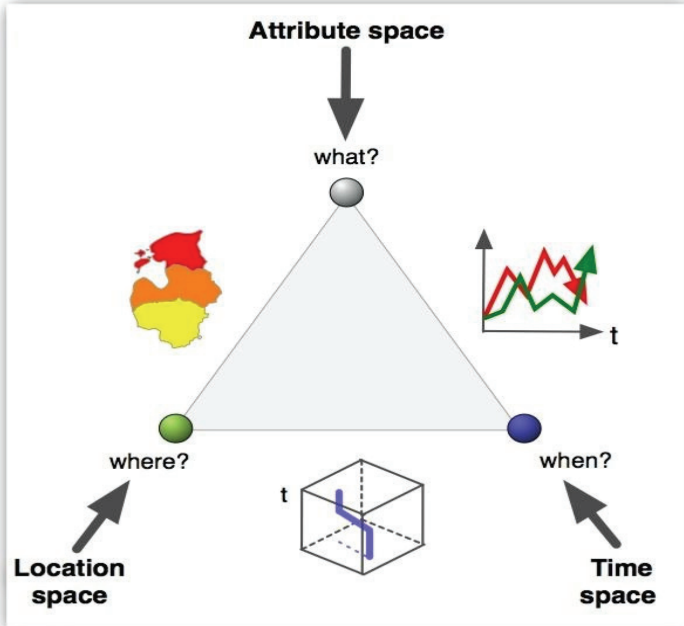



**Figure 3-5. Visualization spaces, with the views from location-space, attribute-space and time-space. A typical combination of location-space and attribute-space results in maps, the combination of attribute-space and time-space in diagrams, and the combination of location-space and time-space in a space-time cube.**

### 3.2.5 Interactive environment

To query and manipulate the graphic representations, interactive tools are required. Andrienko and Andrienko (2006), suggested tools for display manipulation, data manipulation, querying and computation. However, these tools have to be used according to a visualization strategy. A common approach is to apply Shneiderman's visual information seeking mantra (1996) to obtain answers to the questions. The mantras follow an (iterative) three-step approach (Figure 3-6a): first overview, second zoom and/or filter, and third details-on-demand. In the overview mode users can see the whole dataset, and this corresponds with the overview reading level according to Bertin (1983). Subsequent questions will require users to zoom in on a region or time period or to filter out certain attributes (interval level). If a user is interested in particular information, the details-on-demand (elementary level) action shows information from the database related to the object of interest. This process is interactive and iterative, and also scale- (level of details), and space-dependent.

Figure 3-6 shows how this interactive and iterative process might work with example questions in the combined visualization spaces.

1) Which crossing has the busiest traffic in city A at 8 am this morning? location: overview ➔ zoom in ➔ details-on-demand

2) What is the traffic situation at this crossing during the day? location: details-on-demand ➔ time: overview
3) Which car broke down at the crossing at 8:00 am today? location: details-on-demand ➔ attribute: details-on-demand
4) What is the color of that car? Location: details-on-demand ➔ attribute: ➔ details-on-demand
5) What is the spatial distribution of cars with the same color? attribute: details–on-demand ➔ location: overview
6) How long does this car keep moving? time: details-on-demand ➔ time: overview
7) What is the route of this car today? time: overview ➔ location: overview
8) When did the car reach its highest speed during the whole day? Attribute: overview ➔ time: details-on-demand?
9) Where was the car at that time? time: details-on-demand ➔ location: details-on-demand.

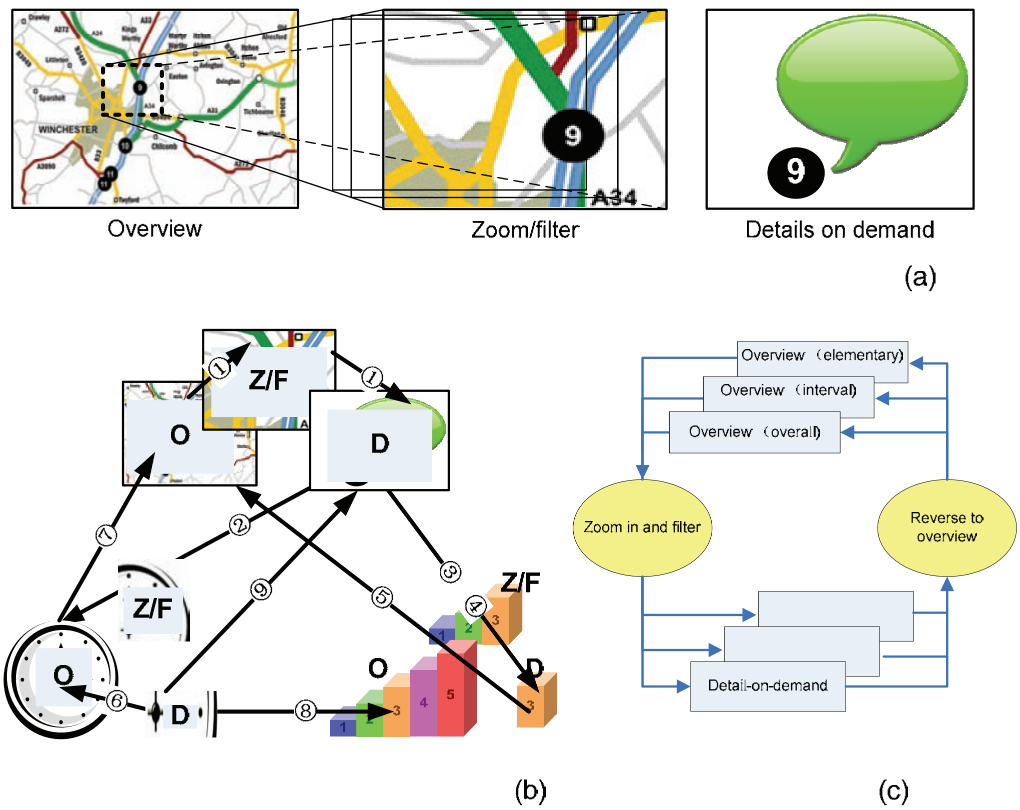



**Figure 3-6. a) Principle of Shneiderman's information seeking mantra (1996); b) scenario of the extension of information seeking mantra; c) extension of information seeking mantra with reading level of Bertin (1967).**

Based on the above example, we can see that 'details-on-demand' for one question could become the overview for the next action. From 'details-on-demand' the user could go back to the original overview or to another overview in a different space. The actions of the exploration process will 'jump' among the different spaces on the different scales. Based on this viewpoint, the information seeking mantra (Shneiderman 1996) and reading level (Bertin 1983) can be combined together to define the exploration process as shown in Figure 3-6c.

### 3.2.6 Coordinated multiple views (CMV)

For an interactive and iterative exploration process, these 'spaces' should be linked (see Figure 3-6b), and they could also function as coordinated multiple views (CMV) (Roberts 2005). The coordinated multiple view is a technique that supports an exploratory environment which allows the user to interact with the data, not only according to Shneiderman's mantra, but also with other perspectives in mind.

Roberts (2005; 2008) provided an overview discussion on CMV for exploratory geovisualization. The term 'multiple views' is all-encompassing: it includes any system which allows a direct visual comparison of multiple windows, including visualizations from different display parameters (Roberts 2008). He stated that several aspects should be considered by the developer or user in an exploratory CMV environment, i.e. where is the information displayed, interactive filtering, interactively adapting the mapping parameters, navigation, and interacting with the environment and coordination.

Roberts' discussion on the CMV focuses on interaction during visualization. He emphasized the interactive links among multiple views. 'Coordinated' is the keyword in the CMV technique. It means the views are linked together in such a way that any user manipulation in one of the views automatically has an effect on the content of any of the other views. For example: a user selects one object in the map view; the record representing the same object in the database will be highlighted in attribute view. In practice, the coordination could be supported by brushing techniques ((Monmonier 1989; Carr et al., 1986; Berker and Cleveland, 1987). This is also known as the highlight technique (Robinson 2006): it is a direct manipulation technique which allows the user to point to and pick interesting elements for selecting, deleting or adapting them. Recently, CMV techniques received more attention from the perspective of high-dimensional data (Lamirel and Shehabi, 2006; McDermott, et al., 2006; Schlesier et al., 2006), exploratory techniques (Andrienko and Andrienko, 2003; Plumlee and Ware, 2003; Hoeber and Yang, 2006; Lawrence et al., 2006) and different applications (Brodbeck and Girardin, 2003; Sifer 2003; Morrison et al., 2006; Wraver, 2006).

The CMV environments are highly interactive systems, relying on the premise that 'insight' is formed through interaction. The environment in which the visualizations are used will influence how easy the questions can be answered, especially when dynamics and interaction are involved.

Based on the above discussion, the three keywords are seen to structure and discuss visualization theories, e.g. data, user tasks and visualization. In the visualization framework, beside the representation, the interactive functions are discussed from both a principle strategy and the support technology (CMV). However, most of the existing implementations deal with spatial and attribute exploration only. The existing graphic representations and interaction have not been elaborated extensively enough for typical temporal visualizations. In the next section, the existing temporal visualization will be reviewed and analyzed based on the three keywords.

## *3.3 Existing methods for time visualization*

In the wider context of GIScience, research on temporal data analysis, modeling and visualization is being given increasing attention (Mackinlay et al., 1991; Harrison, 1994; Allen, 1995; Brown, 1998; Harris et al., 2000; Goralwalla et al., 1998). This trend is resulting in the appearance of many new methods for many different applications. Overviews on visualization can also be found, (such as Chi, 1998; Silva and Catarci, 2000; Andrienko et al., 2003; Muller, 2003; Aigner et al., 2007). Understanding and structuring the taxonomies in these different time visualization overview studies was the starting point for this research.

### 3.3.1 Taxonomies of visualizations

The literature provides several taxonomy models for the analysis of the various visualization methods available. These models can be categorized using the three keywords already mentioned (data, user task, and visualization), as shown in Table 3-1.

| | Type of data | Type of tasks | Type of visualization |
|---|---|---|---|
| (Cleveland, 1993) | x | | |
| (Shneiderman, 1996) | x | x | |
| (Buja et al., 1996) | | | x |
| (Hinneburg et al., 1999) | | | x |
| (Chi, 2000) | x | | x |

**Table 3-2. Summary of the categorization criterion for taxonomy models by Cleveland, Shneiderman, Buja, Hinneburg and Chi.**

Scheiderman’s (1996) taxonomy model for information visualizations was based on the data (seven data types) and user tasks (seven tasks). OLIVE (Oliver, 1997) is an example of a taxonomy which was assembled by students of Scheiderman, and it classified the visualization method using eight visual data types: temporal, 1D, 2D, 3D, multi-D, tree, network and workspace. This data-based taxonomy model divides the field of visualization into several subcategories as well: scientific visualization, GISs, multi-dimensional plots, node and link, trees, etc. Cleveland (1993) discussed the visualization methods from the perspective of number of data components (variables) used, similar to

Bertin's approach. The categorization criterion of this model is data. Buja and others (1996) differentiated the visualization methods into three categories: focusing individual views, linking multiple views, and arranging views. These categories were specified for three principal tasks in data exploration: finding Gestalt, posing queries, and making comparisons. So his approach was based on the type of data and type of tasks. Hinneburg et al.'s (1999) approach to designing his taxonomy model was based on the construction method and visual properties (type of visualization). Gahegan (2000; 2001) extended the work of Hinneburg with support for the style of user interaction. The categorization criterion of his approach was also visualization. Another taxonomy approach was based on the processing operation steps (Chi, 1998; Card et al., 1999). Chi's data state reference model breaks down each visualization method into four data stages (value, analytical abstraction, visualization abstraction, view), three types of data transformation (data transformation, visualization transformation, and visual mapping transformation), and four types within-stage operations (within value, within analytical abstraction, within visualization abstraction, within view) (Figure 3-8a). His approach could be summarized as a taxonomy combining data and visualization.

### 3.3.2 Review on taxonomies of temporal visualizations

The taxonomies for time visualization are based on the content in Table 3-1 as well, with one additional keyword: time. As mentioned in Chapter 2, there are several characteristics of time (linear/cyclic, absolute/relative and single/ multiple scale) which lead to different temporal visualizations and are also used to classify the temporal visualization. For example, linear temporal visualization and cyclic temporal visualization could introduce a clear taxonomy for time visualization. Most linear temporal visualizations are based on the principle of the timeline, with the cartographic animation as probably the most well-known example. Other examples are Lifeline (Plaisant et al., 1998), ThemeRiver (Harris et al. 2000) and the Perspective Wall (Mackinlay et al., 1991) and TOSM (temporal ordered space matrix) (Kraak and Vlag, 2007). For visualizing cyclic time, the time wheel is a common approach. Examples of such representations are the polar coordinate system (Chen, 2005) and a temporal sector chart (Weber et al., 2001). Sometimes the representation is based on the clock or calendar, such as Calendar View (Wijk and Selow, 1999). However, time is not the only categorization criterion in the taxonomy of time visualization. Several studies on the taxonomy of time visualization are reviewed in the next section.

### 3.3.3 Geo-oriented approach by Vasiliev

Vasiliev's (1997) discussion was an early review on mapping time. She supplied an integrated story about time in history, from philosophy to physics and across cultures both in the Western and non-Western worlds. She thought change was the key to people knowing that time exists. From cognitive time to measurement of time, she discussed how humans spatialize time in many ways, both intuitively and objectively (this is discussed in the last chapter). She focused her research on the geographers' view of time. Four branches of geography were chosen with the express purpose of pulling out those elements of time that are common in those subdisciplines in which time plays an overt role. These four branches of geography are: historical geography, cultural geography, time geography and quantitative geography. After addressing the importance of time in geography, Vasiliev reviewed time in cartography and GISs based on her categorization of the cartographic representation of time. Her framework for the symbolization of temporal information in maps was based on two factors: one was the type of time in geography, e.g. moment, duration, structure time, distance or space, as in a clock. The other one covered the spatial dimensions and symbology available to the cartographer for representing spatio-temporal information on a map, e.g. point, line and area. This taxonomy was based on the visualization criterion.

### 3.3.4 Linear visualization approach by Silva and Catarci

Silva and Catarci (2002) performed a survey of many linear, time-oriented visual representations based on the type of time and type of visualization. They proposed their classification model: slice, periodic, multi-scale and snapshot. For the slice visualization, they reviewed most of the visualization methods which are based on the timeline (Harrison, 1994; Karam, 1994; Allen, 1995; Plaisant et al., 1996; Kumar, 1998). The interactive timeline in many applications was studied, such as program debugging and monitoring systems (Heath and Etheridge, 1991; Abrams et al., 1992), analysis of video data (Davis, 1993; Hibino and Rundensteiner, 1997), visualization of medical records (Powsner and Tufte, 1994; Wyatt, 1994; Kilman and Forslund, 1997; Shahar and Combi, 1998), and personal histories (Plaisant et al., 1996; Rekimoto, 1999). They further discussed the distortion techniques affecting the timeline, such as Perspective Wall (Mackinlay et al., 1991) and (Carpendale, 1996). For periodic slice visualization, they discussed the visualization methods according to two basic approaches: one was visual calendars (Kincade et al., 1985; Beard et al., 1990; Mackinlay et al., 1991; Tessler 1993; Mackinlay et al., 1994; Palen, 1999) and the other was the time wheel (Keim, 1996, 1997; Carlis and Konstan, 1998; Elmasri and Lee, 1998).

For spatio-temporal visualization, they reviewed MMVIS (multimedia visual information seeking) (Hibino and Rundensteiner 1997), which extends VIS (visual information seeking) technology (Ahlberg and Shneiderman, 1994), for analysis of temporal trends in video data (Kullberg, 1996) and VRML (Virtual Reality Modeling Language) history (Luttermann, 1999), which incorporates the time dimension in VRML.

### 3.3.5 Information visualization approach by Muller

Muller’s (2003) approach analyzed the temporal visualization methods based on type of time and type of visualization. He assumed two types of time: one was underlying linear discrete or continuous time models, and the other was an event-based time model. For the first model on time, visualization was used as a categorization criterion, and resulted in static visualizations and dynamic visualizations. He discussed the static representation from conventional time visualization methods, such as a sector graph, bar chart and circle graph to multivariable temporal visualization, such as ThemeRiver (Harris et al., 2000) (Carlis and Konstan, 1998; Weber et al., 2001), Spiral Graph, Calendar View (Wijk and Selow, 1999), Lexis Pencils (Brian and Pritchard, 1997) and Wormplot (Matthews and Roze, 1997). An axis-based approach was extended as the time wheel (Treinish, 2003) and used to represent multivariable temporal data as well. The other type of time visualization was the dynamic approach. In his discussion, interval data and discrete time were treated separately to suggest a smooth, dynamic representation. Lastly, he reasoned that event-based time visualization played an important role in the field of simulation, giving details of the virtual environment. The categorization criterion of his approach was the combination of time and visualization.

### 3.3.6 Geo-exploration approach by Andrienko and Andrienko

Andrienko and Andrienko (2003) considered the spatio-temporal visualization from two aspects: one was the type of spatio-temporal data, the other was the type of task. For spatio-temporal data, three types were distinguished according to three kinds of changes, e.g. existence change (object), change of spatial properties (location), and changes of thematic properties expressed by values of attribute (attribute). They reviewed the data framework of Bertin (1983) and Peuquet (1984) and designed their operational tasks typology based on reviews of geo-visualization techniques and tools for spatio-temporal data (Figure 3-7). According to their discussion, they reviewed the exploratory techniques which were applicable to all types of data, such as query, map animation, focusing, link, and arranging views and map iterations. They discussed different techniques of how to achieve various tasks according to their task typology (shown in Figure 3-7).

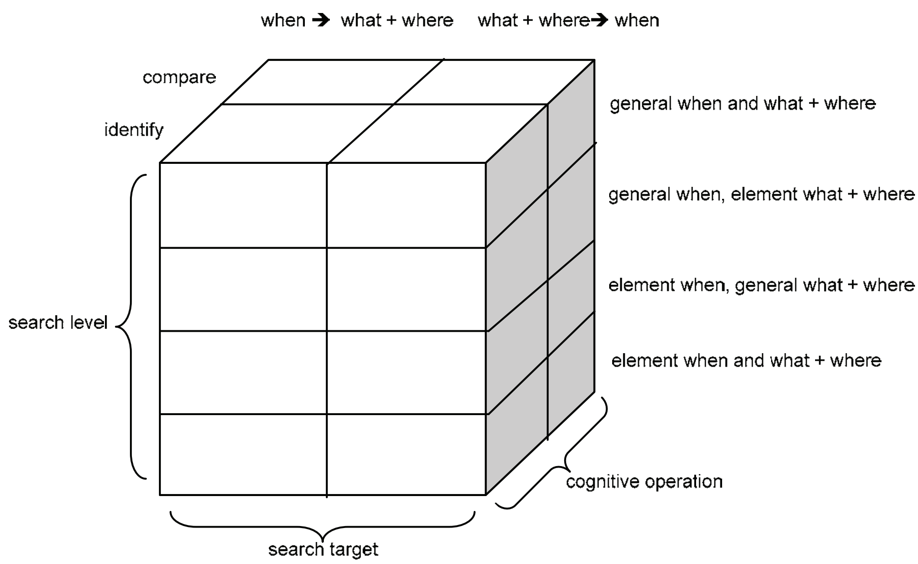



**Figure 3-7. Operational tasks typology by Andrienko and Andrienko (2003).**

### 3.3.7 Visualization process approach by Daassi et al.

Daassi et al.'s (2004) approach was based on Chi's (2000) data state reference model, with data replaced by time data. Related to the four data stages, there were four time data stages, e.g. time, point view of time, time-space, and point of view on time-space were distinguished to structure the process of time visualization. Figure 3-8 shows a comparison of Chi's data state reference model (Figure 3-8a) and how it was applied in time data by Daassi (Figure 3-8b). An example is shown following the four time data stages in Figure 3-8b. The time step defined which time value will be visualized. In the point of time step, the transformation of time value was defined by which point of view of time was used, such as linear or cyclic, time unit, or other. In this case, time was considered as multi-granular and linear. In the time-space step, displaceable space of the time value was defined, and in this case, year, month, and day should be mapped on to the representation. In the point of view on the time-space, the perceptible forms of time were implemented. These forms must be studied according to the human perception of time. Based on the steps of the visualization process, Daassi et al. suggested a taxonomy model. Their approach was based on the possible point of contact between two visualization processes, one being the temporal domain, and the other one the structural domain. In fact, the categorization criterion of their approach was a combination of time and visualization (i.e. how to address the point of view on time in visualization space).

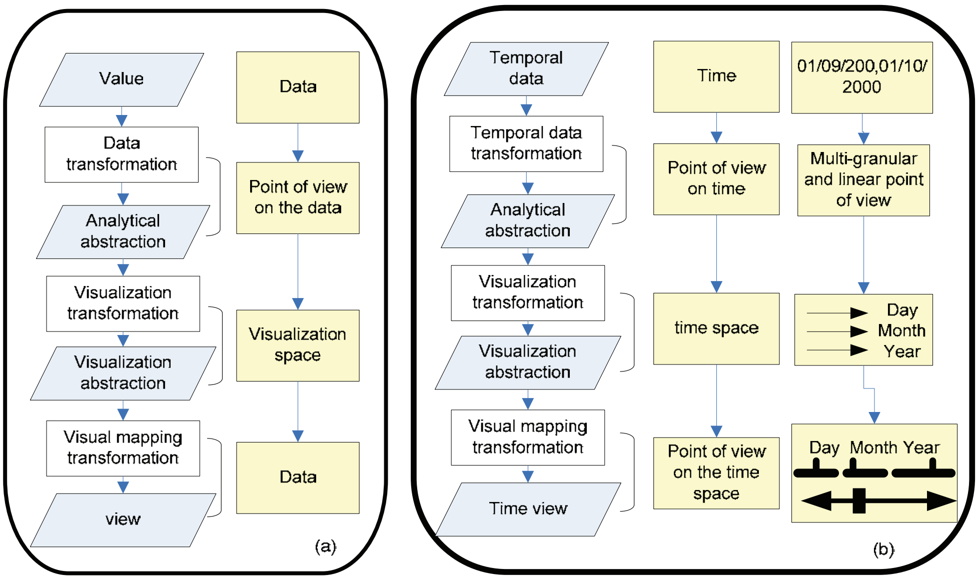



**Figure 3-8. a) Chi's (2000) data state reference model; b) Chi's model extended with time by Daassi et al. (2004).**

### 3.3.8 Combination approach by Aigner et al.

Aigner et al. (2007) took a more generic approach. They discussed temporal visualization based on a time-oriented framework. Their framework suggested a systematic view on three practical questions, so that users and researchers could find an easy entry to the ideas. The three questions were:

- What are the characteristics of the time axis?
- What is being analyzed?
- How is it represented?

Accordingly, the categorization criteria were: time, data and representation. A detailed taxonomy model based on these three criteria is shown in Figure 3-9 and examples of temporal visualization are discussed according to their framework.

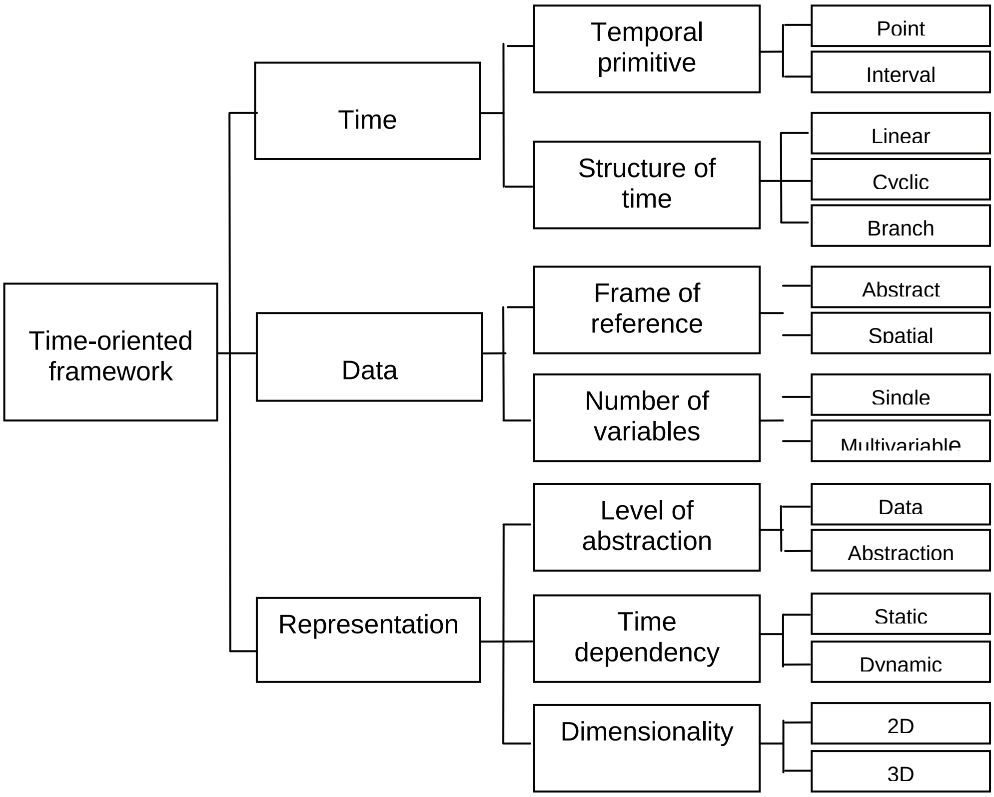



**Figure 3-9. A detailed taxonomy model based on three categorization criteria by Aigner et al. (2007).**

### 3.3.9 Summary of taxonomies of time visualization

Many researchers have discussed the visualization methods and suggested a taxonomy. The different categorization criteria could be captured in our keywords for a general approach to visual problem-solving, namely: data, user tasks, and visualization. Following the above taxonomy model (see Table 3-2) for time visualization, time is introduced, together with data, tasks and visualization as categorization criteria. Daassi et al.'s approach is named as a type of process, but the application of the process is based the view of time and the visualization process. In fact, this taxonomy could be classified as a combination of type of time and type of visualization. A summary of taxonomies for time visualization is listed in Table 3-3.

| | Type of data | Type of tasks | Type of visualization | Type of time |
|---|---|---|---|---|
| Vasiliev (1997) | | | x | x |
| Silva and Catarci (2000) | | | x | x |
| Muller (2003) | x | | x | x |
| Andrienko et al. (2003) | x | x | | |
| Daassi et al. (2004) | | | x | x |
| Aigner et al. (2007) | x | | x | x |

**Table 3-3. A summary of taxonomies for time visualization.**

Even though several authors may have a cross in the same column of Table 3-3, they can still be considered as different, as illustrated in Figure 3-10.

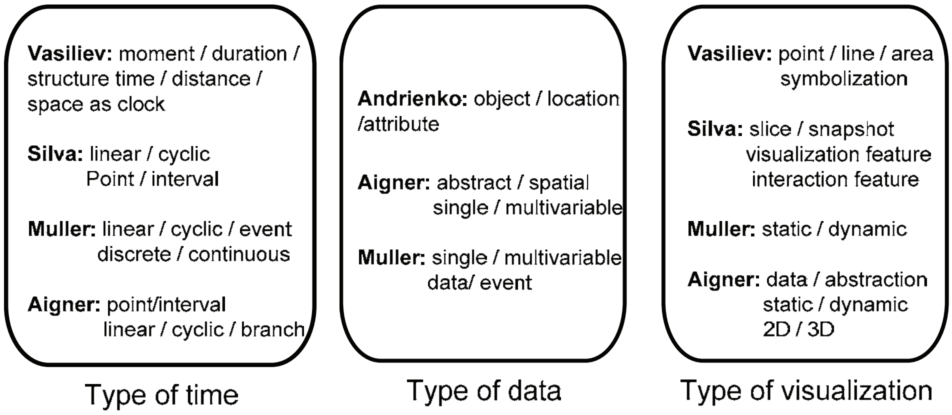



**Figure 3-10. The different classification content in the same column in Table 3-2.**

Table 3-3 shows the criteria of taxonomies in time visualization. Most of them are driven by the type of time and type of visualization. The type of user task is only considered by Andrienko et al.'s approach. The above discussions increase our understanding of how to use visualization to gain a better insight into temporal data, but they do not make clear which temporal visual representations are suitable for which task. In the next chapter, the time-space combined with the time theory will be defined for this research. The time theory is a time framework discussed from four perspectives: time, data, user task and visualization. It is the theoretical foundation for this research work. Based on the time theory, I will propose how to structure a time-space. The guiding question will be how to address different types of data; how to answer the questions in time-space will be discussed.

# Chapter 4 Time-space: approached from a temporal visualization concept

## 4.1 Introduction

There is an urgent need to understand the changes in our society and this can be supported by continuously recorded new data. However, the understanding of time, and the more specific understanding of the temporal component in geodata, is only improving slowly. There is still no single view on a theory related to temporal geodata, nor are there software tools widely available to deal with such data.

The choice for a time-space approach, as discussed in Chapter 3, is explained by the need for an ‘easy way’ to explore and analyze the huge amount of spatio-temporal data from an alternative viewpoint. Before a potential ‘entry’ via a time-space is described, it is necessary to look at the temporal visualization concept, to explain how temporal data should be structured, what kind of temporal questions could be addressed in time-space, and how temporal visualization represents the data and supplies an exploratory environment for users to determine answers to the questions posed. This will be discussed from a theoretical viewpoint based on the combination of earlier discussions about time (in Chapter 2) and of visualization theories in GIScience (in Chapter 3).

To ensure that the temporal visualization concept has practical value, a user study was carried out. A questionnaire was designed and distributed to potential users who major in GIScience. It contained questions on the kind of temporal data they deal with, what kind of temporal questions they have, and what they thought about temporal visualizations. Their feedback assisted in structuring the temporal visualization concept from a user-requirement perspective. Based on these findings existing temporal visualizations will be reviewed here, and from their limitations a new approach for temporal visualization will be discussed in Chapter 5.

## 4.2 Temporal visualization concept

The suggested structure for the temporal visualization concept is based on previous discussions about time and visualization theories. The scheme shown in Figure 4-1 (adopted from Figure 3-1) is used as a guideline in discussing this framework.

Similar to Chapter 3, the temporal data and temporal user tasks are discussed. This is because a different temporal view on the data and/or tasks might require different visualization approaches. In time-space, the visual representations show the data’s temporal characteristics, temporal distribution or temporal trends. Temporal interactive tools support the user in interactive tasks, such as finding a temporal location or identification, or comparing moments or events.

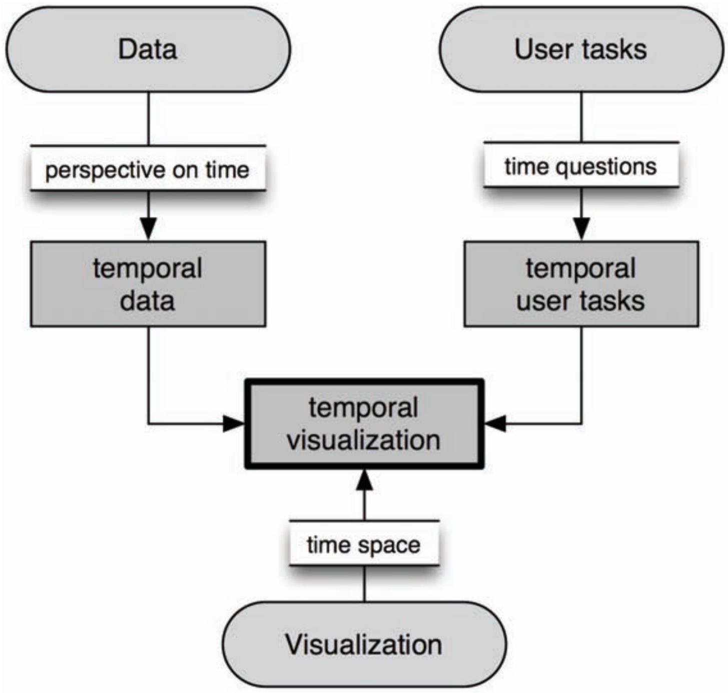



**Figure 4-1. Visual problem solving: a temporal perspective.**

- ***Temporal data***

How to deal with temporal data is closely related to the different views of time. These views are based on human cognition and perception of time. The diverging viewpoints are found in many disciplines such as philosophy and physics, and even in GIScience (reviewed in Chapter 2). However, there are also notable similarities between the views, particular between the notions of linear and cyclic time, absolute and relative time, and discrete and continuous time. In Chapter 3, these different views of time were used as criteria for a taxonomy to discuss time visualization. These different views on time should be taken into account in time-space because they describe how temporal data are abstracted and how different temporal questions are answered.

- ***Temporal user tasks***

Solving a problem can be split into a set of user tasks, which can then be translated into separate questions. Complicated questions can be further split into elementary questions. These are composed out of ‘atoms’, such as ‘what’, ‘when’ and ‘where’. In other words, all questions can be converted into a set of atoms and provide a taxonomy to structure all the questions. Here they will be used to analyze the temporal user tasks.

A phenomenon's temporal characteristics are defined by changes. Different types of changes can be distinguished (Blok, 2005; Andrienko and Andrienko, 2006):

- existential changes (appearing and disappearing)
- changes in spatial properties (location, shape, size, orientation, altitude, height, gradient and volume)
- changes in thematic properties, including qualitative changes, and changes in ordinal or numeric characteristics (increases and decreases).

This change taxonomy links well to Peuquet's framework of spatio-temporal data. Starting from time-space (when), the corresponding questions are:

when >> object (whether): existential changes

when >> location (where): changes in spatial properties

when >> attribute (what): changes in thematic properties.

The taxonomy could also be related to Bertin's question types, because besides object, attribute and location, time can also be considered as one of the data components.

Another approach is based on the nature of the temporal questions asked (MacEachren, 1995; Kraak et al., 1997). They distinguished seven elementary time query types. These address the existence of an object (if?), its location in time (when?) its duration (how long?), its temporal texture (how often?), its rate of change (how fast?), the sequence of entities (in what order?), and synchronization (do entities occur together?). Furthermore, at a higher level of abstraction, temporal distribution and temporal trends should also be taken into account. Questions relating to these patterns are often complex and consist of combinations of elementary questions.

With the above discussion in mind, I propose a combined approach to temporal user tasks. It is a combination of time query, reading levels and the change taxonomy (Figure 4-2) and will be called Temporal Task Space (TTS). There are several arguments for making this combination. In Figure 4-2a the time query is combined with the change typology, which in itself is directly related to the changing data component (the object, location and attribute) as explained above, for example (TQ time query; C change):

(1) How long did the hurricane last?
TQ C

(2) When did the car pass the crossing?
TQ C c

(3) In what order did the ownership of the parcels change?
TQ C c

Questions can be put forward for each matrix cell in the figure (e.g. the above questions (1), (2) and (3) can be found in Figure 4-2a). In Figure 4-2b, the relation between temporal questions and reading levels is given. Not all the time queries can be linked to all the reading levels, as can be seen in Figure 4-2b (Li and Kraak, 2008), which shows a summary of the reading levels for different time queries.

Figure 4-2c links the reading levels with the change typology and is related to the complexity of the question. Do the changes occur only with a single object or for a whole set? The whole matrix can be filled in and has been discussed from a spatial and temporal perspective by Koussoulakou and Kraak (1992).

The reading level of a time query (4-2b) depends on the reading level of the data component (4-2c). For example, in question (2) above, if one car (object on elementary level) is involved, the reading level of the time query must be on an elementary level as well. If several cars (object on intermediate level) are involved, the reading level of the time query must be on an intermediate level too. Similar examples can be given for the different reading level of location components. If only one crossing is involved, the reading level of the time query is on an elementary level, but if several crossings are involved, the reading level of the time query must be on an intermediate level too. In the TTS, the reading level is defined on the data components (change) only. To answer the temporal questions at each level, a representation which includes elementary and intermediate levels in time-space is required.

The combined scheme in Figure 4-2d allows a flexible approach to deal with temporal questions and helps to structure the temporal user tasks. It links the different questions efficiently to the data (type of change), reading level and time query in detail. It is possible to divide complex questions into simpler questions and enter the diagram from different sides. For example, the question ‘what is the temperature trend in location A’ defines the location component on an elementary level for a trend query; the question ‘what is the difference between temperature trends in location A and location B’ defines the location component on an intermediate level for a trend query, while the question ‘what are the trends of the whole research area?’ defines the location component at an overview level for a trend query.

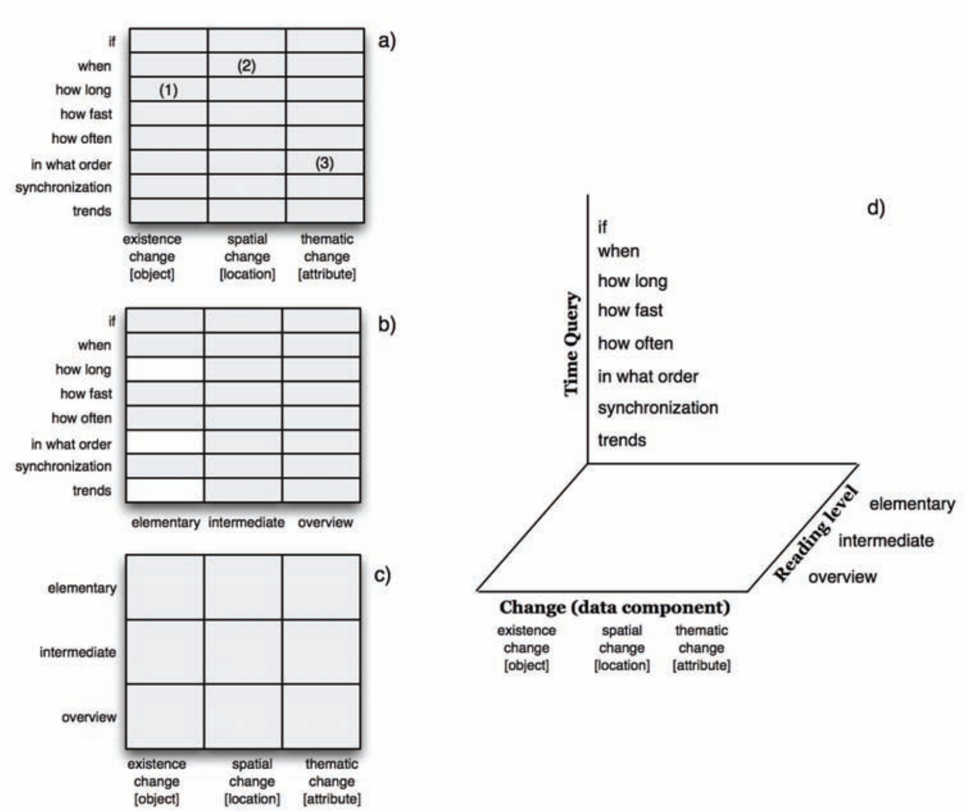



**Figure 4-2. Temporal Task Space (TTS). a) Time query versus change typology; b) time query versus reading levels; c) reading levels versus change typology; d) combined approach to the temporal user tasks.**

As examples, typical questions for each block of the task space are listed in Appendix . A few additional remarks are needed:

- Not all the blocks of TTS hold a question, e.g. no sensible question can be formulated for the block defined by 'How fast' (Figure 4-2d, time query axis) and 'Object' (change axis) and 'Elementary' (reading level axis).
- The object, location and attribute data components along the change axis could be combined in many different ways to represent more complicated questions. For example, 'did the event happen in location A' is a question which combines 'If + Object + Elementary' with 'If + Location + Elementary', so the existing change and spatial characteristics are queried at the same time.
- The reading levels only act on the data components (change), since the reading level of the time component is defined by the combination of reading level and data components, and the reading level of time query in nature. For example, for the question 'does the object A exist?' (If + Object + Elementary), the overview of time reference should be checked to find the answer. The question could be further defined at an elementary or

intermediate level if a time instant and interval was part of the question, e.g. ‘does the object A exist now (elementary level)?’.

In Chapter 3, the direction of temporal question was formulated with a constraint and a target, based on Andrienko and Andrienko’s work. In summary, the temporal user tasks are based on two kinds of questions:

- When what + where + object
- What + where + object When

For example, the question ‘when could be distinguished as ‘When did you visit China?’ (What + where + object When) and ‘Where were you in 2007?’ (When what + where + object). This principle, in a slightly modified way, is also used in TTS (see Figure 4-3). Arrows could be inserted into the TTS to show the direction of questions. The ‘in’ arrows show the constraint of the question and the ‘out’ arrows show the targets of the questions. For example, the question ‘when did the car pass the crossing?’ would have an ‘in’ arrow from the data component, and an ‘out’ arrow from the time query (whether + (or where) + (or what) ➔ when). Questions like ‘which car passed the crossing at 8 pm?’ or ‘which crossing is passed by the car at 8 pm?’ would give you ‘in’ arrows from the time query, and ‘out’ arrows from the data component (meaning: when ➔ whether + (or where) + (or what)).

As an example, the question: ‘when was the car in this street?’ is shown in Figure 4-3a in 3D view. A 2D view for same question is shown in Figure 4-3b, because all the data elements in this question are in the elementary level only. For ‘where was your car yesterday?’, Figure 4-3c shows this question in TTS in 2D view. The TTS in Figure 4-3a is turned around from the TTS in Figure 4-2d for a much clearer view in a 3D environment.

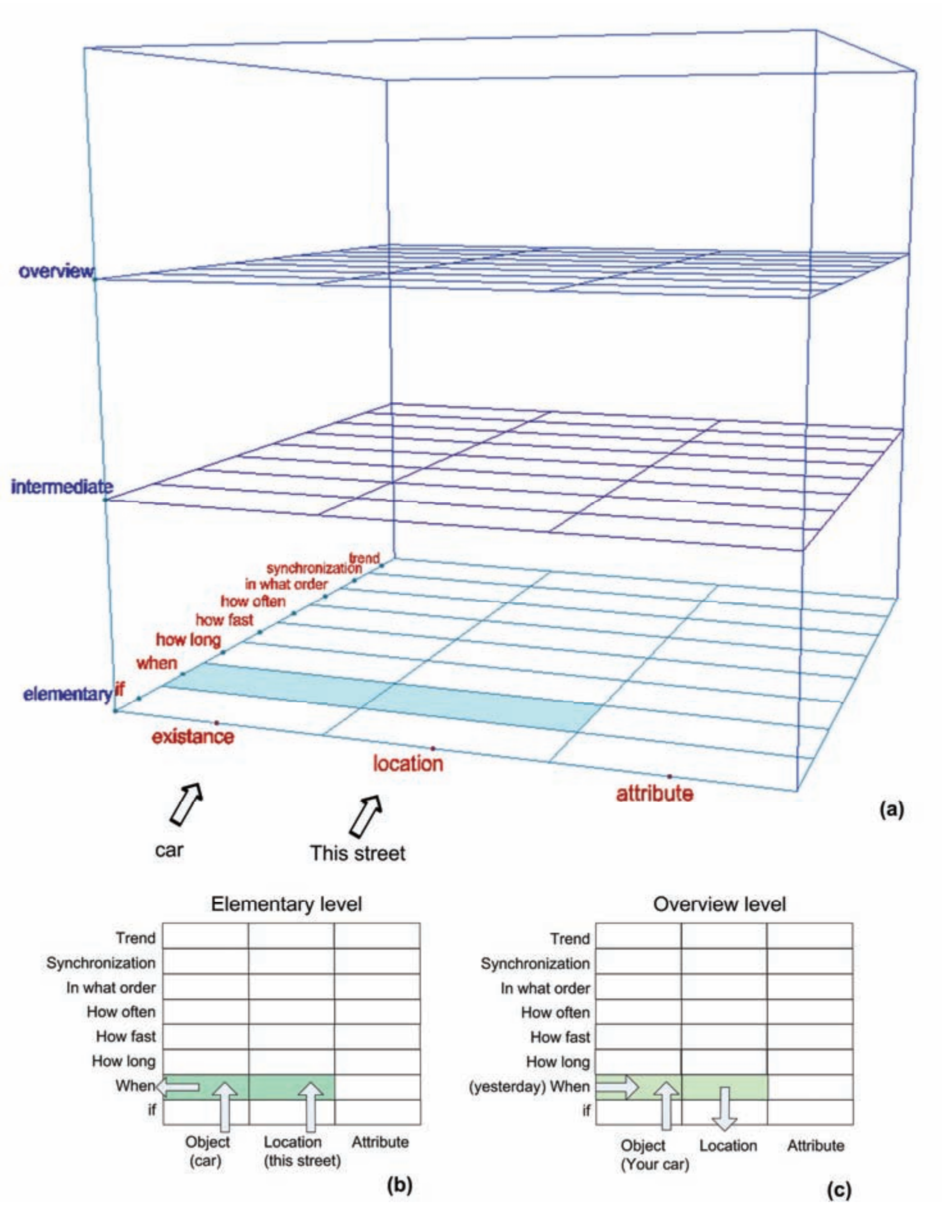



**Figure 4-3. Examples of how the temporal questions are positioned in TTS: a) question 'when was the car in this street?' in TTS; b) 'when was the car in this street?' in the 2D view of TTS; c) 'where was your car yesterday?' in the 2D view of TTS.**

For each temporal question, a distribution (region) could be defined by covering one or more blocks in TTS. The direction of arrows, which shows the direction of questions, can distinguish diff**erent kinds of questions with the same distribution in TTS. In other words**, entering and exiting from one side or multiples sides of the TTS indicate the target and constraint of questions. Some questions which are discussed as examples in the study of Andrienko and Andrienko (2006) will be used to show how these temporal questions are addressed in TTS:

1. Where were the most burglaries last month? (Figure 4-4a).
2. Compare the proportions of children in district X and district Y with time (i.e. find relations between the characteristics corresponding to the references ‘district X’ and ‘district Y’) (Figure 4-4b).
3. Describe the variation of the proportion of children in the whole country (Figure 4-4c).
4. Which storks were near Lake Victoria and when (Figure 4-4d).
5. Which storks were near Lake Victoria on 1st September (Figure 4-4d).

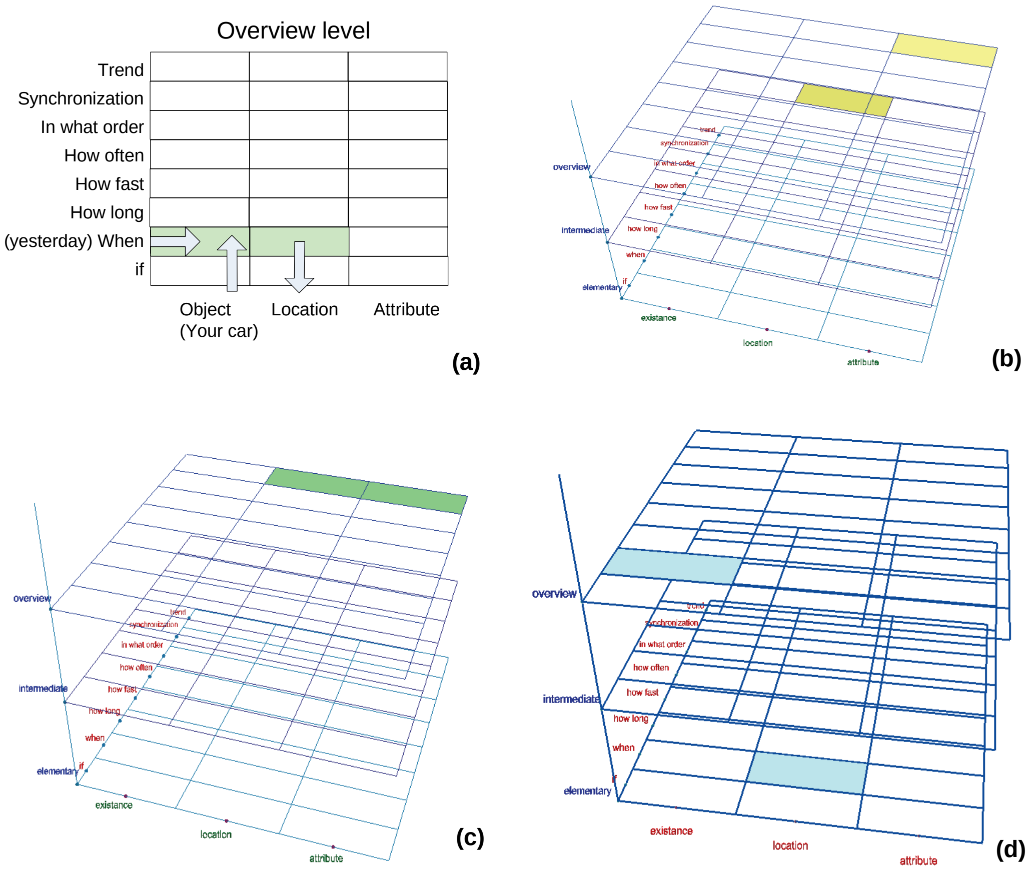



**Figure 4-4. Examples that show how user tasks are located in TTS.**

For question 1, a 2D view is used because all the data elements for this question are in overview level only. To find the answer, we need an overview of the whole region. For question 2, district X and district Y are defined on an intermediate level, but the proportions of children are defined on an overview level and the time query is about trends. For question 3, both the variation of the proportion of children and the whole country are defined on an overview level, while the trends query is part of this question.

Questions 4 and 5 have the same distribution in TTS, because the data components involved are the same. However, these two questions could be distinguished in TTS by the arrows, which would show the different direction of the questions due to the role taken by time, e.g. constraint or target.

All actions in TTS (questions and answers) are closely related to the views of time in different applications. For example, the question ‘When did it rain?’ could be answered as ‘a while ago’ (relative time) or ‘between 10:55 and 11:14 08/08/2009’ (absolute time). It could be answered at different scales as well, such as ‘yesterday afternoon’ or ‘in the last half-hour’. Scale might also be defined if a phenomenon is considered to be linear or cycli, e.g. on an annual scale, monsoons return every spring (cyclic), but in April it always rains (linear). The question ‘how does temperature change over time?’ would require a continuous answer, but since temperature is measured at certain intervals, the answer is discrete.

- ***Temporal visualization: a combined approach with temporal data and temporal user tasks***

Visualization is about representation (how should the data be displayed?) and about interaction (how can the data be queried?). There are many possible temporal representations, such as 1-dimensional, 2-dimensional or 3-dimensional, static or dynamic, single view or multiple views. However, it is not a trivial task to select the proper temporal visualization, even when we assume that the character of the temporal data is known. Temporal visualization also depends on the kind of temporal user task that is at hand. This section looks at visualizations from these two perspectives.

**Temporal data and visualization**

Temporal data can be considered to be linear or cyclic, continuous or discrete, absolute or relative, and it can occur at single or multiple scales. In relation to the task, each view on time might have different requirements for temporal visualization. For example, the question ‘how did the city expand?’ could be answered with discrete multiple views showing a set of snapshots of the city’s extent. Alternatively, an animation could be used to answer the same question in a continuous view. The dynamic nature of the animation could also attract attention to other aspects of the expansion. Based on the characteristics of the data, a linear or cyclic representation might be appropriate. Both representations could express either continuous or discrete time. Even though there might be a straightforward solution in selecting the visual representation, it can often be useful to try other visualizations as well, because an alternative view might reveal patterns or aspects of the data that might otherwise remain hidden in the straightforward solution.

The different temporal visualizations, classified according to their view of time, are:

- **Linear and cyclic**

In most visualization methods, time is considered to be linear and one-dimensional. Silva and Catarici (2002) did a survey and discussed many linear, time-oriented visual representations. Most linear temporal visualizations are based on the principle of the timeline. The cartographic animation is probably the most well-known example. Other examples are the Lifeline (Plaisant et al., 1998), ThemeRiver (Harris et al., 2000), the Perspective Wall (Mackinlay et al., 1991) and the TOSM (Temporal ordered space matrix) (Kraak and Vlag, 2007). Other solutions apply the third dimension as the time axis. A typical geo-example is the Space-Time Cube (Hägerstrand, 1970), while the Lexis pencils (Brian and Pritchard, 1997) originated from the information visualization domain. In some representations, time is considered discrete and shows a list of 'snapshots' at different points in time, such as the Temporal PCP (Edsall, 2003) or Pixel bar charts (Keim et al., 2002).

The frequent occurrence of cyclical representations of time is a reflection of its close association to nature and the rhythms in everyday life (Hornsby and Egenhofer, 2002). Examples of these representations are the polar coordinate system (Chen, 2005), and a temporal sector chart (Weber et al., 2001). Sometimes the representation is based on the clock and calendar, such as the calendar view (Wijk and Selow, 1999). In Chapter 2, more methods about linear and cyclic time visualization were listed in figures 2-8 and 2-9. However, methods for analyzing branching time are still rare (Aigner et al., 2007). Aigner (Figure 2-11u) discussed a solution for branching time, named PlayingLines (Aigner et al., 2005) which is in kinds of application like project management or medical treatment planning.

Interactive tools, based on the timeline, are popular in many applications, such as the animation controller. Figure 2-11r shows a linear temporal browser, named pointwise temporal object browser, which works on several temporal units. Figure 2-11s is an example which includes a non-linear and linear temporal browser which could query time in different granularities. For cyclic time, Figure 2-11t shows a combination of linear and cyclic query tools that simultaneously query cyclic time in the wheel and linear time in the timeline.

- **Discrete and continuous**

Another view on time is discrete time versus continuous time. The question is if continuous phenomena can really be captured? There is no doubt that some attributes change continuously over time, but are always observed in a discrete way because the data collection techniques applied are always 'time'-scale dependent, e.g. a temperature recorder. The measurement results could be shown as Figure 2-10f.

Table 4-1 shows the classification of many temporal visualization methods, which are distinguished by their continuous or discrete nature of time, as illustrated in Chapter 2 (figures 2-10 and 2-11). It should be noted that some discrete time is visualized on a continuous reference, e.g. in Figure 2-10h, each vertical axis represents a time point. The space between two axes is meaningless and there is no value on the line between two axes. Another example can be found in Figure 2-10y. Here each TimeTube represents a situation at a certain moment in time, but the space in between has temporal meaning. These are discrete references for discrete representation. Figure 2-10l shows an example of discrete representation in a continuous reference. Bars show statistical values according to a certain time unit, but the reference (x-axis) is continuous, as in Figure 2-10f. In the other words, the representation is discrete according to time units in a continuous temporal reference. Both the continuous and discrete representations can be useful depending on the application. In general, the discrete temporal representation is useful for showing the situation at a certain moment. This representation can show not only the moment of collection in a discrete format, but can also be used to show the statistical results, such as sum and average, which are easy features to identify and compare. Many static maps are examples of this kind of representation. The continuous temporal representation has a continuous temporal reference, which helps in locating temporal questions (such as when, in what order), and trends, and supports the exploration user tasks, such as identification and comparison.

Discrete interaction is realized by selecting a time instant in the visualization environment. For example, in Figure 2-11t, a discrete time instant can be defined by selecting the required temporal granularity based on a time wheel reference. The timeline in Figure 2-11t is a typical example of a continuous interactive tool to play the animation. The notion ‘continuous’ is of course relative, because the granularity depends on the number of snapshots available in the animation. For example, the timeline in figure 2-11t can be used to show phenomena year by year, but not in greater detail. A more interesting example can be found in Figure 2-11r. It looks as if the temporal browser is based on a continuous linear slider, but in fact it is only based on a discrete time instant in each year, month and day that can be defined.

| | **Representation** | **Interactive tools** |
|---|---|---|
| **Discrete** | 2-10h, 2-10i, 2-10j, 2-10k, 2-10y, 2-10m, 2-10s, 2-10y, 2-11b, 2-11d, 2-11e, 2-11g, 2-11m, 2-11n, 2-11o, 2-11q, 2-11p | 2-7, 2-11u, 2-11r |
| **Continuous** | 2-10a, 2-10b, 2-10c, 2-10d, 2-10e, 2-10f, 2-10g, 2-10l, 2-10n, 2-10o, 2-10q, 2-10p, 2-10r, 2-10t, 2-10u, 2-10v, 2-10w, 2-10x, 2-11a, 2-11c, 2-11h, 2-11i, 2-11j, 2-11k | 2-11s, 2-11u |

**Table 4-1. The classification of the temporal visualizations shown in figures 2-10 and 2-11 based on their discrete or continuous temporal nature.**

- **Absolute and relative**

Linear and cyclic time and discrete and continuous time result in different temporal representations. This is not so obvious for absolute and relative time. Both absolute (temporal instant or interval) and relative (event) time are shown by regular time units, as an absolute reference in most representations. Applications such as those in Figure 2-10a-c project event time with respect to an absolute temporal reference. Figure 2-11I shows a relative representation with an absolute cyclic reference. Minard's well-known map of Napoleon's 1812 Russian campaign (Figure 2-10v) is an example which presents relative temporal information.

Most interactive tools work based on absolute time, not relative time. There are many applications which require detecting the temporal relationship between events. Beside absolute temporal visualization, the relative visualization is necessary for both representation and interactive tools and will be discussed in more detail at the end of this chapter. Table 4-2 shows a classification of visualization according to absolute and relative time (according to figures 2-10 and 2-11, Chapter 2).

| | Representation | Interactive tools |
|---|---|---|
| **Absolute** | 2-10d, 2-10e, 2-10f, 2-10g, 2-10h, 2-10i, 2-10j, 2-10k, 2-10n, 2-10m, 2-10o, 2-10p, 2-10t, 2-10u, 2-10s, 2-10t, 2-10w, 2-10x, 2-10y, 2-11a, 2-11b, 2-11c, 2-11d, 2-11e, 2-11f, 2-11h, 2-11j, 2-11k, 2-11l, 2-11m, 2-11n, 2-11o, 2-11q, 2-11p | 2-7, 2-11u, 2-11r, 2-11s, 2-11u |
| **Relative** | 2-10a, 2-10b, 2-10c, 2-10l, 2-10q, 2-10r, 2-10v, 2-11i, | |

**Table 4-2. The classification of the temporal visualizations shown in figures 2-10 and 2-11 based on their absolute or relative temporal nature.**

### Temporal user tasks and visualization

Even though the selection of a graphic representation is based upon the nature of the data, the user task also plays an important role because the graphic representation has to answer questions at the end. For instance, the question ‘When did these countries get their independence?’ might require different representations depending on the focus of the question. A timeline with names and years will do if the focus is on the temporal distribution, but if the user is also interested in the spatial distribution, a world map with labels indicating the year of independence could be a more suitable representation. If both items are of interest, a space-time cube could be a solution. If the user is also interested in the season of independence, a graphic representation would be able to handle both linear and cyclic time and the time wave might be a solution.

TTS combines several approaches which are well accepted in the visualization domain, and these have been extended temporally. The aim is to offer a general view on temporal user tasks, structured by changes in the data component, different reading levels and specific time queries. These elements can be combined flexibly, and can summarize most user tasks. They also bridge the gap between visualization theory and the users' applications. If users can understand this approach, TTS can indeed help to structure their data and tasks according to visualization theory. The next section discusses a user evaluation study aimed at gathering information on users' insights and experiences with temporal data, temporal user tasks and temporal visualizations.

In general, visualizations include representation and interaction tools. The representation locates the temporal data and shows the temporal characteristics, temporal pattern and temporal relationships, and the user can identify and compare the temporal information with the interaction tools. Each temporal visualization method has specific capacities for answering temporal questions and will have a characteristic distribution (region) in TTS, e.g. Figure 4-5a shows a distribution of the Lifeline (in Figure 2-10a).The Lifeline represents a person's existence. Different attributes, such as problems, diagnosis and complaints is viewed on a timeline to answer the temporal questions, such as 'if', 'when', 'how long', 'in what order', 'how often', synchronization and trends. Figure 4-5b shows a distribution of Figure 2-10f in TTS. This typical representation for temporal variable data is good for answering all the questions of attribute change not only at an overview level, but also at the intermediate and elementary levels. The synchronization question is easier to answer by replacing the curve with a line to avoid the overlap under the same reference. The distributions in TTS show the capacity of a particular temporal visualization to answer temporal questions.

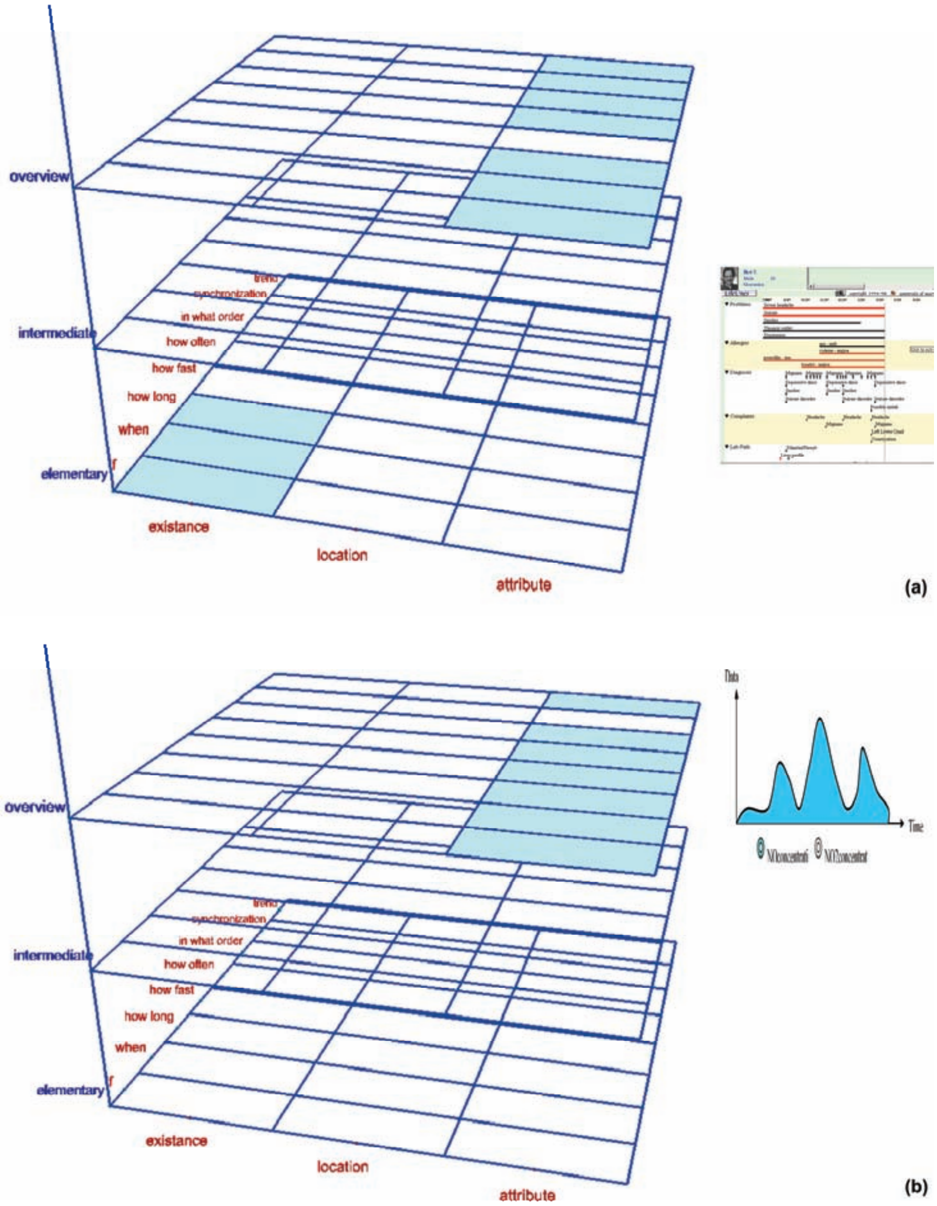



**Figure 4-5. Two examples of how the time visualization relates to the TTS: a) lifeline in TTS; b) curve graph in TTS.**

Executing user tasks is often an interactive and iterative process which requires the close combination of temporal visual representation and temporal interactive tools. To assist in answering questions, time-space should not only supply the proper representation to locate the temporal data, but also allow the user to identify single or multiple points in time, or points at periodic intervals, or define intervals of certain length in both a linear and cyclic format. Some people have experience with this approach, e.g. Koike et al. (1997) with TimeSlider, which can interact with continuous multiple scales in both linear and non-linear time. Edsall et al. (1997) reported an experiment with a time wheel query device in the TEMPEST system, which can interact with both linear and cyclic time.

In this section, temporal data, temporal user tasks and temporal visualization from the perspective of visualization theory have been discussed. However, the user's perspective is also important. We need to know whether the user can understand the theoretical methods and what kinds of requirement the users have in their applications. These aspects are described in the next section.

## 4.3 Users and applications in TTS

A questionnaire was designed, based on the above discussion of the temporal visualization concept, to collect requirements from users working in GIScience on temporal problems and to assess if the framework makes sense to them.
The aim was to answer the following questions:

1. What kinds of temporal data are used in applications, according to the different views on time?
2. What temporal questions did the users have, and can these be structured in TTS?
3. What kinds of temporal visualizations are required by the users, according to the temporal data and temporal user tasks?
4. Can the users understand the different views on time and elements in TTS?

A questionnaire (see Appendix Ⅱ) was distributed to 40 PhD students and 40 MSc students in ITC, the Netherlands, the Institute of Tibetan Plate Research (ITPR) and Wuhan University (WU), both in China. The students were all majors in GIScience, working on problems in natural or water resources, urban planning, and Earth observation applications. They were asked to answer the questions with respect to the temporal nature of their own research problem. Their feedback (awareness indicators and needs) was analyzed to answer our four questions and was translated into specific temporal user tasks. This was the first part of the user study conducted. The results of this evaluation were used to design three more evaluations which are discussed in detail in Chapter 7.

**Temporal data in applications**
To gain insight into the temporal characteristics of the data, two questions were formulated (see Appendix II). Firstly, were the researchers aware of the temporal characteristics of their data before they started to work with it? The result is shown in Figure 4-6: most people (89%) knew the temporal characteristics of their data. This was especially true for those with a major in natural or water resources because the phenomena of their research topic changes according to the regular rhythms of nature. These students expected to find certain temporal patterns in their data and needed temporal visualization

to see the changes. However, 11% of the students had no idea of the temporal characteristics of their data. For them, a visualization method that provides alternative views of their data, with different temporal characteristics, is needed to raise their awareness.

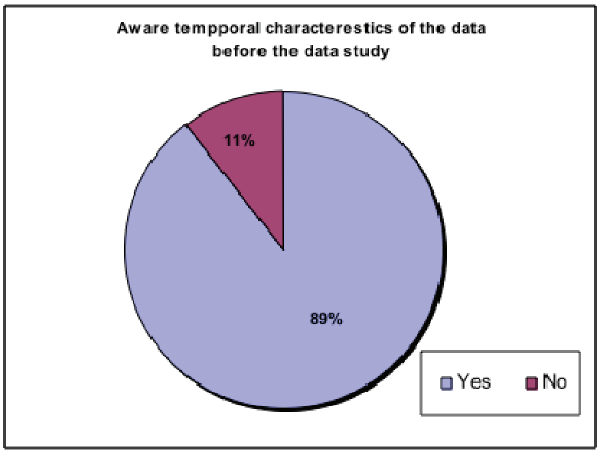



**Figure 4-6. Results of whether the researchers were aware of the temporal characteristics of their data before they started working on it.**

The second question aimed to find out what kinds of temporal characteristics can be found in various applications. According to the results shown in Figure 4-7, we see that all kinds of temporal characteristics are experienced. About half (48%) of the applications dealt with both the linear and cyclic nature of time (Figure 4-7a). Applications covered discrete and continuous time almost evenly (Figure 4-7b). When single and multiple time scales were compared, the latter had a distinct majority (69%) (Figure 4-7c). The relation between relative and absolute time offered a more varied view: 43% of the applications deal with absolute time, 19% with relative time and 38% with both kinds. Overall, this gives an impression of the various kinds of time in use.

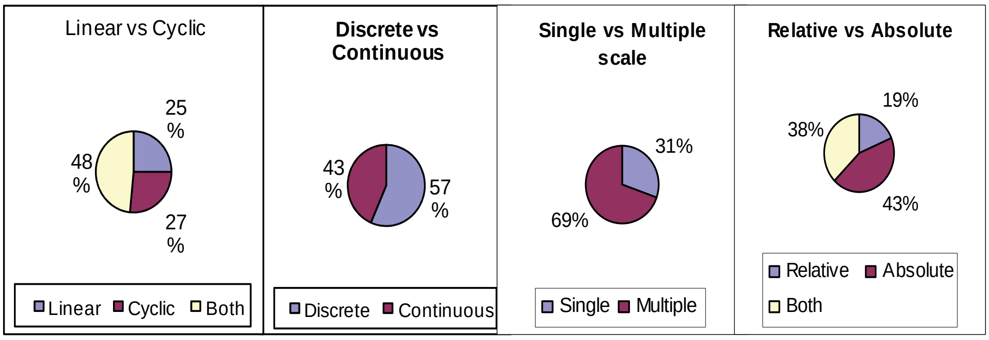



**Figure 4-7. The different kinds of time reported in applications: a) linear versus cyclic temporal data; b) discrete versus continuous temporal data; c) single versus multiple scale data; d) relative versus absolute time.**

**Temporal user tasks**
Structuring temporal user tasks is difficult because the varyious applications have multiple objectives. The students were given a brief introduction to the data and user tasks in visualization theory (object, location, attribute and time). Even though this approach is widely accepted in the visualization domain, it proved to be difficult for the students to understand. They sent in many questions after they had tried to answer this part of the questionnaire. We gave a supplementary explanation with examples to the students and then asked them to position their temporal research question in a table view (see Appendix II). 108 questions were collected from different applications; all these questions could be located in TTS. Examples were:

**Natural resources**
- When is the best season for mapping the distribution of bamboo? (when (cyclic) + attribute (elementary))
- What are the seasonal movement patterns of the giant panda in the Qinling Mountains? (trends (linear + cyclic) + object + location (overview))
- How many times does acacia bloom during a year? (how often (linear + cyclic) + object + attribute (elementary))
- Which kind of tree species has the longest lifespan? (how long (linear) + attribute (overview))

**Human geography**
- Did people migrate more in the 1980s than in the 1990s? And what was the reason? (when (cyclic + linear) + attribute (overview))
- When can we speak of the highest migration trend ever? (when (linear) + attribute (overview))
- What kind of people migrated first (educated, rich, poor, ...)? (in what order (linear) + attribute (overview))

**Water resources**
- How fast is a drought area changing over time (size)? (how fast (linear) + location (overview) + attribute (elementary))
- What chemical changes take place in this lake throughout the season?

Most questions include multiple changes involving several data components. In addition, some questions are so complicated that an iterative exploration process is necessary, e.g. ‘What is the spatial distribution of the giant panda when the acacia is blooming in the Qinling Mountains?’. In this case, the ‘acacia blooming’ should be identified in attribute space, the ‘when’ questions should be answered in time-space, and the spatial distribution in location space. It requires a temporal and another representation, and interactive tools can combine the parts of the question.

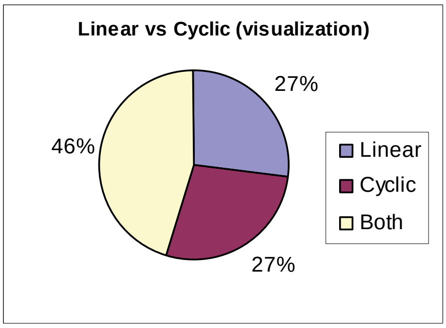
A further analysis of all the questions led to the table below. It shows that all kinds of changes in all the data components were observed and that, together with the time query, they all have representations.

| | | Data component (change) | | | |
|---|---|---|---|---|---|
| | | Object | Location | Attribute | Total no. of questions |
| Time query | If | 14 | 16 | 13 | 43 |
| | When | 26 | 28 | 33 | 87 |
| | How long | 12 | 10 | 16 | 38 |
| | How fast | 12 | 10 | 19 | 41 |
| | How often | 10 | 8 | 18 | 36 |
| | In what order | 19 | 9 | 20 | 38 |
| | Synchronization | 5 | 13 | 20 | 38 |
| | Trends | 23 | 8 | 22 | 53 |
| | Total of changes | 121 | 102 | 161 | Total: 384 |

**Table 4-3. Data components (change) of time queries from the students.**

### Temporal visualization

The questionnaire revealed that the majority of students would visualize their data (Appendix II), and proved that the temporal characteristics of the data influenced the type of temporal visualization chosen. This is why the diagrams in Figure 4-8 are very similar to those in figure 4-7a and 4-7c. Table 4-4 shows which functions (select, identify, locate) the students executed with the interactive visualizations in relation to the kind of time. This resulted in the requirements for temporal representation and in interactive tools that are both linear and cyclic on multiple time scales.



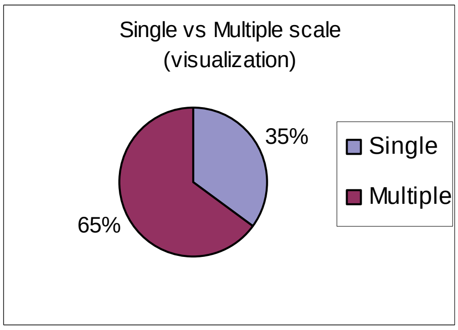




**Figure 4-8. The visualization of different types of time by the students.**

| | Linear | Cycle | Both | Single scale | Multiple scale | **Total in function** |
|---|---|---|---|---|---|---|
| Select time (interval) | 6 | 8 | 16 | 5 | 23 | 58 |
| Identify moment | 7 | 6 | 17 | 5 | 19 | 54 |
| Locate in time | 6 | 7 | 13 | 6 | 19 | 51 |
| **Total in time view** | 19 | 21 | 46 | 16 | 61 | 163 |

**Table 4-4. The relation between (interactive) functions and the kinds of time as used by the students.**

**Insight into the temporal visualization concept**

The last part of the questionnaire (see appendix II) tried to gain insight into the students' understanding of the time theory, based on temporal data, temporal user task and temporal visualization (figure 4-1). The different views on time were acknowledged and frequently used by most of the students in their research, however their awareness of temporal user tasks and visualizations varied, as Figure 4-9 shows. About half of them had difficulty understanding the TTS, although the user questions they supplied in response to the questionnaire did all fit properly into the temporal visualization concept as described. Face-to-face discussions with some ITC PhD students after they had filled in the questionnaire enable them to better understand the taxonomy of the temporal visualization concept. This shows that the temporal visualization concept is a solution to structuring research questions, but it does require time to learn how it works.

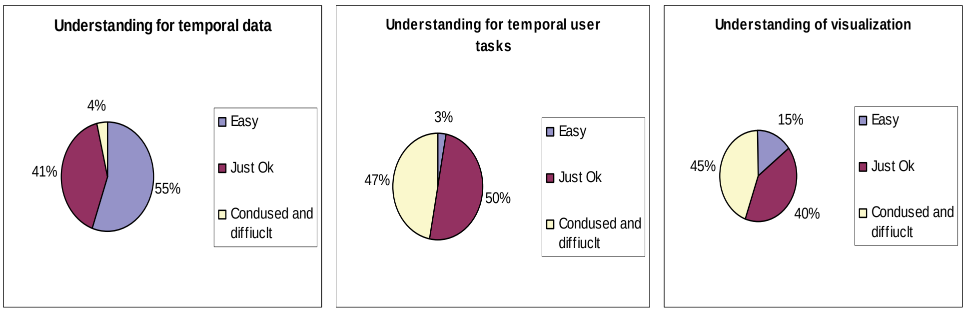



**Figure 4-9. Students' understanding of time theory: a) understanding of temporal data; b) understanding of temporal user tasks; c) understanding of temporal visualization.**

## *4.4 A summary of views on time-space*

This chapter aimed to discuss time-space from two perspectives: first from a temporal visualization concept based on accepted visualization theories, and second from users' requirements in applications. By combining these two aspects, the gap between theory and application can be closed if the following points are considered:

- **Linear and cyclic time**

There are many temporal visualization solutions for either linear or cyclic time. However, various applications require both linear and cyclic visualizations to explore different characteristics of their temporal data. A combination of linear and cyclic visualization methods is therefore necessary. Because most applications deal with time in different granularities, the visualization should be able to cope with multiple scales. However, existing visualizations only support limited time scales.

- **Relative time**

Relative time is important for understanding the temporal relationship of data. If we look at the question ‘what is the temporal relationship between event A and event B’, we could say B started 3 hours later than event B, or in a relative view, event B started halfway through event A. There are not many temporal visualizations available to deal with relative time.

- **Close integration of representation and interactive tools**

Executing user tasks is often an interactive and iterative process, supported by interactive tools in time-space. According to Shneiderman’s (1996) visual information seeking mantra, visualization techniques can be used to obtain an overview of data collections, zoom into interesting sections, filter datasets by comparing the data, and finally obtain details on demand. A specific exploration environment is required to carry out these tasks. For a temporal perspective, the temporal representation is used to locate the temporal data and show the temporal patterns and temporal relationships. To further assist in answering questions and starting from this representation, temporal interactive tools should allow the user to identify single or multiple points in time, or points at periodic intervals, or to define intervals of certain length in both a linear and cyclic format. For instance, the question ‘where is the country which became independent one year later than country B?’ is an example of when the user moves to location space because he/she needs to see spatial patterns next to temporal patterns. Therefore, one requirement for time-space is a close integration of temporal representation and temporal interactive tools to support an interactive and iterative exploration process. The different views of time apply to both representations and to interactive tools.

- **Coordinating time-space with location space and attribute space**

To explore multivariate spatio-temporal data and answer complicated questions, time-space should be properly coordinated with location space and attribute space. This could be supported by the coordinated multiple views (CMV) technique, which was discussed in Chapter 3. However, with a focus on time-space, supported by representational and interactive tools, the question of how to coordinate triple space remains. Starting from time-space, the driving question is ‘When . what + where + object’. It means both the instant and interval of time should be selected in time-space, and the results shown in linked views: the status of the object in the attribute space and its position in location space. To answer more complicated questions, coordinated elements should be joined for identification. There are the following combinations:

- When + where — what is the object and what happens at a certain location at a certain time
- When + what — what is the object and where does a certain situation happen at that certain time
- When + object — what happens with the object at a certain time
- When + where + what — what object are there with a certain value at a certain location and time
- When + what + object — where is the object with a certain value at a certain time
- When + where + object — what is the value of the object at a certain location and time

To discuss the above integration of coordinated elements in triple space, the operations should work not only in time-space but also in location space and attribute space.

In Chapter 5, I propose how to close four of the gaps identified above by introducing a new temporal representation for time-space: the time wave.

# Chapter 5 Time wave

## 5.1 Introduction

In Chapter 4, the gap between the requirements for temporal exploration in user applications and the existing temporal visualization possibilities were discussed. To close this gap and improve temporal visualization, this chapter introduces a new graphic representation for time.

The representation of time by a timeline (linear time) or a time wheel (cyclic time) does not always result in a satisfactory solution because many phenomena have both linear and cyclic characteristics, e.g. in the fields of meteorology, finance and physics. This is supported by the results of the questionnaire, which have been discussed in Chapter 4. This revealed that 48% of the applications involved both linear and cyclic characteristics, however neither the timeline nor time wheel is sufficient to detect temporal patterns that have both these characteristics. In these circumstances, we need to be able to represent both the linear and cyclic nature of the data, and often at different levels of granularity.

As a potential solution for this situation, the time wave is introduced. It is a combination of the timeline and time wheel. The time wave (Figure 5-1) is developed along the x-axis, which represents the characteristics of the timeline (dashed line below the time wave). The wavelength represents one period of time, which is one cycle of the wheel. In its basic form, the period corresponds with a certain time unit, e.g. a year or a day. The offset of the wave shows the start of cyclic time. It could be designed to meet the start of cyclic time which is familiar to people, e.g. starting at the top to simulate the starting time of 12 o'clock. The amplitude of the wave along the vertical axis corresponds with a quarter of the time unit, i.e. the radius of the time wheel.

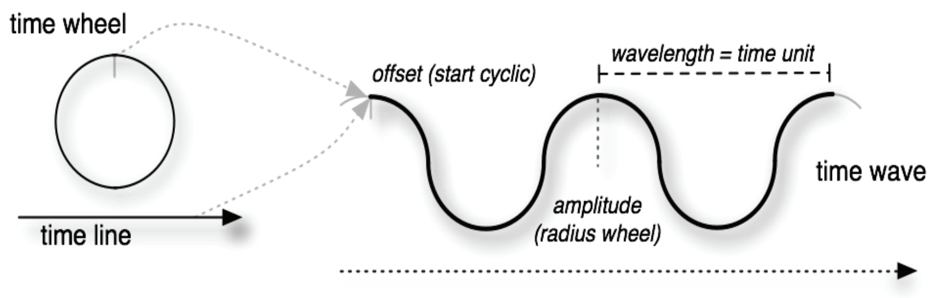



**Figure 5-1. The time wave, composed from the timeline and the time wheel.**

The wave is not completely unknown when it comes to visualizing time. The most familiar example will be the so-called ‘day-night’ maps which show, for any particular moment, which parts of the Earth are dark and which parts are light. This wave has the day unit as shown in Figure 5-2.

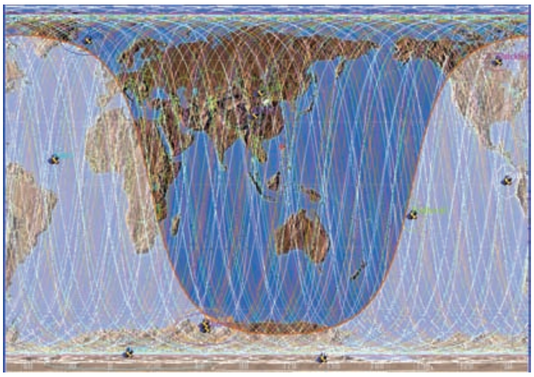


**Figure 5-2. An example of the wave as a time reference.**

In the context of time-space (see Figure 3-5), the time wave can have three different functions:

Temporal reference system

Temporal data representation system

Temporal interaction tool.

## *5.2 The time wave as a temporal reference system*

The time wave can address different temporal characteristics of temporal data. Linear characteristics can be shown in the horizontal direction and cyclic characteristics 2 (time unit) can be represented in the vertical direction.

The main aim of a temporal reference system is to localize an event in time. Specific temporal questions (MacEachren 1995) focus on time only. In Chapter 2, Figure 5-3, these questions were plotted on a time wave, and each question could be linked to a reading level (e.g. elementary, intermediate and overall). ‘If?’ queries an event’s existence; ‘when?’ results in a particular date; ‘how long?’ and ‘how often?’ refer to a particular time interval. To answer ‘what order?’ one needs to have a full overview of the time wave. There are many more questions with a time component incorporated, but these will also refer to object, spatial or attribute components, e.g. ‘how fast?’ which enquires about the rate of change in two variables, one time-related and one attribute-related.

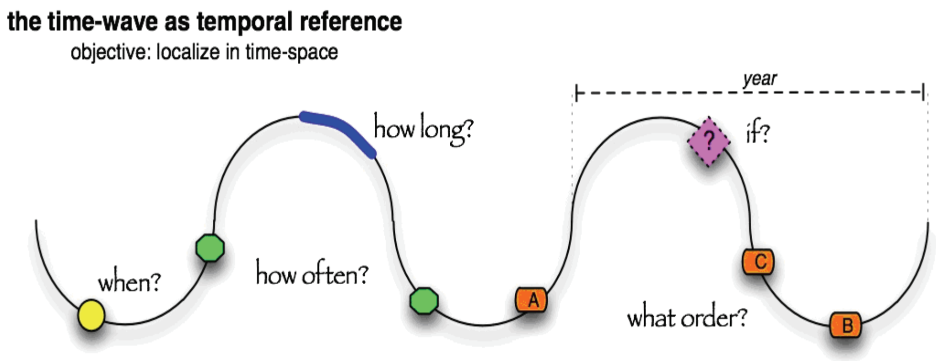



**Figure 5-3. The time wave as a temporal reference system. The different temporal questions are 'plotted' on the wave.**

In Figure 5-3 the wave represents 2.5 years. But events do not always occur uniformly along the time axis and in most cases they even occur at different scales. To visualize these different granularities, different temporal reference systems have proposed various solutions with different efficiency. An example of the timeline is the perspective wall (Mackinlay, Robertson et al. 1991). It allows temporal zooming in on the period of interest and a distortion of the 'non-interesting' periods. A time wheel is often only defined for a certain cyclic scale, and the user has to switch units to represent cycles at different time scales (Edsall et al., 2000). For multiple cycles some have suggested the use of a spiral (Weber et al., 2001). The time wave approach can handle multiple levels of granularity, as Figure 5-4 demonstrates. It is possible to embed different temporal granularities in a single time wave, through nested multiple waves, each with their own wavelength and amplitude.

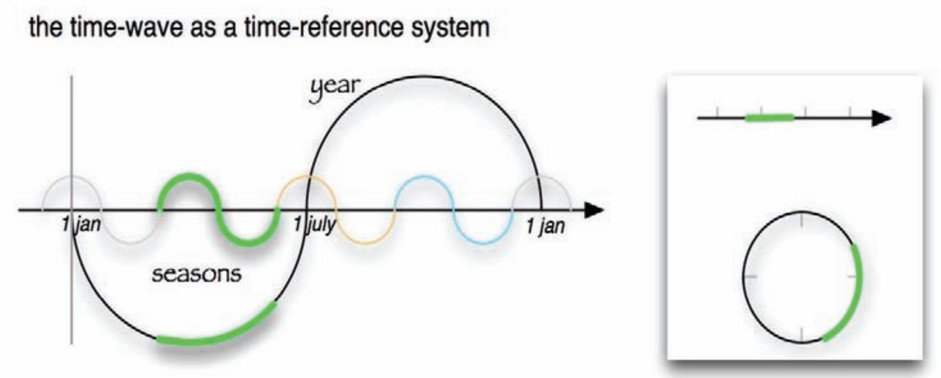



**Figure 5-4. An example of how multiple scales of time are represented by the time wave through nested multiple waves. The 'how long' question is plotted on the wave, timeline and time wheel.**

Figure 5-4 shows a comparison of plotting the ‘how long’ question on the time wave, timeline and time wheel. In the time wave, it is possible to answer the “how long” question based on several time units. In this case the answer could include a season and year. Without supporting interactive tools which allow for identification for instance, the answer derived from a timeline will recognizing the year, but not the season. In a wheel, only a single cycle can be defined. In this case, it not difficult to see which season it is, but it is difficult to determine which year. For other time questions, Table 5-1 gives a comparison between the three options. In general, a timeline is good at showing continuous linear characteristics of time; the time wheel is used to show a single cyclic pattern of data; and the time wave can give an overview pattern of both linear and cyclic time. However, this comparison is only a preliminary result. In Chapter 6 describes a case study and evaluates this comparison in more detail.

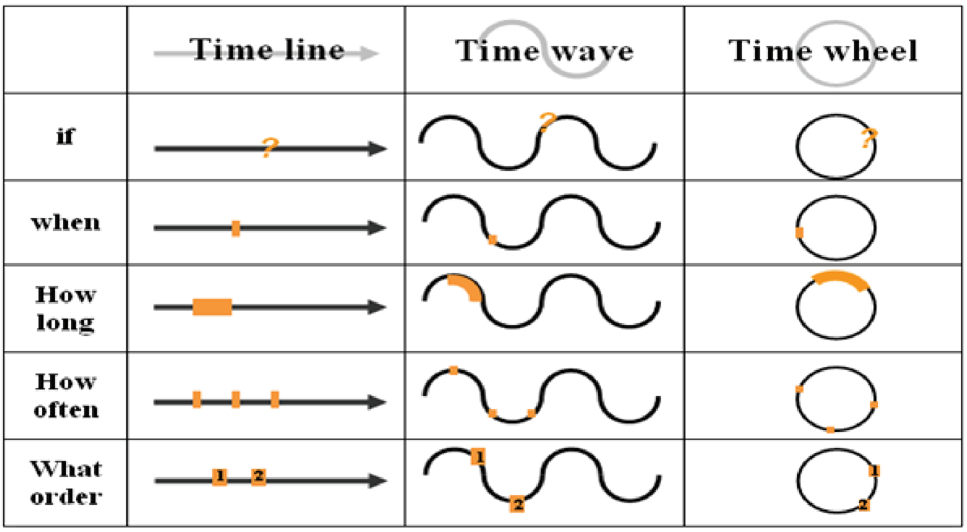


**Table 5-1. Comparison of the timeline, time wave and time wheel while answering the time questions.**

## 5.3 Time wave as a temporal data representation system

Events are only seldom time-related. The user usually has to answer more complicated questions by combining an event’s spatial, attribute and time components. In principle, this means the user has to study a problem from multiple perspectives, as suggested by Figure 3-5, e.g. from location-space, attribute-space, and time-space. However, this study discusses the time-space perspective via the time wave. The time wave allows us to incorporate elements from location- and attribute space, and still keep our attention on time.

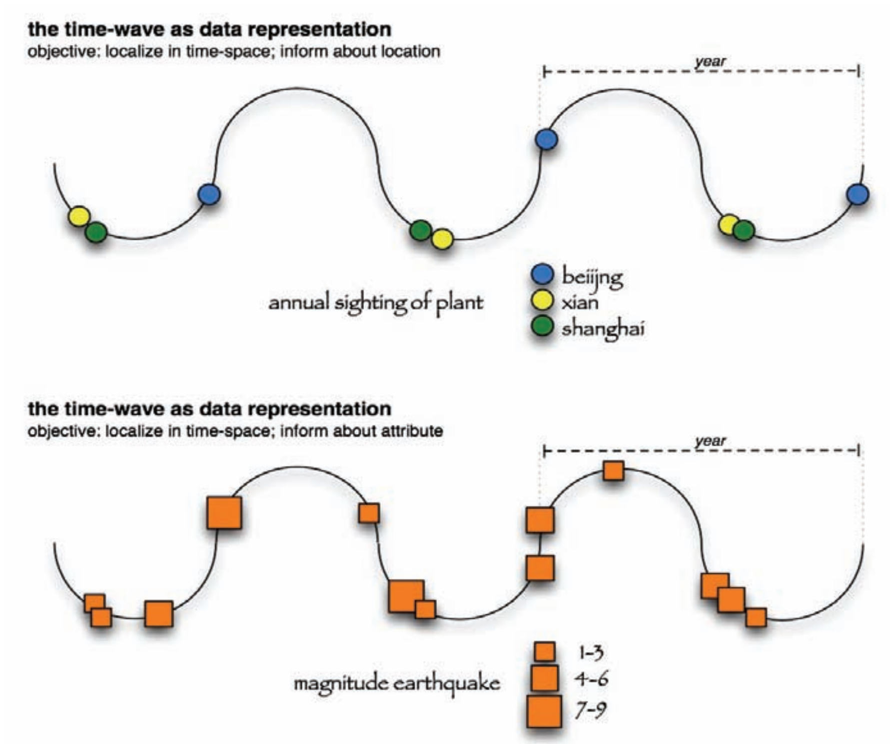



**Figure 5-5. The time wave as a data representation system. The main purpose of the wave is to localize events in time, but additional, specific, location- and attribute-based characteristics of the event can be represented as well. The upper time wave also provides information about location and the lower wave about attributes.**

Two examples are shown in Figure 5-5. The upper time wave shows the annual sighting of certain plants for three Chinese cities. The sighting in Beijing is always the latest, while Xi'an has two first sightings and Shanghai has one. With some additional geographic knowledge, a view via location-space, these observations might be easily explained. Beijing is located much further north, and Xi'an is located a little further south than Shanghai. Additional climate data (the attribute-space perspective) might help to explain the whole plant-sighting story. The aim of the lower time wave is to localize events (here earthquakes) in time and to provide information about their severity. The link with location- and attribute space might again provide more explanation of the phenomena.

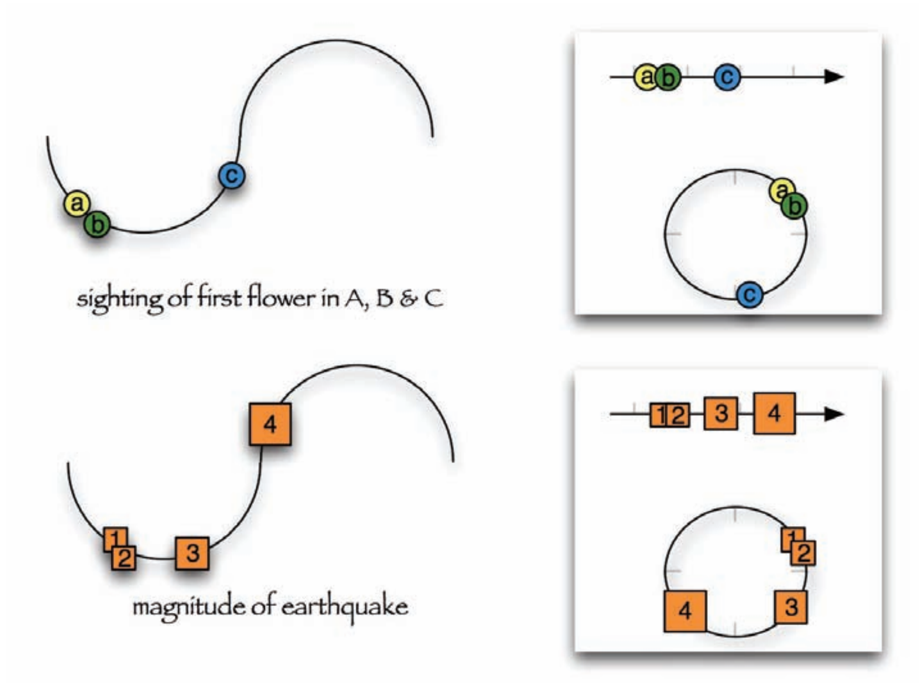



**Figure 5-6. Comparing the time wave with timeline and time wheel, based on questions related to time and location (upper wave) and related to time and attribute (lower wave).**

Figure 5-6 compares the time wave, timeline and time wheel as data representations. In the upper part of the figure, time and location are combined. As in Figure 5-5, it shows the sighting of the first flower in locations ‘A’, ‘B’ and ‘C’. The lower one shows the magnitudes of earthquakes 1–4. In the upper example, besides the temporal order which is shown clearly in the timeline, the ‘A’ and “C’ in the first quarter and ‘B’ in the second quarter could be viewed in the time wave as well. In the lower example, it is difficult for the time wheel to show the order without a clear starting point and direction symbol. Even after adding these symbols to the time wheel, it remains difficult to show the order if the time period covers more than one year.

## *5.4 Time wave as a temporal interactive tool*

Kraak (1997) and Edsall (1997) discussed how the timeline and time wheel can be used as temporal legends to explore or interact with the time in a map, for instance as a control bar for a map animation. The time wave can be used as a tool to navigate time-space as well. This section will discuss some of the working environment’s tools. These were designed with Shneiderman’s (1996) mantra in mind: “overview first, zoom and filter, then details-on-demand”. Figure 5-7 shows the time wave’s basic interaction tools: locate a point in time, select a time interval, and compare and temporal zoom. The time-bar, based on the timeline, is the temporal reference system and can be controlled by a vertical slider. The bar also supports the comparison function. These interactive tools assist the user in answering simple temporal questions such as, whether, when, how long, and how often.

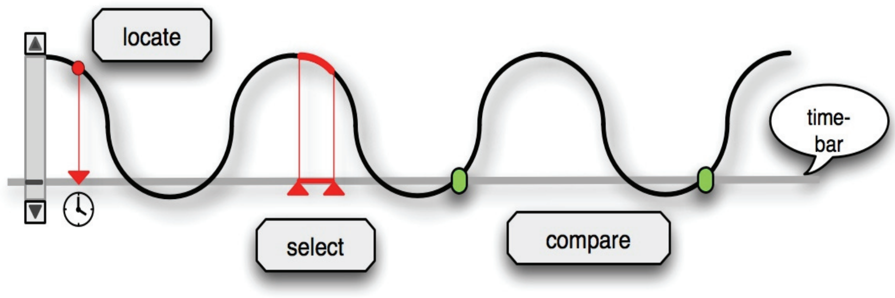



**Figure 5-7. Interacting with the time wave. The user can locate, select, and compare time. There is an interactive time-bar, which can be moved vertically as a temporal reference to display time depending on the user's actions.**

Besides the "offset" being defined as the familiar start of a cycle of time, e.g. by setting a day wave with the highest point of the wave at 12 o'clock, the "offset" can also be defined according to other user requirements. The change of the offset will relocate the data on a different place on the wave. Figure 5-8a shows a distribution of each day on a week wave with the original offset. In Figure 5-8b, the offset is defined based on the weekend with Saturday and Sunday on top. The option to be able to play with the offset could reveal interesting patterns. In other words, the 'start' of the wave can be selected depending on the problem at hand and may reveal interesting patterns and stimulate further exploration.

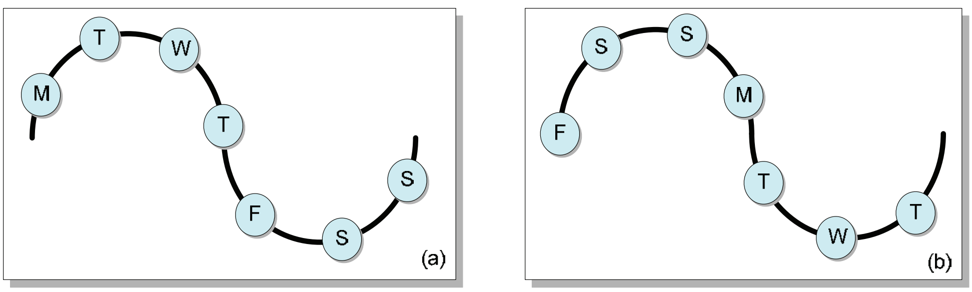



**Figure 5-8. The offset function in the time wave: a) the original distribution of 7 days on a week wave; b) the readjusted distribution of 7 days on a week wave with a purpose focusing on the weekend (Saturday and Sunday) (on the top of the wave).**

Most users will be aware of the cyclic characteristics of their data before starting their research, and will set appropriate time units for the wave via the scale definition function, e.g. years or months.

During the exploration, temporal selection can be done based on linear and cyclic time. Figure 5-9 illustrates three kinds of selection based on the time wave.

a) Linear time selection: both the instant and interval time can be selected based on the linear characteristics of the time wave (Figure 5-9a)

b) Cyclic time selection: Both the instant and interval could be selected according to the cyclic time (Figure 5-9b)

c) Block selection: with the block defined, any interesting time instant or interval can be selected flexibly (Figure 5-9c).

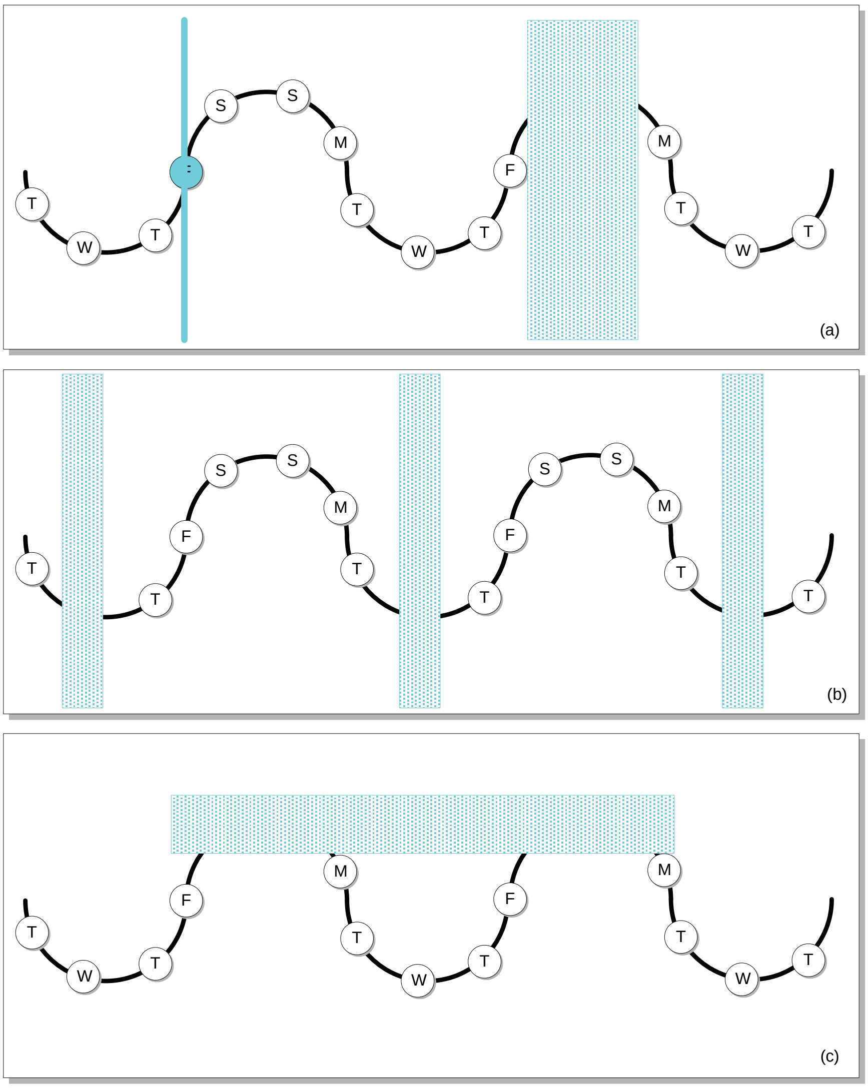



**Figure 5-9. Temporal selection and the time wave: a) linear, b) cyclic, and c) box selection.**

The time wave can be used as an animation control to interact with individual frames of the animation. Figure 5-10 shows a sketch map of this flexible control in the context of location, attribute and time-space. The timeline can provide clear insight for the user that the time passes, but it has no capacity to provide information about the potential cyclic nature of time. With a time wheel, it is difficult to know which year a snapshot shows if the animation covers several years and each circle represents one year. The time wave provides the user with a feeling not only of the time passed from left to right, but also about the cyclic time (phase of time) from the vertical shape of the wave.

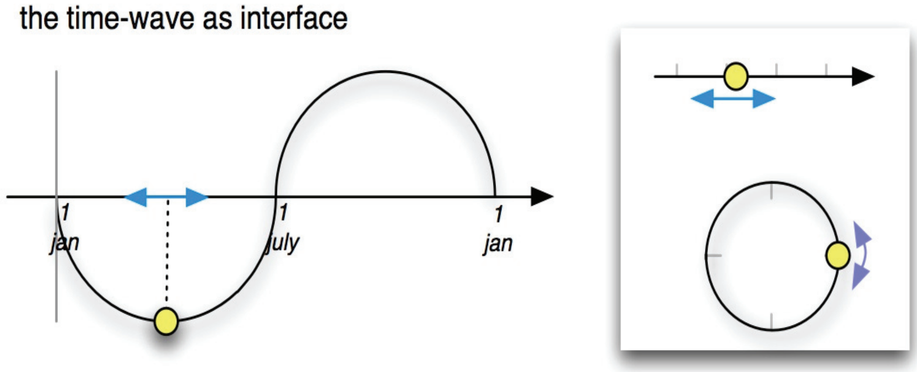



**Figure 5-10. Animation control by the time wave, comparing the timeline and time wheel.**

## 5.5 Event wave

A special variation of the time wave is the event-based time wave. Here the basic time unit is not a regular unit such as a year or month, but is defined by the event. For instance, a person runs a specific track every day. The time that it takes to cover the distance is different for every run. The wave is adapted to this period and different runs are represented by different cycles of the wave (use a time wave cartogram if you like). If the time wave construction was applied as described so far, each of the tracks would result in a wave of different height, since the height corresponds to a quarter of the wavelength (figure 5-11d). Since the main aim of the event wave is to compare events (e.g. compare the different runs), a view with waves of different height might distract from the 'comparison' task and it was therefore decided to keep the wave height equal for all events (figure 5-11a). An additional argument is that if the user plots attributes on the wave, like heart rate or pace, there might be a visual inequality because of the different wave amplitudes (figure 5-11a). In Figure 5-11a, the choice was made to position the individual waves sequentially to obtain a certain wave pattern for comparison. Alternatively, figure 5-11b plots the runs on day waves to make them comparable with the time of day when the run took place. This could reveal a relation between the running times and the time of day. In Figure 5-11c, the different waves were stacked for direct comparison. Each of these options are interactive options – a user would be able to select one for an optimal exploration of the temporal data.

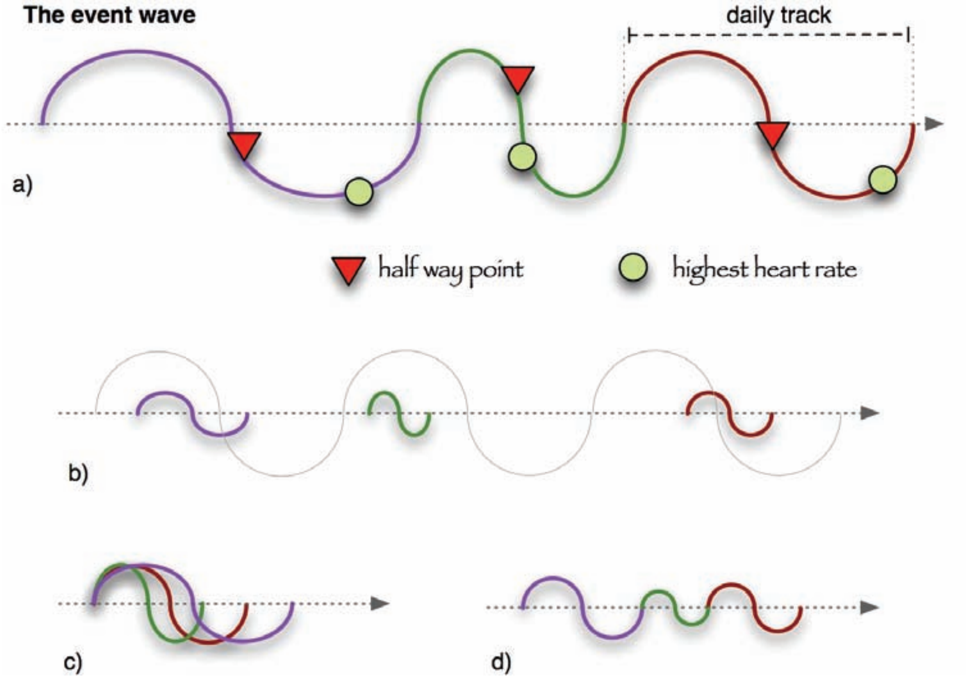



**Figure 5-11. The event wave. The duration of an event defines the length of the wave. Here is an example of daily runs on the same track. a) Waves of individual runs sequentially grouped together: the middle wave period represents the track that took the runner the least time. The symbols refer to location- and attribute space, the halfway point of the track, and the moment when the runner registered the highest heart rate. b) The running wave on the day time-scale. c) The running waves are stacked. d) The running waves at their original sizes.**

The event wave is a good means of studying aspects in relative time. There are many events related to each other, not only in spatial or attribute characteristics but also in temporal characteristics.

## *5.6 Multiple waves*

To improve and extend the comparison function, multiple waves have been introduced. Multiple waves are a series of parallel waves with the same temporal unit. The user can define, group and sort the objects, attribute, and location which are mapped on the time wave (see Figure 5-5). For example:

1. Objects: the temporal characteristics of different persons or different weather stations could be compared by addressing them individually on multiple waves. Reclassification could be done by grouping persons, such as males and females, or in different age ranges, or by grouping stations, such as ID starting with 1.
2. Location: the temporal characteristics of different places could be compared by addressing them individually on multiple waves. Reclassification could

be done on a north versus south basis, east versus west, high elevation versus low elevation, east of the river versus north of the river, etc.

3. Attribute: the temporal characteristics of different values of an attribute could be compared by addressing them individually on multiple waves. Reclassification could be done by user-defined value ranges.
4. Event: could be any change, or combination of above items, such as precipitation, earthquake and bird flu. Reclassification could be done by the above items, e.g. precipitation in different places, or event definition, e.g. ranking of earthquakes.

Figure 5-12 shows an example of event A ordered by elevation (5-12a) and longitude (5-12b). The orange circle represents the intensity of event A. The time wave shows when event A happened, and multiple waves are ordered by the spatial attribute. It is obviously that the intensity of event A is related to elevation, not to longitude.

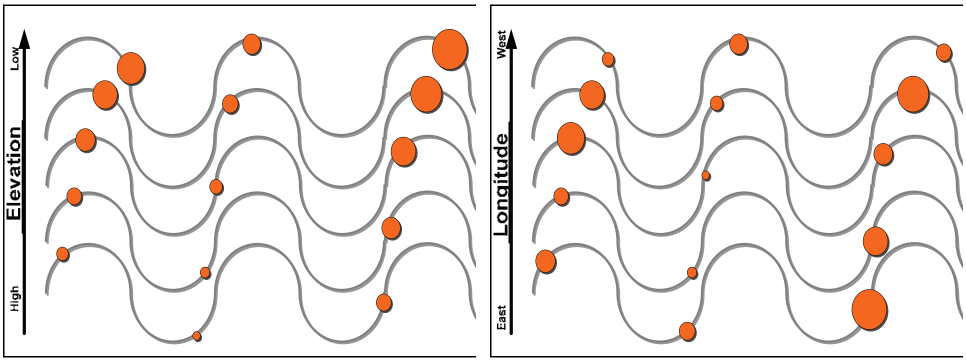



**Figure 5-12. Multiple waves ordered by different attributes: a) elevation, b) longitude.**

## *5.7 Time wave in time-space: a theoretical perspective*

In Chapter 4, the temporal visualization concept was discussed based on temporal data, and temporal user tasks, and time-space was introduced. In this section the multiple roles of the time wave will be discussed.

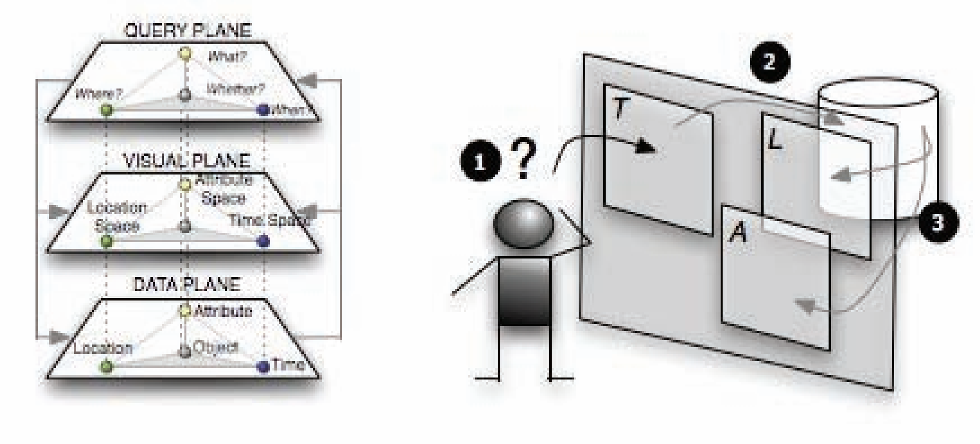
**Temporal data and time wave as time-space**

The time wave not only deals with the nature of time, e.g. it is continuous and passing, but can handle cyclic phenomena at different granularities. It can also represent phenomena on the same time scale but which are out of synchronization, e.g. display them with a different offset. Both the instant and intervals can be shown with the wave. That the time wave can represent absolute time could be addressed directly, while for relative time, the event wave can be used. Here, using the time wave, solutions to two problems (linear and cyclic time, and relative time), which were listed in Chapter 4, are proposed.

**Temporal user task and time wave in triple space**

The elementary temporal questions, such as ‘if’, ‘when’, ‘how long’, etc. could be plotted on a time wave, as discussed above (in section 5.2.1). To answer slightly more complex questions, which are also related to ‘what’ and ‘where’, a limited number of attribute or locational data can be plotted on the wave as shown in Figure 5-5. However, really complex questions require interaction with location- and attribute space as well, where it is assumed the views are dynamically linked supported by the ‘coordinated multiple view’ (CMV) technique.

Triple space is a structured CMV environment organized via a systematic view on data and user tasks. It supplies the user with a reasonable clue about where to represent data and where it is easier to find answers to questions, because the corresponding data type is addressed in the relevant space. At the same time, triple space simplifies the user’s interactivity environment by suggesting a work flow. For example, the user wants to answer the question ‘where did 5 mm of rain fall yesterday?’ In this case, he/she can define the “5 mm yesterday” in the time-space and find the corresponding answer in the location space. Figure 5-13a shows the relationship between a query plane (the questions), a visualization plane (the interface) and the data plane (data components). The data plane symbolizes the inherent link between the data components (location, attribute, time and object) and is the core of the triple-space environment. Through the visual plane, the user can see the links between the data components. The query plane shows the relationships between the questions which are displayed in the visual plane. The dotted lines in Figure 5-13a represent the links between components in each of the planes. Figure 5-13b shows an example of the query process. The user (1) asks a question via time-space (2) and gets an answer in location space (L) and attribute space (A); (3) the database provides the answer through a visual environment. This process is represented by the gray arrows on both sides of Figure 5-13a.




(a) (b)

**Figure 5-13. The theoretical framework of the CMV environment of triple space. For an explanation see section above**

Based on different representations, interactive tools need to be designed properly. In this CMV environment, starting from different time characteristics, it is necessary to select instants and intervals, both in linear and cyclic time, and at different granularities to further explore the thematic and spatial characteristics of the object. With the time wave used as a time coordinate in time-space, this requirement can be satisfied. The time wave not only deals with the nature of time, e.g. its continuous passing, but can also handle cyclic phenomena at different granularities. Figure 5-14 shows a prototypical CMV environment with location space, attribute space and time-space.

Figure 5-14 shows an interpretation of time-space with the time wave combining the representation and manipulation functions. In line with Shneiderman's visual information seeking mantra, it offers a temporal overview, temporal zooming and temporal filtering options, including details-on-demand. The figure also demonstrates the link among time-space, location space and attribute space. With a temporal question, the user starts in time-space, depending on the nature of the question. The answer can be found in time-space itself or one 'jumps' out of time-space into location- or attribute space. In answering complex questions, the user might have to jump from space to space in an extensive iterative process in order to identify and compare temporal, spatial and attribute patterns.

Triple space is implemented as CMV and as such supports exploration as an interactive and iterative process. This requires a close combination of the temporal representation and temporal interaction in time-space. After the temporal distribution is shown in temporal representation, zoom in or select interesting temporal characteristics, such as irregular time intervals. The corresponding results will be shown as a map and diagram representation in the location- and attribute space, respectively. This is typically an iterative process and could include actions directed from location- and attribute space affecting the representation in time-space.

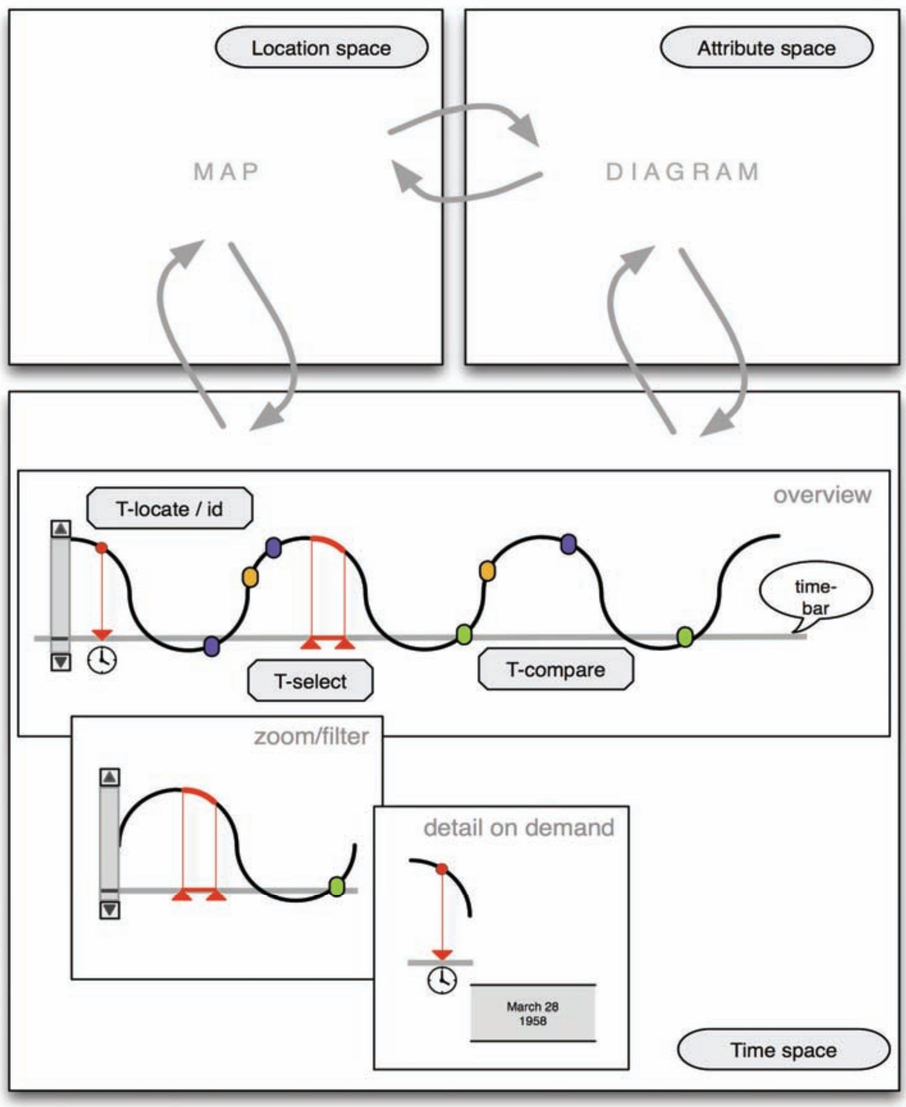



**Figure 5-14. The time wave in time-space. The wave allows for selection, identification, comparison and animation of events, as well as interactive links with location- and attribute space.**

**Summary**

In Chapter 4, a temporal visualization concept was discussed in relation to how to structure a time-space properly. Several methods were analyzed according to this concept to clarify the lack of time visualization. With the stated aim of limiting the disadvantages of time visualization and expanding the temporal exploration solution, in this chapter the time wave has been introduced as a new visualization method. How to address the different views of time and answer different temporal questions has been discussed from a theoretical perspective. The prototype of the time wave has been explained and the interface of triple space introduced. Following this, based on this prototype, case study was implemented in this environment and how to address the data and how to answer questions was explored. These points will be explained in more detail in Chapter 6.

# Chapter 6 Implementing the time wave – working environment, prototype and case study on meteorological data

## 6.1 Introduction

The time wave as a new visualization method was introduced in the previous chapter. In this chapter, a prototype of the time wave in time-space, coordinated with location- and attribute space will be discussed. A case study will be used to elaborate proper visualizations based on the analysis of temporal data and user tasks. It will illustrate how questions can be answered with the time wave.

## 6.2 Working environment and time wave functionality

In Chapter 5, triple space, consisting of location space, attribute space, and time-space was introduced. Based on the Coordinated Multiple View (CMV) technique, these views are linked to each other to support an interactive and iterative exploration process. The environment has been realized in the uDIG GIS environment. uDig is an open source, desktop application framework under the LGPL (Lesser General Public License) to provide a Java solution for GIS data access, editing and viewing. The time wave is a plug-in in uDig open source and the program language is 3D Java. Figure 6-1a gives a snapshot of the software interface. Several views are used to represent the data: layers view, map view (location space), time wave view (time-space), and graph view (attribute space). Figure 6-1b shows the general tool bar. Most functions in the tool bar are generic GIS functions; here only the plug-in functions are highlighted and the functions in the time wave toolbox will be introduced separately (Figure 6-2).

The time wave environment has two modes: zoom and select (see upper left of Figure 6-2). The zoom mode is the default, supporting zoom in/out, overview and pan. The selection mode disables the zoom mode and activates three selection methods to allow the user to select any time instant or interval.

The time scale box, found in the middle left of the box (see figure 6-2) allows the user to display the temporal unit of the chosen wave. Multiple units in a single view are possible and Figure 6-1 shows where the day, week and month are activated. Choosing the right level of detail is important for a smooth temporal exploration process and to see and discover relevant patterns; too many units will complicate the view and too few units will not reveal any patterns.

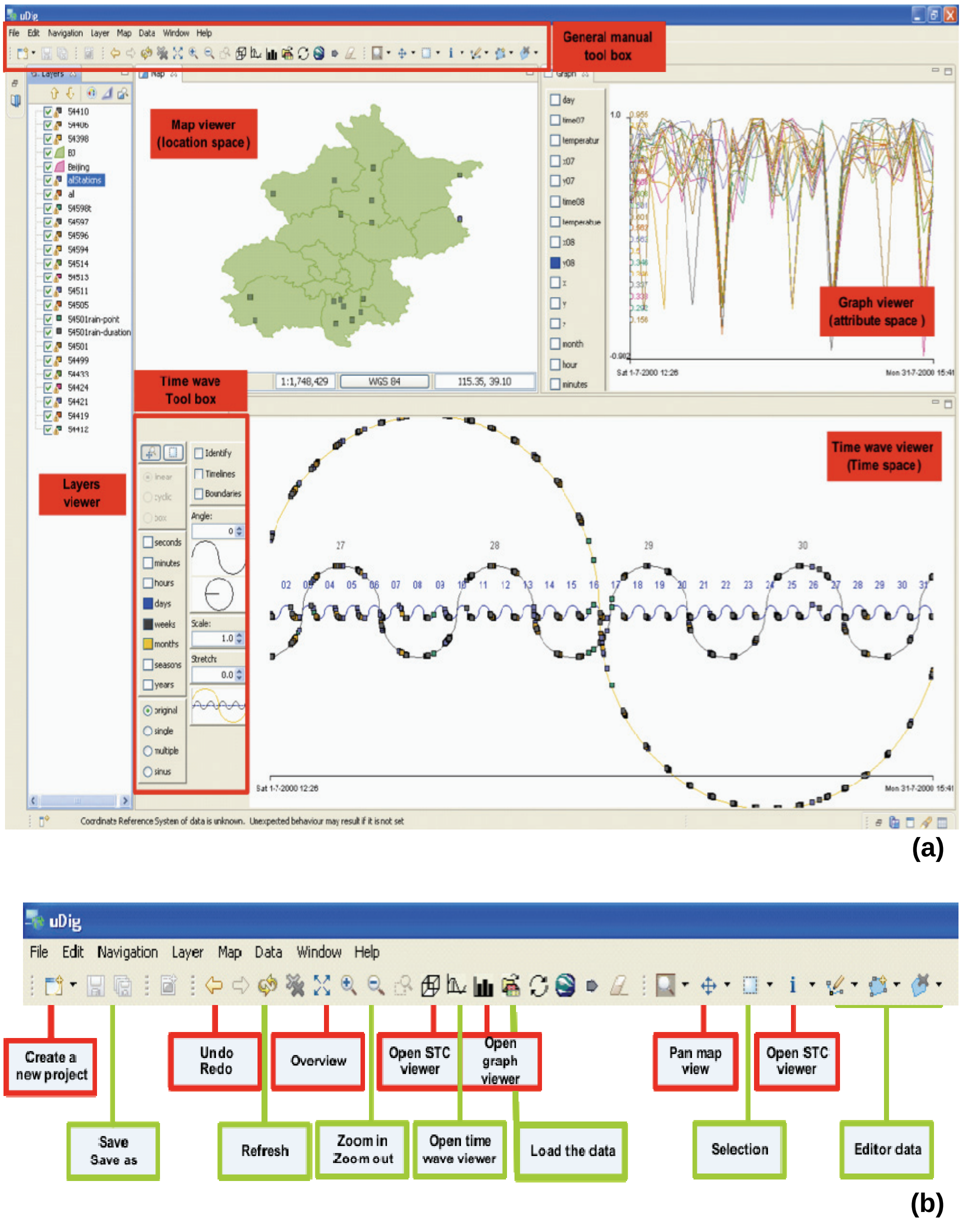



**Figure 6-1. The triple space interface in uDig: a) generic overview; b) the toolbar.**

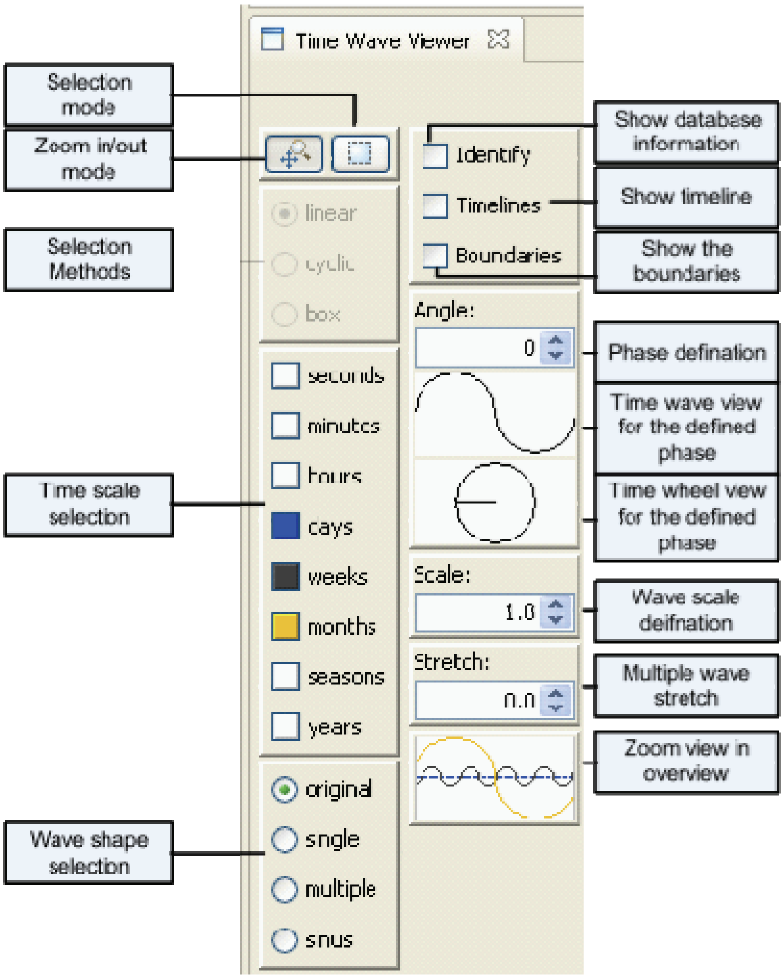



**Figure 6-2. The time wave toolbox.**

In the upper right of the toolbox, there are several functions to identify and compare time (see also the design view in figure 5-7).

To locate time, a timeline function is activated. For each point on the time wave, a corresponding point on the timeline can be found, and vice versa. Figure 6-3 shows this function in action: here it indicates Wednesday, 5-7-2000 00:03.

Below the timeline function, there is a boundaries function available. It draws vertical lines based on the largest active time unit. In Figure 6-4, the boundary of the week wave is shown (here the largest active time period).

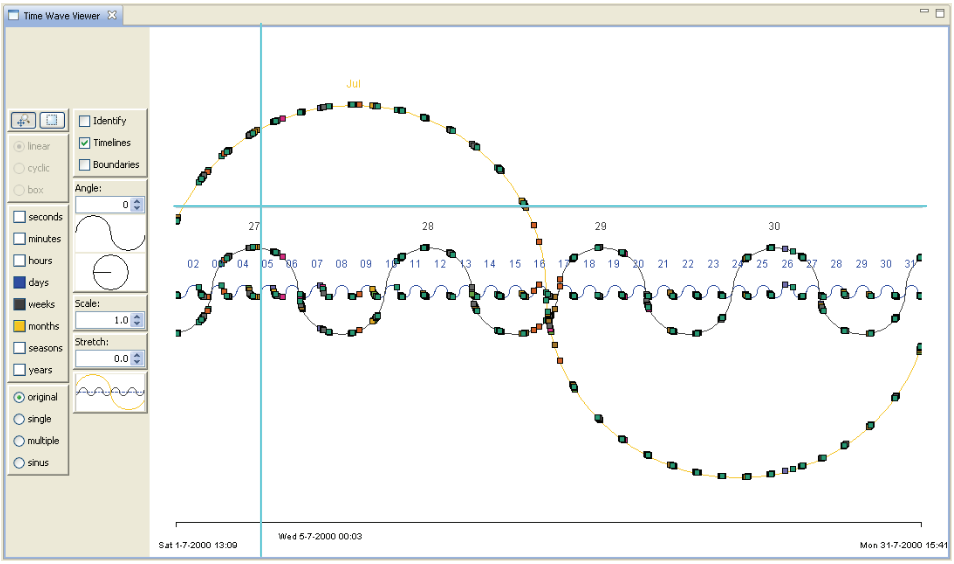



**Figure 6-3. The timeline function.**

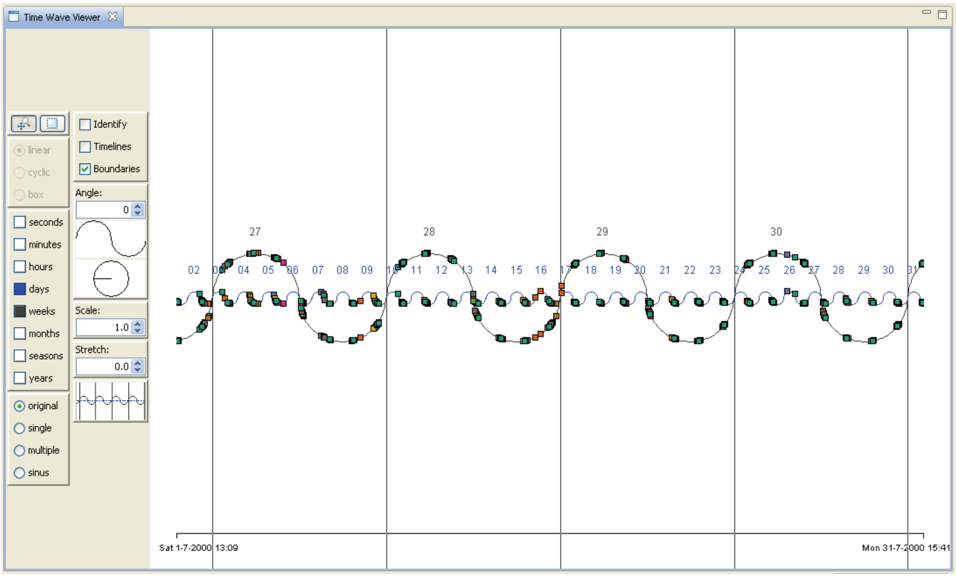



**Figure 6-4. Boundary function of one week.**

The working of the selection function depends on the time scale. When selection is activated, the minimum selectable time unit corresponds to the smallest time unit active, e.g. in Figure 6-5 the minimum selectable time unit is a day. The maximum time unit active is a so-called repeatable time unit and will be elaborated on in the discussion of cyclic selection. The menu shows three kinds of selection methods:

Linear selection (horizontal selection): a click on the time wave will select one minimum unit. Via click and drag, a longer interval can be selected. It is also possible to select multiple instants or intervals; figure 6-5 shows how one day is selected. Red boxes in the menu indicate the selection mode with linear selection enabled. In the time scale box, the minimum selectable time unit is day. The box with a green line in Figure 6-5 shows the selected result. Figure 6-6 shows two other selection examples, one with a longer interval selection and one with multiple selections.

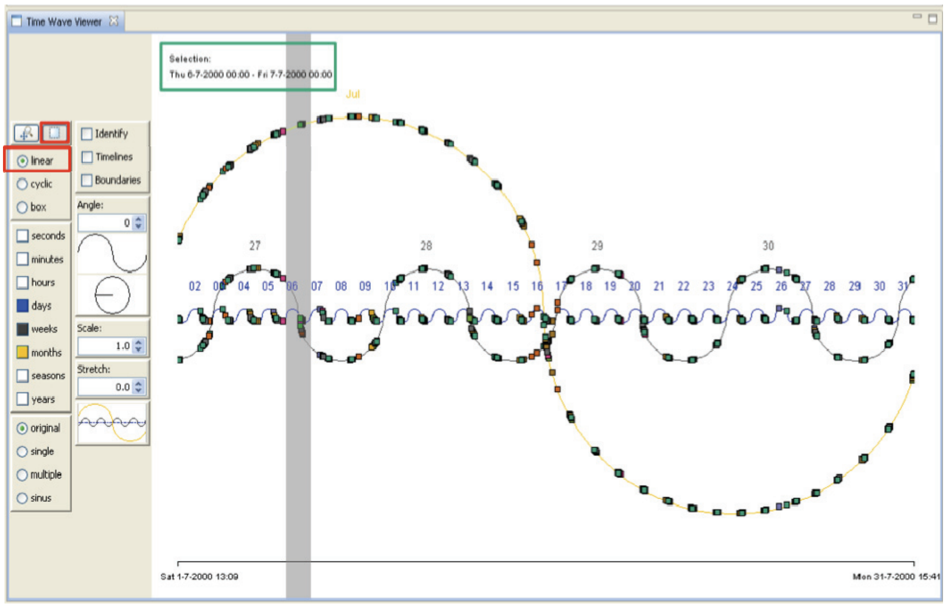
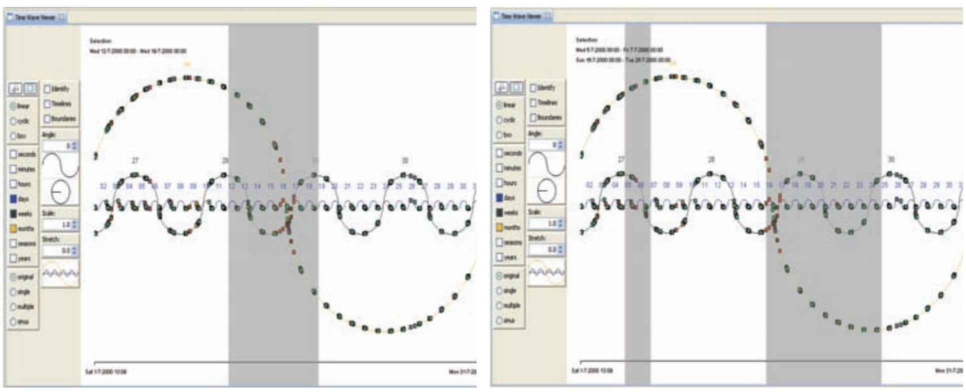


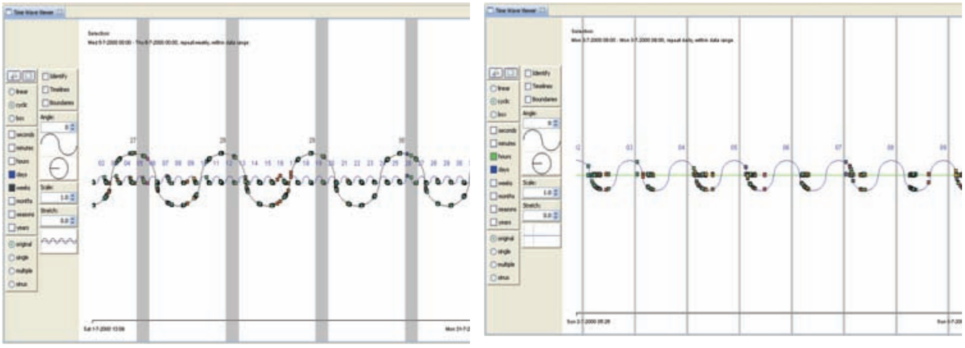

**Figure 6-5. Selection mode activates the linear selection and one day is selected.**



**(a)** **(b)**

**Figure 6-6. Extended selections: a) longer interval selection; b) multiple selections.**

Cyclic selection (vertical selection): the results of the cyclic selection depend on the time scale. One click will select the enabled minimum time unit and the selection will repeat itself based on the maximum time unit defined. For example, if the minimum enabled time unit is a day and the maximum enabled time unit is a week (figure 6-7a), one click on a Tuesday will select the Tuesday in all the available weeks. Or when the maximum unit is a month, one click on 19th will select all the 19$^{th}$s in every month available. Figure 6-7b shows another example in which the hour is defined as the minimum selectable time unit and a day is defined as the repeatable time unit. The selection will repeat itself every day. Figure 6-8 shows an example of multiple cyclic selections.



**(a)** **(b)**

**Figure 6-7. Cyclic selection: a) select the Tuesday in every week; b) select 19$^{th}$ in every month.**

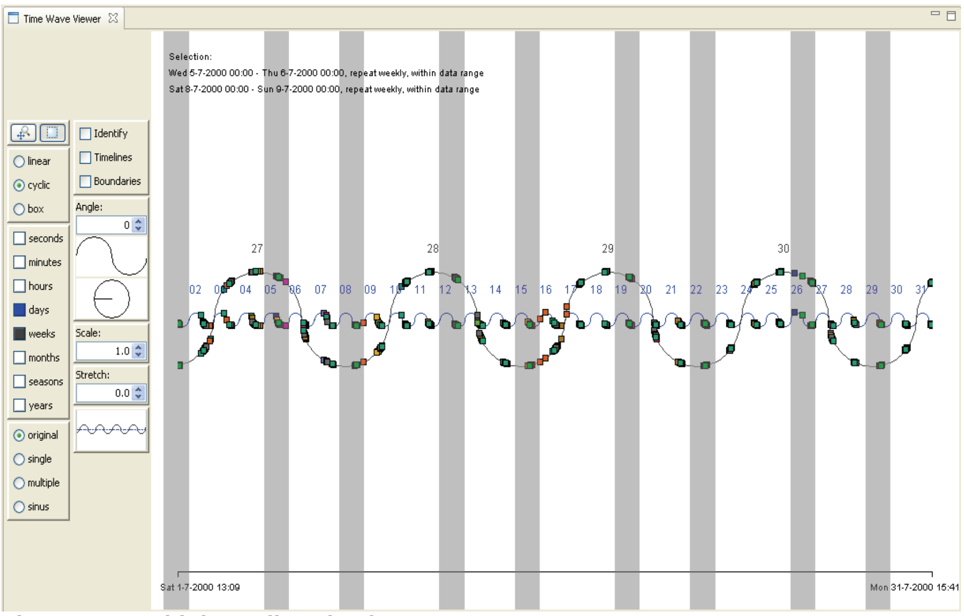
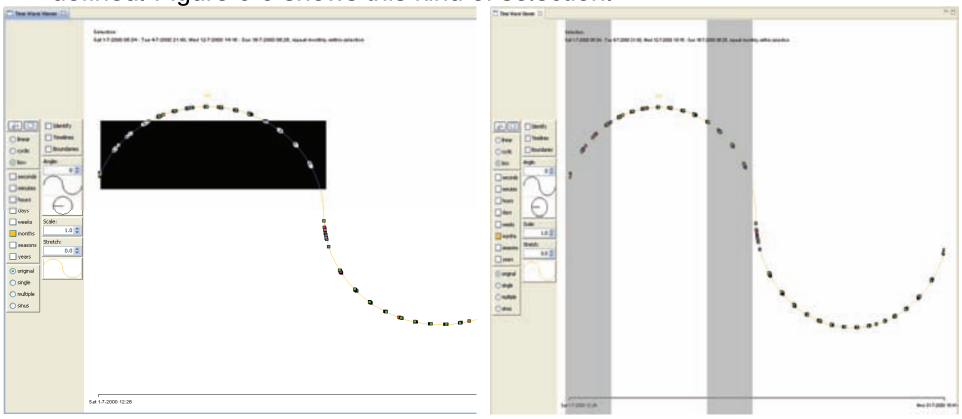



**Figure 6-8. Multiple cyclic selections.**

Block (or box) selection: this function is designed to select a temporal pattern of interest seen in the wave, in which the user wants to explore the spatial and attribute characteristics in more detail. A selection box can be defined. Figure 6-9 shows this kind of selection.



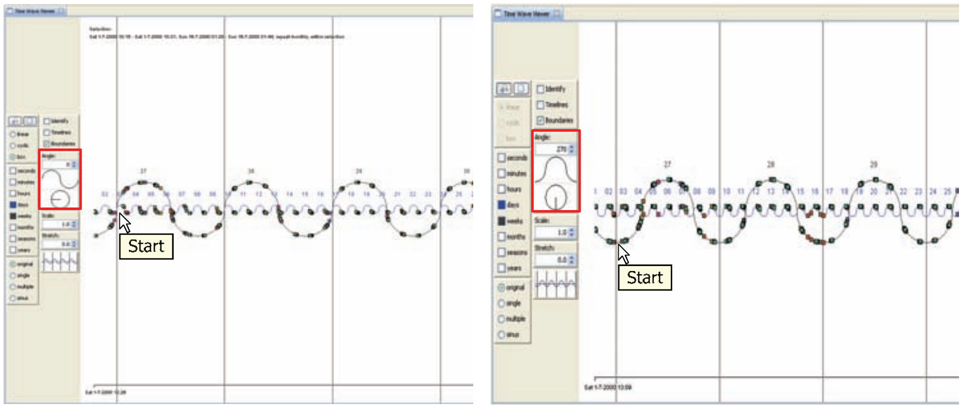
**(a)** **(b)**

**Figure 6-9. Block or box selection: a) define the selection box; (b) result of the selection.**

Several functions are available to compare temporal patterns and are accessible via the toolbox. These functions cover the wave shape, the phase definition, the wave scale definition, and the multiple parallel waves stretch. They allow the user to 'play' with the wave and discover any interesting patterns. The functions are discussed in more detail below.

The wave shape selection function decides whether the shape of the wave is sinus-like, circle-like, or something in between.

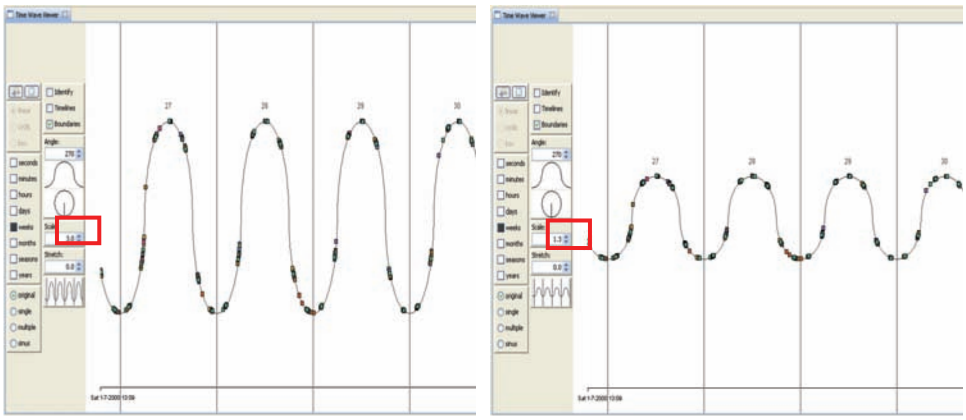
Phase definition is used to define the starting angle of the time unit. In Figure 6-10a, the start angle is $0^{\circ}$ and in Figure 6-10b it is $270^{\circ}$. This function is useful to create a suitable view for the user, e.g. starting at the top to simulate the start of 12 o'clock for the hour wave. For the defined phase, the wave view and time wheel provide the 'legend' information.




(a) (b)

**Figure 6-10. The phase definition function: a) wave starting from 0°; b) wave starting from 270°.**

Another function is the wave scale definition. It is possible to stretch the wave in the vertical direction to give more space to the data plotted on the wave. Figure 6-11 shows two different wave scales.



(a) (b)

**Figure 6-11. Two different wave scales: a) wave scale is 3.0; b) wave scale is 1.3.**

The final function is the multiple parallel waves stretch, which allows the user to create an individual wave for each element plotted on the wave. For instance, in Figure 6-12, the cities of Beijing, Shanghai and Xi'an are plotted on a single wave. This function would show each city on their own wave but close together with the others. The vertical order can depend on the location and attribute characteristics. Figure 6-12 shows two examples of multiple parallel waves with different shape selections.

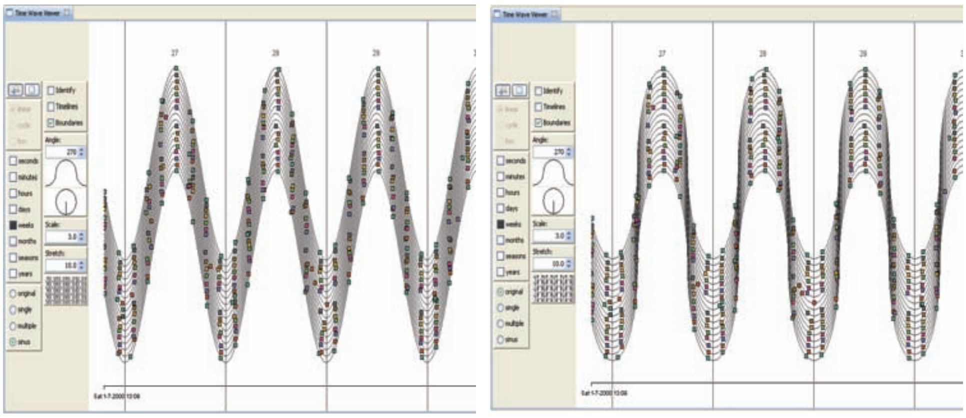


**Figure 6-12. Multiple parallel waves stretched with the different shape selections.**

The identification function works with a mouse-over-function and can reveal more detailed information from the database as shown in figure 6-13.

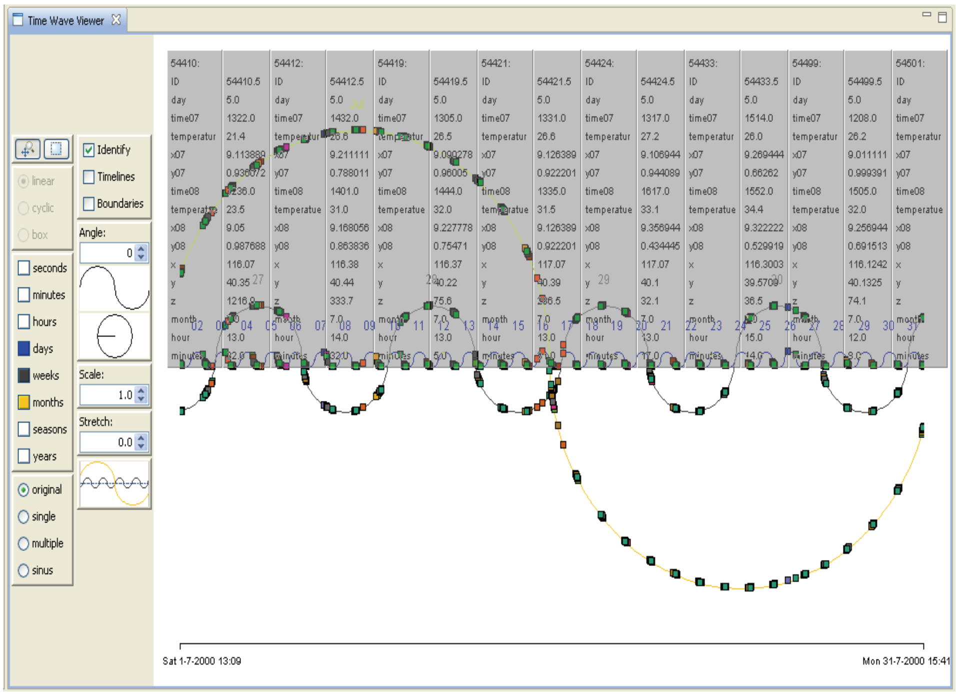



**Figure 6-13. Detailed information in the database is shown via the identify function with mouse-over-function.**

In the next section these functions will be used on a real case study, which will demonstrate how the time wave in the triple space environment can be used to answer the users' questions.

## 6.3 *Case study*

A case study was developed to demonstrate how the time wave represents and interacts with temporal data and how it works together with location space and attribute space. The study was also used as part of a usability evaluation, described in Chapter 7.

**Data analysis**

The dataset in the case study contains observations from nineteen meteorological stations in the Beijing area in China. For each station, the location (x, y, z), temperature records and dominant land use are known. The temperature was measured every minute in the months of July for 2007 and 2008. Based on figure 3-3c in Chapter 3, a data overview is shown in figure 6-14. The locational data is point data in the context of geographical units (districts in Beijing city); the attribute data is quantitative (temperature in ºC) and qualitative (land use); the temporal data has linear characteristics (measurements over a month) and multi-scale cyclic characteristics (July for two separate years, and days and nights for 24-hour periods).

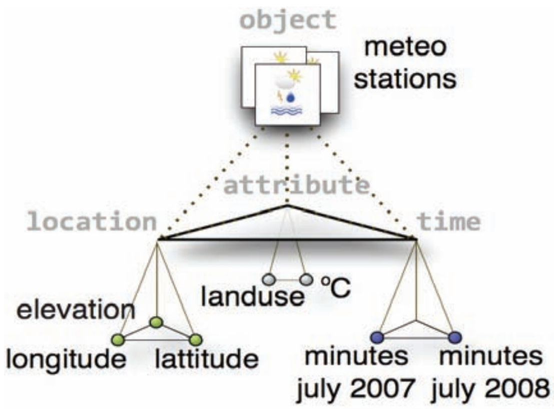



**Figure 6-14. Case study data: the characteristics of the meteorological station in the Beijing area.**

**User tasks' analysis**

The user task is to find out when the temperature reached its daily maximum value at the different meteorological stations. Is the answer related to the longitude, latitude or elevation of the meteorological stations? What are the other impact factors, such as land use? Is there a difference between the two years? The temporal questions, such as 'when', 'how often', 'in what order', synchronization and trends, always have a relation to other data components, e.g. from an object perspective (station name, station id); location perspective (height; east/west; north/south); or attribute perspective (low, high or average temperature; land use categories (urban, vegetation, water, other)).

Based on the above tasks and according to the temporal tasks space (TTS) concept, there are two types of questions about change:

What + where + whether . when

When what + where + whether

Examples of such questions are:

- Object (overview) + What (overview) when
  When did the temperature reach its daily maximum value at the different meteorological stations?
- Object (elementary) + What (overview) if
  Was station D1005 the first station to reach its maximum value on $7^{th}$ July 2007?
- Object (intermediate) + What (overview) . how often
  How often did the most eastern station reach its highest temperature first among the 19 stations?
- Object (elementary) + What (overview) . how long
  How long does it take for the temperature to decrease from the highest to lowest value?
- Object (overview) + What (overview) . how fast
  How fast does the temperature drop from its highest to lowest value?
- Object (overview) + What (overview) . in what order
  In what order did the stations reach their highest temperature between $4^{th}$ and $9^{th}$ July 2007?
- Object (intermediate) + What (overview) . Synchronization
  Do the temperatures of stations D1005 and D1007 reach their highest values synchronously?

Based on the TTS concept, the above questions can be further extended by reading level: object (elementary/intermediate/elementary); attribute (elementary/intermediate/elementary); location (elementary/intermediate/ elementary) and time as well (elementary/intermediate/elementary). For example:

**Object**

Overview: When did the temperature reach its daily maximum at the different meteorological stations?

Intermediate: When did the temperature reach its daily maximum at the meteorological stations whose IDs start with D?

Elementary: When did the temperature reach its daily maximum value at station D2007?

**Attribute**

Overview: Is the order by which the stations reached their daily maximum temperature related to the land cover?

Intermediate: When did the temperature reach its daily maximum at the meteorological stations whose land cover is vegetation?

Elementary: On which day was the value of the daily maximum temperature at station D 2007 equal to <u>32°C</u>?

**Location**

Overview: When did the temperature reach its daily maximum value at the <u>different meteorological stations</u>?

Intermediate: When did the temperature reach its daily maximum value at the meteorological stations which are <u>in the south of Beijing</u>?

Elementary: When did the temperature reach its daily maximum value at the meteorological station <u>in the Forbidden City of Beijing</u>?

**Time**

Overview: When was the highest temperature reached on each day for the <u>whole month</u>?

Intermediate: When was the highest temperature reached <u>on each day in the first week of July</u>?

Elementary: When was the highest temperature reached <u>on 1st July</u>?

Similar to the ‘what + where . when’ questions, ‘when . what + where’ questions can be formulated:

- If: Did station D1007 reach its daily maximum temperature after 12 am on 5th July 2007?
- When: what was the highest temperature on 10th July at station D1007?
- How often: where are the stations located that were the first to reach the highest daily temperature in July 2007 more than three times?
- How long: how many stations reached their daily maximum temperature between 12 am and 2 pm on 12th July 2007?
- How fast: which station had the fastest temperature increase from the lowest to highest value?
- In what order: which stations reached their daily maximum temperature later than station D 1008 on 15th July?
- Synchronization: do the stations in the north of Beijing reach their daily maximum value at the same time?

Questions 1 to 7 has been mapped in the TTS (see figure 6-15). The next section discusses how the time wave and the triple space environment can be used to answer these questions.

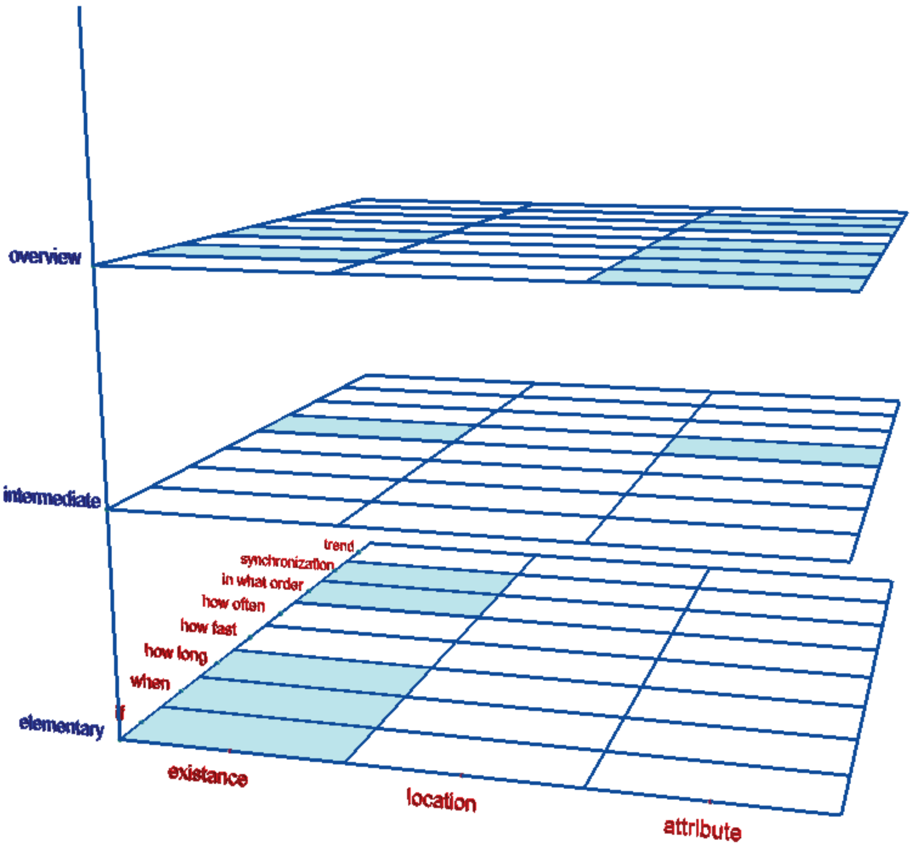



**Figure 6-15. The distribution of questions 1-7 in temporal task space (TTS).**

**Working with time wave**

Figure 6-16 gives a schematic overview of the CMV environment in which time-space plays a key role. The time wave was selected as the graphic representation because it can handle the temporal data requirements of the case study: linear and cyclic multi-scale time. The wave length could be months, weeks, days or any other time unit the user needs. It also allows user interaction and is directly linked to location- and attributes space, which is needed if the user has to switch spaces while executing tasks. In figure 6-16 this is represented by the in and out arrows. Location space shows a map with the positions of the meteorological stations and attribute space shows a scatterplot of the stations' temperature versus their land use. The time wave can also include a visual representation of the data's attribute and location characteristics. In figure 6-16, for example, symbols related to the meteorological stations (object), the temperatures observed (attribute value), as well as their land use (attribute value) can be plotted on the wave. To answer questions 1 to 7, 'what', 'where' or 'object' should be distinguished and shown on the time wave. This can be done by using visual variables or interactive tools.

In Figure 6-18, the boxes on the right and left (representation on time wave) show these kinds of options.

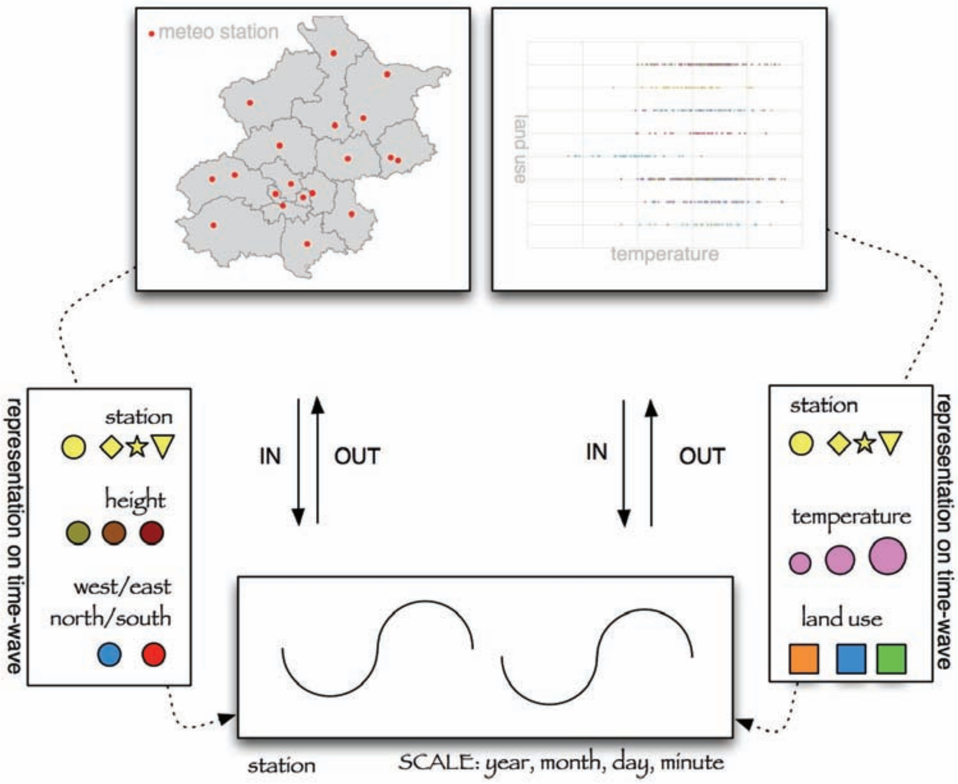



**Figure 6-16. The working environment of the time wave, with the option to visually represent characteristics from location and attribute space on the wave.**

*Question 1. When did the temperature reach its daily maximum value at the different meteorological stations?* To answer this the day unit is selected (Figure 6-17a) and to obtain a good view the middle of the night is defined at the bottom of the wave (Figure 6-17b). With these settings Figure 6-17c shows an overview of the 19 stations' highest temperatures in July 2007. It can be seen that most of the stations reached their highest temperature at about 2 pm. However, there are several irregularities in this overview, such as on 2nd, 4th, 5th 16th and 26th July. It is possible to explore these irregularities by zooming in and studying the other spatial and attribute characteristics of these stations.

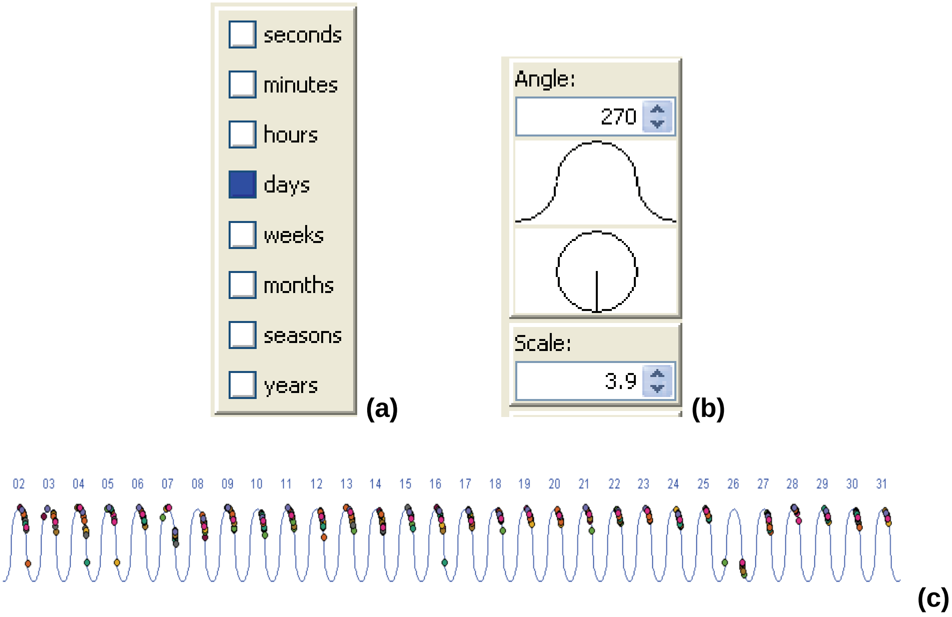
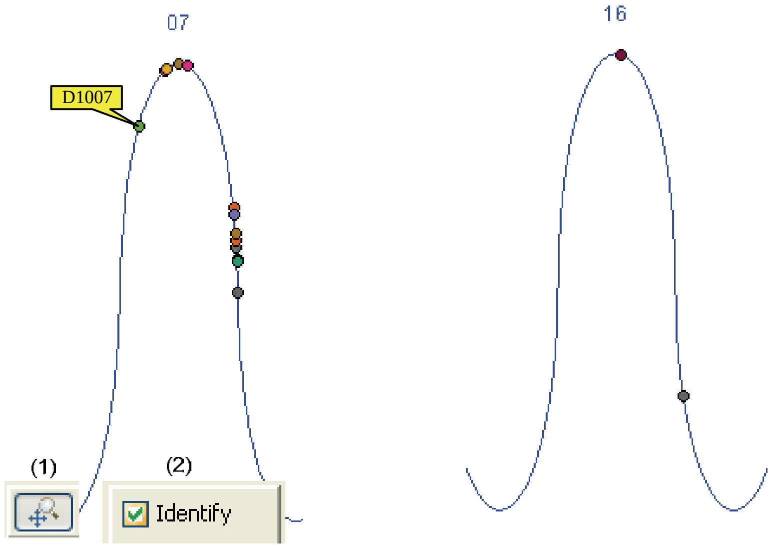



**Figure 6-17. Question 1. When did the temperature reach its daily maximum value at the different meteorological stations? a) setting of time scale; b) setting of phase definition and wave scale definition; c) the answer shown as a time wave.**

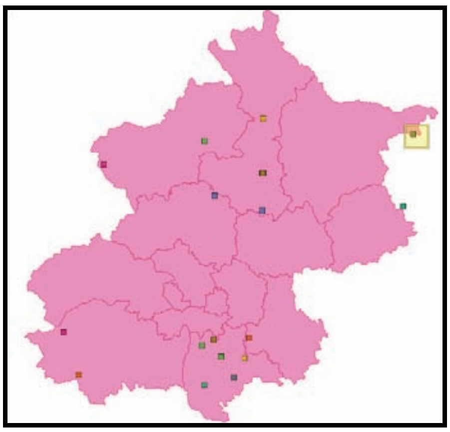
*Question 2. Was station D1005 the first station to reach its maximum value on 7th July 2007?* There are two possible strategies to answer this question. First, select station D1005 and see if station D1005 appears first on the wave for the 7th July. The other solution is to zoom into 7th July and use the identification function to point to the first data circle on that day and see if it is station D1005 (Figure 6-18a).



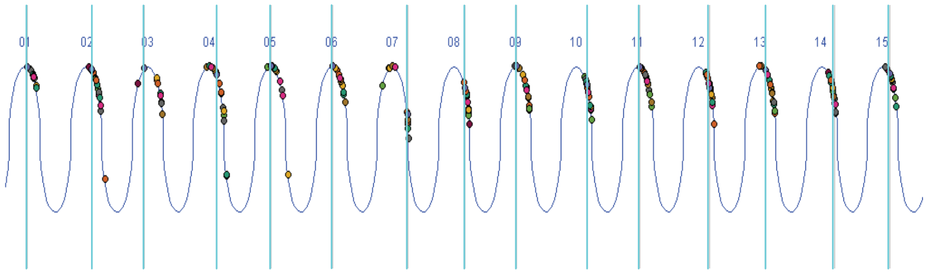

(a) (b)

**Figure 6-18. a) The identification function is used to answer question 2, Was station D1005 the first station to reach its maximum value on 7th July 2007?; (b) Question 4, How long does it take for the temperature to decrease from the highest to lowest value?**

*Question 3. How often did the most eastern station reach its highest temperature first among the 19 stations?* For this question, select the most eastern station on the map (Figure 6-19a), and check the wave for if and how often it was the first.



**(a)**




**(b)**

**Figure 6-19. The answer for question 3, How often did the most eastern station reach its highest temperature first among the 19 stations? a) The most eastern station is selected on the map; b) the time when the most eastern station reached its highest temperature in each day is highlighted by the vertical blue lines in each day.**

*Question 4. How long does it take for the temperature to decrease from the highest to lowest value?* To answer this, the moment with the highest and lowest value of station D1007 are shown on the wave (Figure 6-18b). Calculating the difference gives the answer.

*Question 5. How fast does the temperature drop from its highest to lowest value?* There is no data available to answer this question directly.

*Question 6. In what order did the stations reach their highest temperature between 4th and 9th July 2007?* To answer this, the user zooms into 4th to 9th July 2007, and can view the order of stations. It is obvious that the order changes every day (Figure 6-20). Whether this is related to their location or another attribute could be explored by interacting with location space and attribute space.

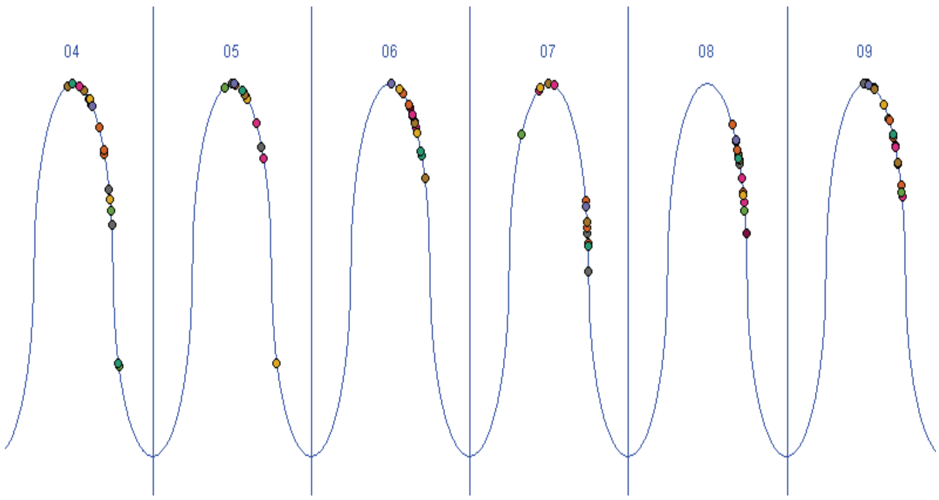



**Figure 6-20. The answer to question 6, In what order did the stations reach their highest temperature between 4th and 9th July 2007?**

*Question 7. Do the temperatures of stations D1005 and D1007 reach their highest values synchronously?* To study stations D1005 and D1007, only these two stations are plotted on the wave (Figure 6-21), which shows that most of time station D1005 (blue) is earlier.

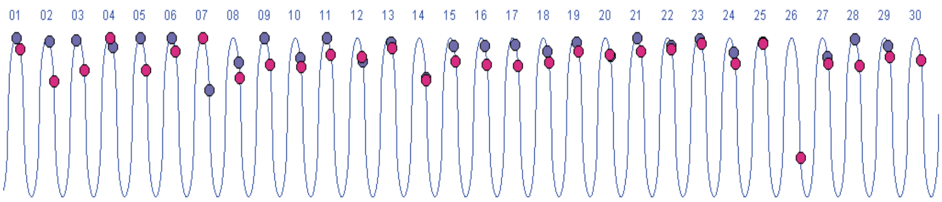



**Figure 6-21. The answer for question 7, Do the temperatures of stations D1005 and D1007 reach their highest values synchronously?**

In questions 8-14, the task is expanded further by reading level.

*Question 8. Did station D1007 reach its daily maximum temperature after 12 am on 5th July 2007?* If we define the angle as 270° (Figure 6-22a), the answer is difficult to answer at first glance but in Figure 6-22b, the angle is defined as 0, and the clear answer is "Yes".

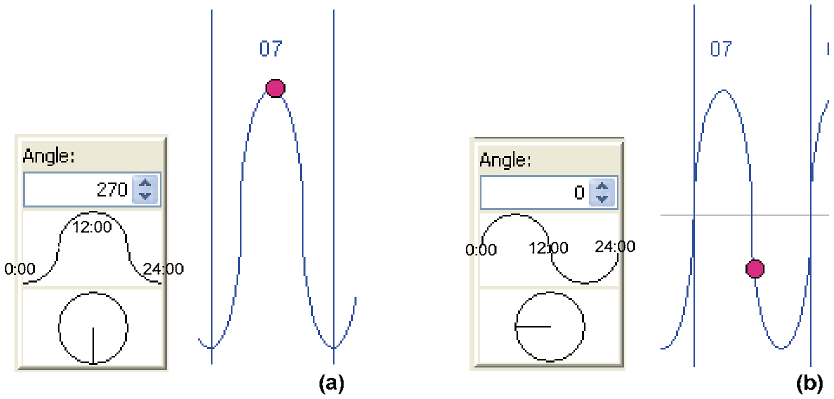



**Figure 6-22. The answers to question 8, Did station D1007 reach its daily maximum temperature after 12 am on 5th July 2007? (a) phase angle is defined as 270º; (b) phase angle is defined as 0º.**

*Question 9. What was the highest temperature on 10th July at station D1007?* To answer this question, the user can switch on station D1007 only in the data layer and show the information on D1007 in each space. If the user selects the 10th July, the temperature value will be highlighted and shown in graph view (Figure 6-23). It could be argued that, for this question, a graph representation in attribute space would be more efficient than the time wave, which is true for this simple question. However, for more complicated questions, such as 'what is the highest temperature of the station which last reached it highest temperature on 12th July?', it is not so easy to answer from a graph directly, because the temporal order needs to be shown clearly next to attribute value. Figure 6-24 shows the answer for this question. Based on the temporal distribution of the time when the stations reached their highest temperature, the last one on 12th July is easy to select and highlight. Supported by the CMV, the temperature value could be shown in the corresponding attribute space, with the thicker line showing all the value change of the “last” station, and the vertical value list showing the highest temperature for different stations on 12th July in different colors, while the bold value (orange) shows the highest temperature of the “last” station on 12th July.

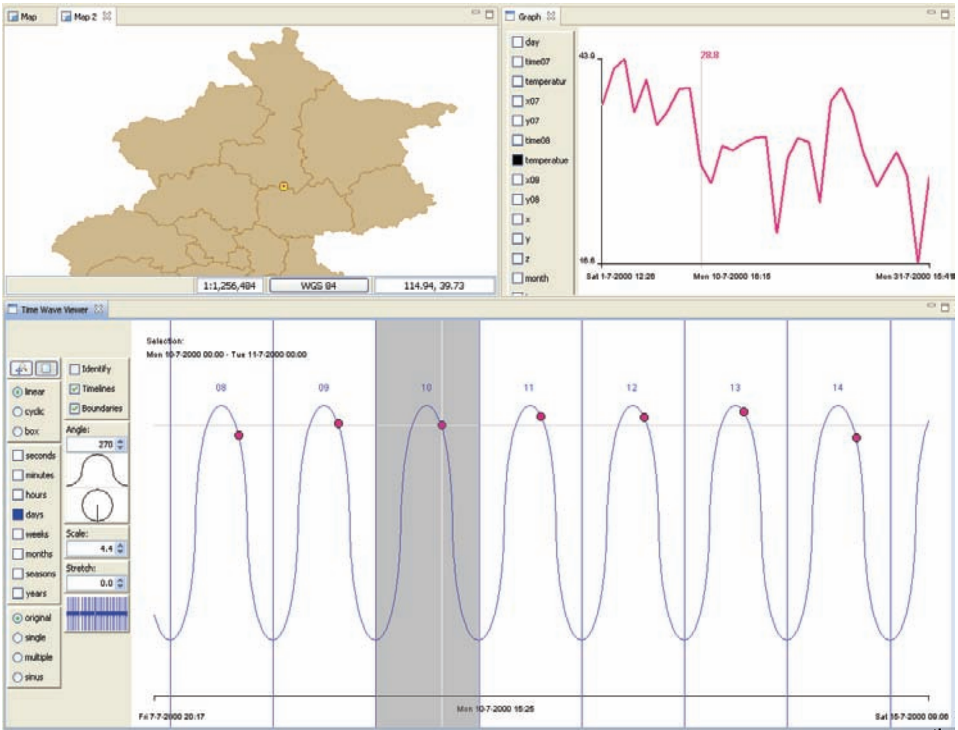



**Figure 6-23. The answer to question 9, What was the highest temperature on 10th July at station D1007?**

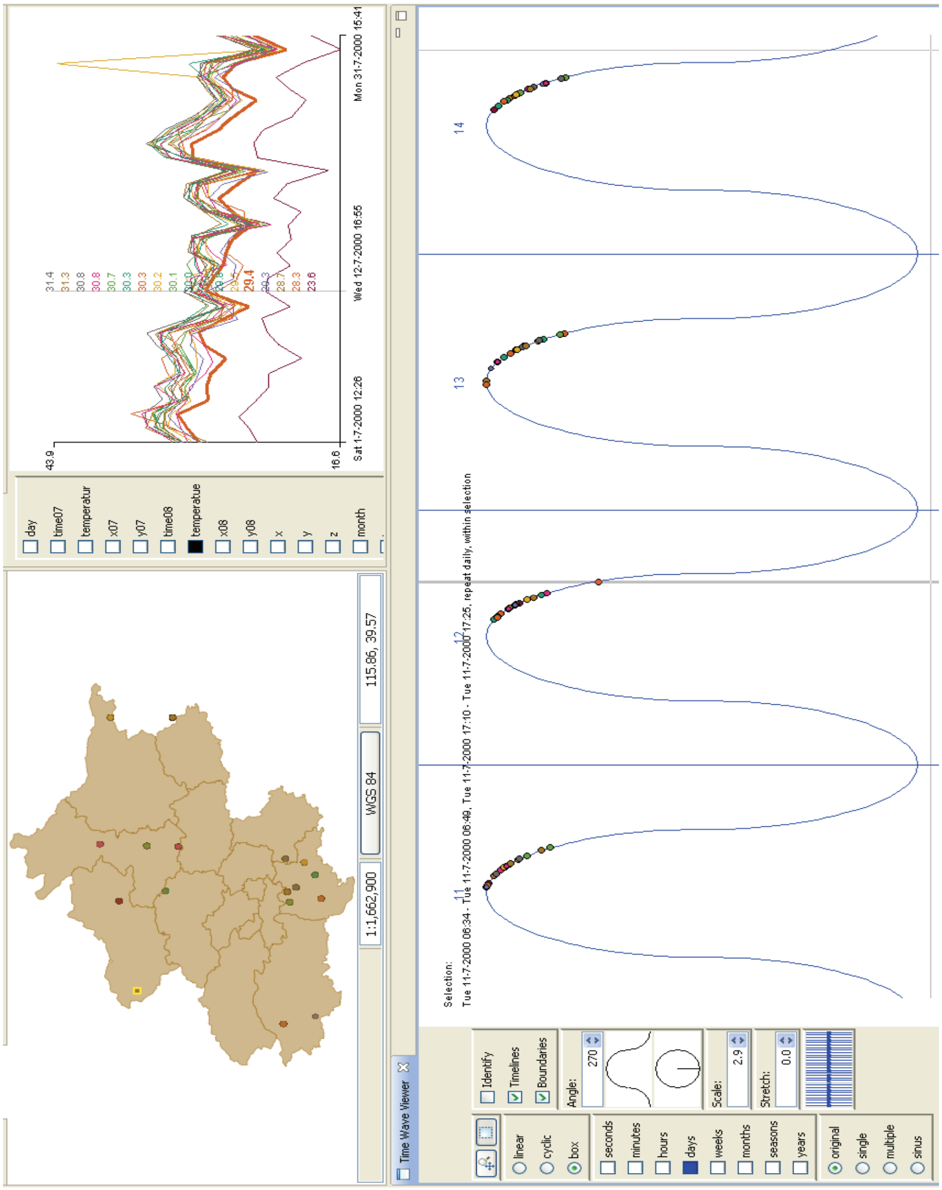


**Figure 6-24. The answer to question 9: what was the highest temperature of the station which last reached its highest temperature on 12th July?**

*Question 10. Where were the stations located that were the first to reach the highest daily temperature in July 2007 more than three times?* The user should find and identify the stations which have been first to reach the highest daily temperature in July 2007 more than three times. Then to finish this task, the multiple parallel waves could be used. Sorting waves based on the values (the time when they reached their daily maximum temperature) of 1st July 2007, the temporal distribution of ‘in what order’ will be shown (an example is also shown in Figure 6-29c). The user compares the order in each day and accounts for the times, leading to the stations which satisfy the condition posed by the question; their locations can be shown on a map.

*Question 11. How many stations reached their daily maximum temperature between 12 am and 2 pm on 12th July 2007?* To answer this question, the user locates 12th July 2007 and selects the period 12 am to 2 pm by linear selection. Figure 6-25 show the answer clearly with a zoom-in view.

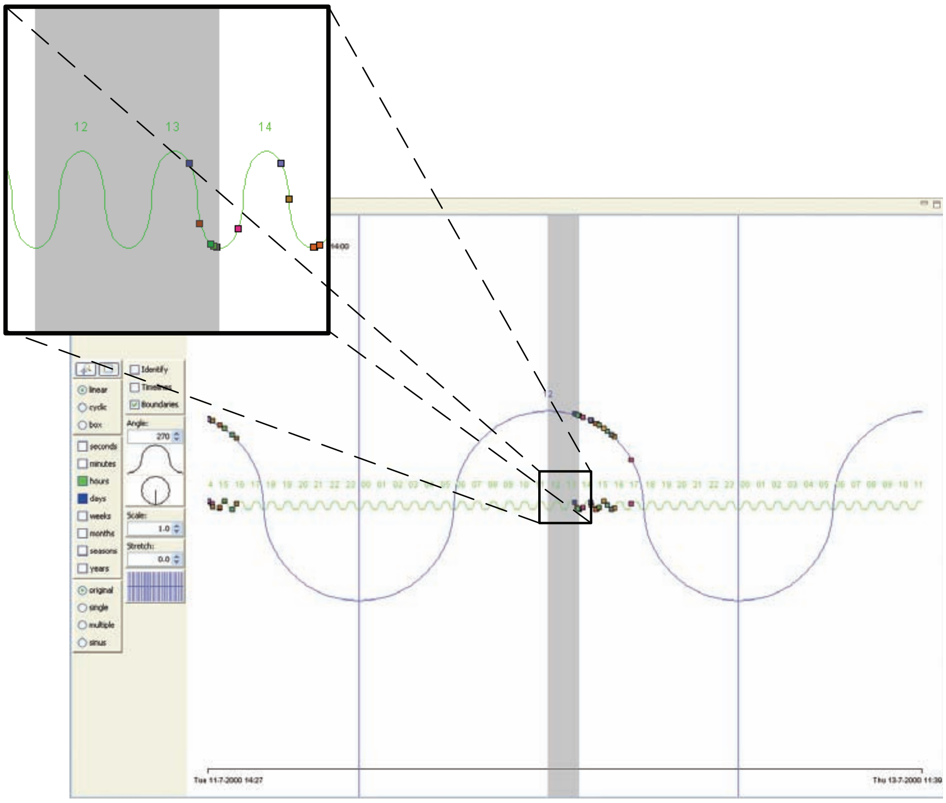


**Figure 6-25. The answer to question 11, How many stations reached their daily maximum temperature between 12 am and 2 pm on 12th July 2007?**

*Question 13. Which stations reached their daily maximum temperature later than station D1008 on 15th July?* For this, D1008 is selected and highlighted. Based on this representation, the stations which are later than D1008 can be easily identified (Figure 6-26).

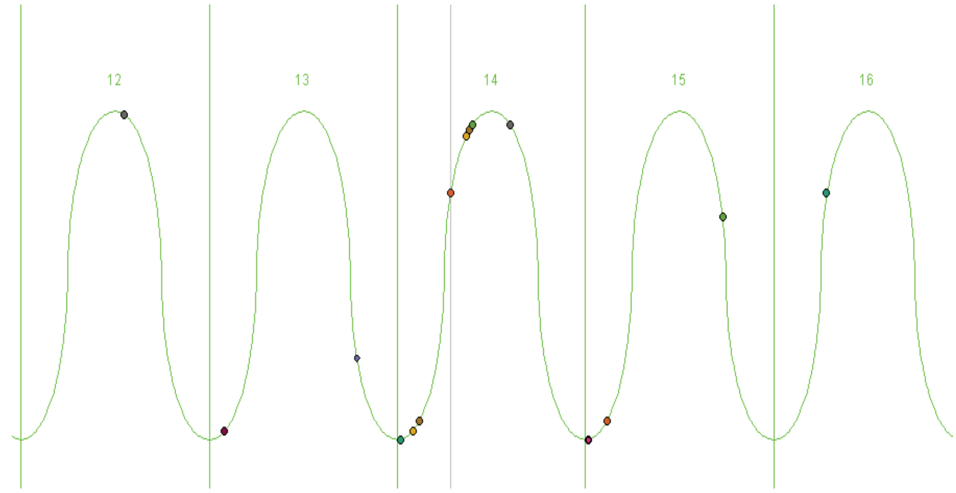



**Figure 6-26. The answer to question 13, Which stations reached their daily maximum temperature later than station D1008 on 15th July?**

*Question 14. Do the stations in the north of Beijing reach their daily maximum value at the same time?* For this, the stations in the northern part of Beijing can be selected in the map view, and the temporal patterns for these stations can be compared. Figure 6-27 shows the temporal pattern from 9th to 14th July and that they are similar.

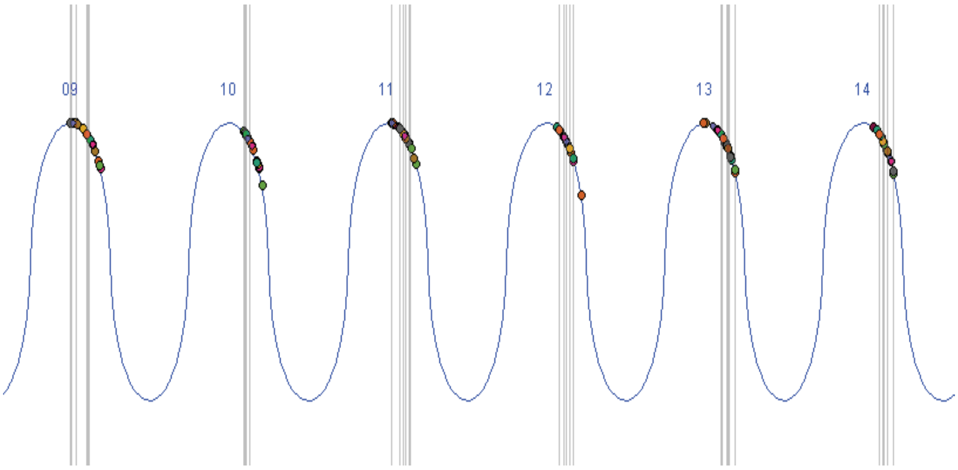



**Figure 6-27. The answer for question 14, Do the stations in the north of Beijing reach their daily maximum value at the same time?**

Figure 6-28 gives two examples of how time-space works in practice. In the upper section of the figure, an overview of the month July 2007 is given. The wave length represents days. A symbol is located on the wave – for each day and for all the meteorological stations – at the time when each station recorded its highest temperature. It is obvious that a wave like this will only offer an overview. A first glance at the data shows that the highest temperature was reached a few hours after 12 noon (the top of the wave). However, both at the beginning and at the end of the month, an anomaly in the temporal pattern can be observed. These two anomalies have been further explored in the figure. In both cases, the user can first zoom in on the wave to see more details. At the beginning of the month (left-hand side of the figure), two stations were rather late in reaching their highest temperature and at the end of the month (right-hand side of the figure), there was a single day on which all the stations were late in reaching their highest temperature. In the first situation it makes sense to obtain more details on those two particular stations, and to switch to location space to see if there is anything special about their locations. The map does not reveal anything unusual, since stations with similar geographic conditions can be found. For the second situation it was decided to switch to attribute space and have a closer look at the temperature ranges of all the stations on that particular day and the days before and after. We see that the maximum temperature for that particular day was also considerably lower than the days before and after but the available data do not give a good explanation. Other weather data, such as cloud cover, may be required. The user will have to continue exploring the data and perhaps obtain additional information in order to be able to explain these anomalies.

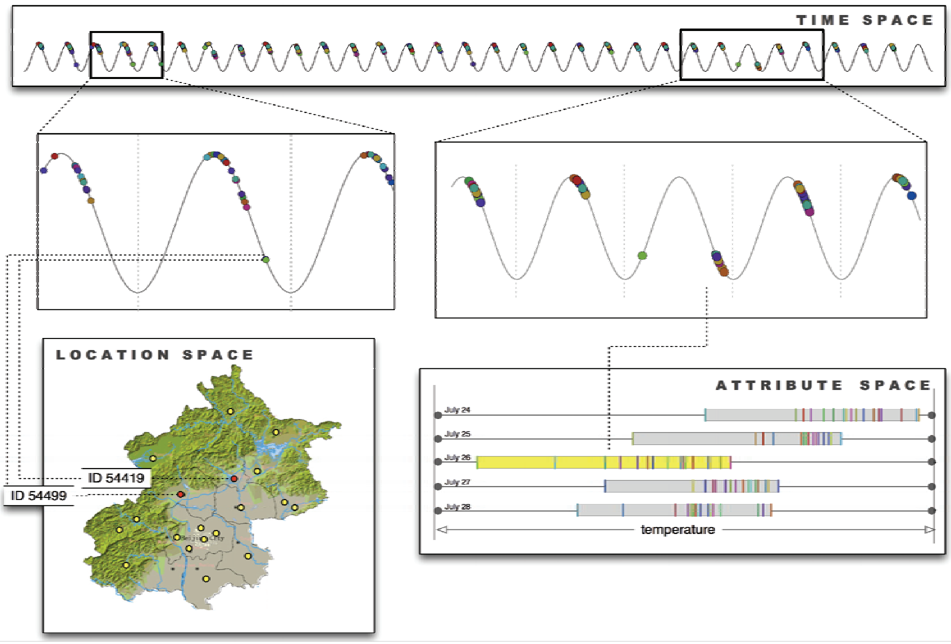



**Figure 6-28. Working with the time wave: identifying and explaining temporal patterns. In the top bar, there is an overview of July 2007 showing all the stations at the moment they observed their highest temperature. In the middle of the figure, the user zooms in on two clear anomalies in the monthly temporal pattern. In the lower left of the figure, there is a map in location space and, on the lower right, a temperature diagram in attribute space.**

Figure 6-29 shows another useful function of the time wave. The top wave is the normal time wave, here again showing the moment that each station observed its highest daily temperature. It is possible to create a set of multiple parallel waves (figure 6-29b). A separate wave can be created for each station to obtain a better view of the patterns. This approach has been derived from the parallel coordinate plot. The wave in figure 6-29c shows how the data are sorted based on the values of July 1$^{st}$, with the station that observed its highest temperature first on the lowest parallel wave. The following days show a different station order. It is possible to sort the data based on any other available variable selected for a particular day, e.g. on the height of the station locations (figure 6-29d), or sorted from east to west or north to south. After sorting, the observed patterns might urge the user to jump to location or attribute space, to ask for more detail, to switch back to overview mode, or even to retrieve more data. Working with the time wave to explore temporal patterns is clearly an iterative process. The next section deals with the specific benefits and possible disadvantages of this approach.

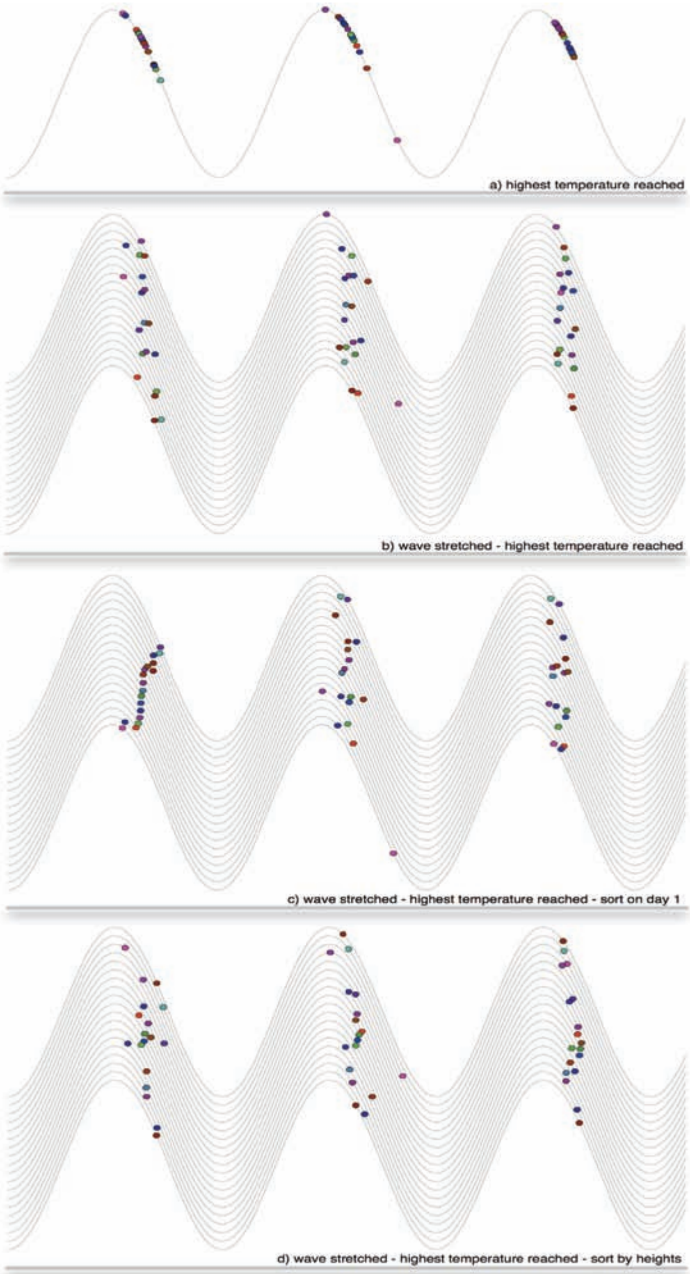



**Figure 6-29. Working with the time wave: comparing temporal patterns. (a) an overview of the first three days of July 2007 showing when the highest temperature was observed at each station; (b) temporal stretch by creating a set of parallel waves to un-clutter the pattern seen in the upper wave; (c) sorted wave based on the values of 1st July 2007; (d) sorted by station height (highest elevation is in lowest parallel wave).**

The examples given demonstrate that the time wave in the triple space environment is a good tool for answering temporal questions in many variations. The link between those three spaces can be made even more useful if the user also wants to explore questions about 'why?' Below two examples of this kind are elaborated. The first looks at whether geographic location has anything to do with reaching the highest temperature. The second example looks at whether land use influences the answer.

Is the moment when the temperature of station reaches its highest value related to the longitude, latitude and elevation? This is a question which brings 'when' and 'where' close together. The user could select the two eastern stations to compare them with two of the western stations. The stations can be selected in location space and the temporal distribution can be seen on the time wave. For an easy comparison, the eastern and western stations are shown in different colors. Figure 6-30 shows a temporal distribution of the two most eastern (green line) stations compared to the two western stations (red line). This reveals that the eastern stations reach their highest temperature first. The alternative solution would be to use the multiple parallel waves function.

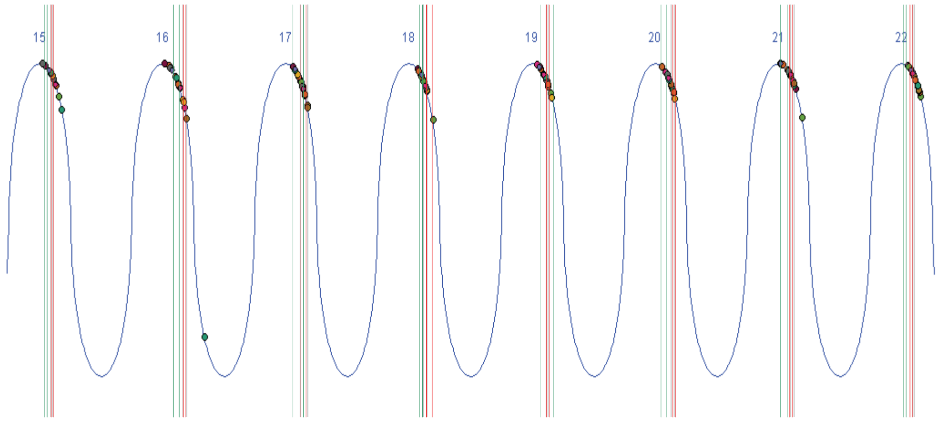



**Figure 6-30. A temporal distribution of two eastern stations (green lines) and two western stations (red lines), showing that longitude influences the moment of maximum temperature at the stations.**

To study whether an attribute, such as land use, has an effect on the time, can be done by plotting the attribute on the wave using appropriate symbols. Land use is a nominal variable, so different colors and shapes are used to represent the different land uses at the stations in Figure 6-31 to enable further exploration. The map shows the spatial distribution of stations with different land use and the time wave shows the temporal distribution when the highest temperature is reached in stations with different land use types. Attribute space shows the value of the highest temperature for stations with different land use. According to the graph, the stations in bare land reached their highest temperature before those stations in areas of vegetation.

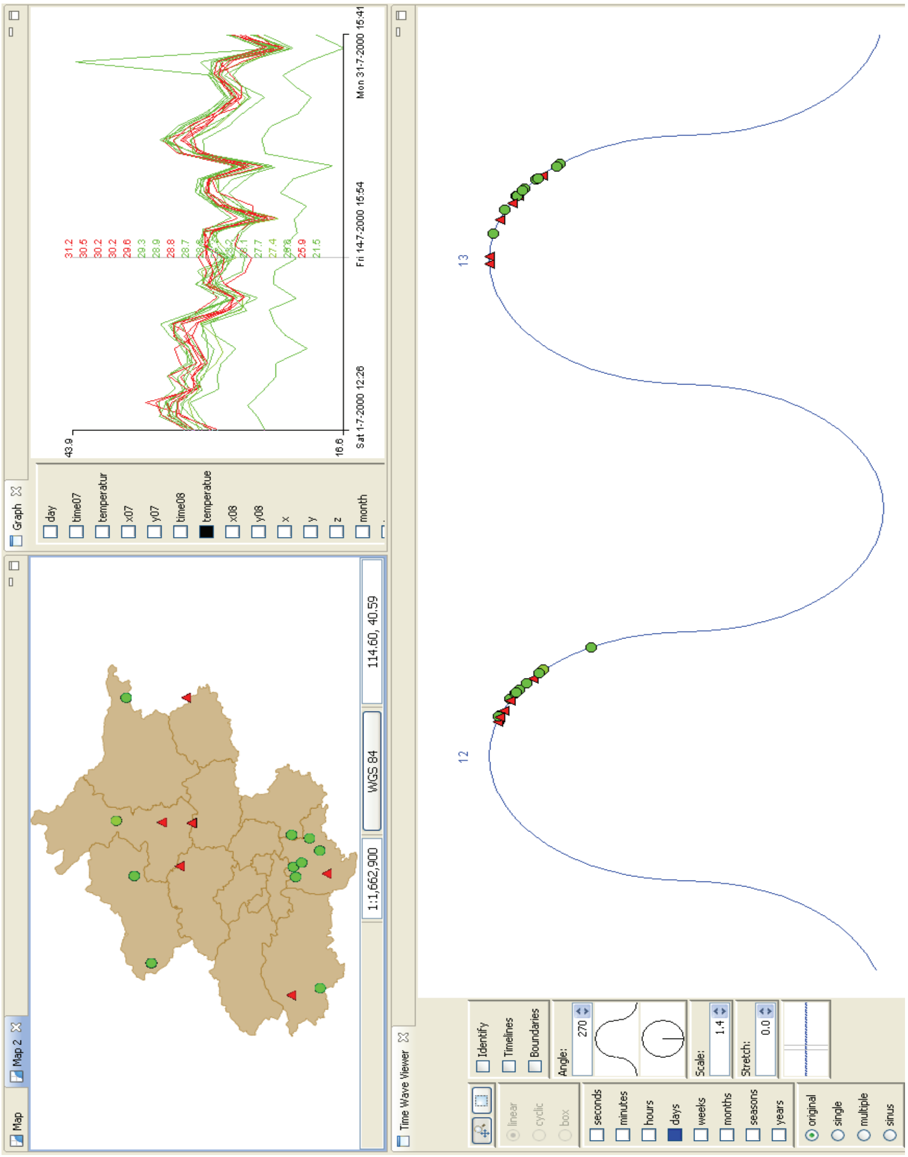


**Figure 6-31. Land use at the meteorological stations in the study. The red triangles show stations in bare land and the green circles show those in areas with vegetation.**

## 6.4 Conclusions

Based on the discussions described in earlier chapters a prototype of the time wave and the triple space environment has been developed. A case study based on meteorological data was used to see how the time wave works with maps and graphs and how it can be used to answer multivariate spatio-temporal questions.

The time wave was able to supply the answers to most of the questions. In combination with a map and graph, the time wave supplies a temporal link in the CMV environment and supports continuous exploration in the triple space environment. However, it is still unclear whether the time wave has a better performance than the timeline or time wheel for temporal representation and temporal interactive tools. Whether users understand this flexible triple space environment and can ‘play’ with their data in it is also unknown. Chapter 7 presents an extensive evaluation of the time wave approach to gain a better understanding of how usable it is.

# Chapter 7 Usability evaluation of time wave

## 7.1 Introduction

The time wave was designed and realized in a CMV environment to support users needing to answer temporal questions. However, it is unclear if the time wave is fit-for-purpose or how well it performs. Do users understand how it works? Is it better in providing answers to temporal questions than other temporal visualization methods, such as those based on the timeline or time wheel? What kinds of temporal questions are answered more efficiently and easily by time wave? How does it work in time-space, in combination with location space and attribute space to answer complex questions? Can triple space support users in exploring their data? It is important to find the answers to questions like these to gain insight into the usability of the time wave and triple space. This can be done by studying the behavior of users while they try to answer temporal questions and by analyzing their results. This chapter describes the usability evaluation performed to acquire insight into the performance of the time wave.

Usability evaluations of visual representations have been given much attention in recent GIScience research (Slocum et al., 2001; Brodersen et al., 2002; Fuhrmann, 2004; Fabrikant et al., 2008; Haklay and Zafiri, 2008; Çöltekin et al., 2009). The evaluations typically deal with user requirements, trying to find out how people solve spatial problems, and which cognitive processes might be behind their actions. A number of evaluation methods were used to derive qualitative or quantitative measures of users' experience. Examples of these methods are: card sorting (Nielsen, 2004; Turnbow et al., 2005; Hannah, 2008; Paul 2008), verbal protocol analysis (VPA) (Ericsson and Simon, 1993), focus group studies (Suchan and Brewer, 2000; Stewart et al., 2007), interviews (Suchan, 2002; Slocum et al., 2004), direct observations (Kumar, 2005), questionnaires (Burkhard and Meier, 2004), think-aloud protocols (Someren, Barnard et al., 1994; Boren and Ramey, 2000; Nielsen et al., 2002), screen logging (Flaherty 1991; Barnicle, 2000) and eye movement recording and analysis (Goldberg and Kotval, 1999; Fabrikant et al., 2008).

The ISO9241-11 standard defines usability 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 (Bevan, 1994). ISO9241-11 defines usability at three levels – effectiveness level, efficiency level, and the degree of satisfaction with which users achieve their tasks with the test object in question:

- Effectiveness: The accuracy and completeness with which users achieve specified goals.
- Efficiency: The resources expended in relation to the accuracy and completeness with which users achieve goals.
- Satisfaction: The comfort and acceptability of use.

With the above three usability levels in mind, suitable evaluation methods were selected to evaluate the time wave and its working environment.

## 7.2 Evaluation objective and evaluation design

In the context of the whole research project, figure 7-1 gives the overview of the usability evaluations executed. A four-step evaluation plan was designed and is shown in detail in Figure 7-2.

The aim of the first step was to find out about generic user requirements related to temporal issues: temporal data, temporal questions, temporal visualizations and temporal understanding. For this purpose a pre-test questionnaire with the following questions was drawn up:

1. What is the kind of temporal data used in applications, according to the different views on time?
2. What temporal questions do users have, and can they be structured in TTS?
3. What kinds of temporal visualization do users require in relation to the temporal data and temporal user tasks?
4. Do users understand the different views on time and the elements in TTS?

This pre-test and its results were discussed in section 4.3.

The aim of the second step (Test 1) was to find out how the time wave compares with the timeline and time wheel as a temporal data representation and interaction tool:

1. Which temporal questions can (or cannot) be answered by the timeline, time wheel and time wave? (Effectiveness)
2. How efficient is each method in answering the different temporal questions? (Efficiency)
3. What is the user satisfaction in using the different methods to answer the user task questions? (Satisfaction)

Answers to the above questions were collected via a questionnaire and direct observation while users' executed tasks, followed by interviews with them. The case study used for this test was designed to be in line with the pre-test. Users were asked to answer a series questions while they tried to execute specific tasks with data in the time wave working environment. Their answers and the time spent on each question was recorded. The interviews were done to collect the users' personal experiences while they executed the tasks. The results enabled us to judge both quantitative and qualitative aspects of the effectiveness, efficiency and user satisfaction of the time wave, timeline and time wheel.

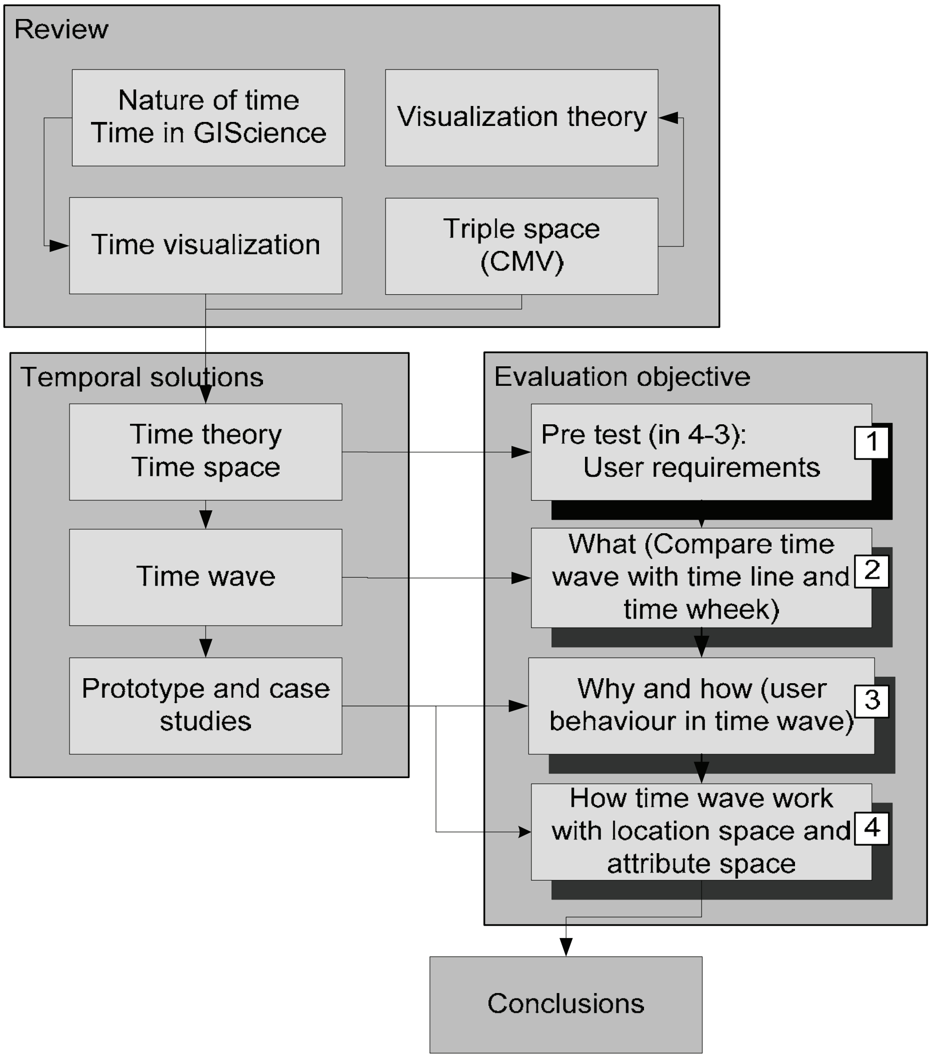



**Figure 7-1. The usability evaluation in the context of this research project.**

The third step (Test 2), took a more detailed look at the time wave, based on selected results from Test 1. The aim of Test 2 was to study users' behavior while working with the time wave:

1. Why does the time wave show a better performance in answering particular types of questions?
2. How do the users behave while they answer temporal questions with time wave?

The fourth step (Test 3) evaluated the workings of the time wave in an overall CMV environment. The aims were to find out:

1. How do the users behave in a CMV environment based on triple space?
2. How can triple space assist users to find answers?

Both tests 2 and 3 were implemented through a combination of eye movement registration and the 'think-aloud' method of studying behavior and users' thinking processes.

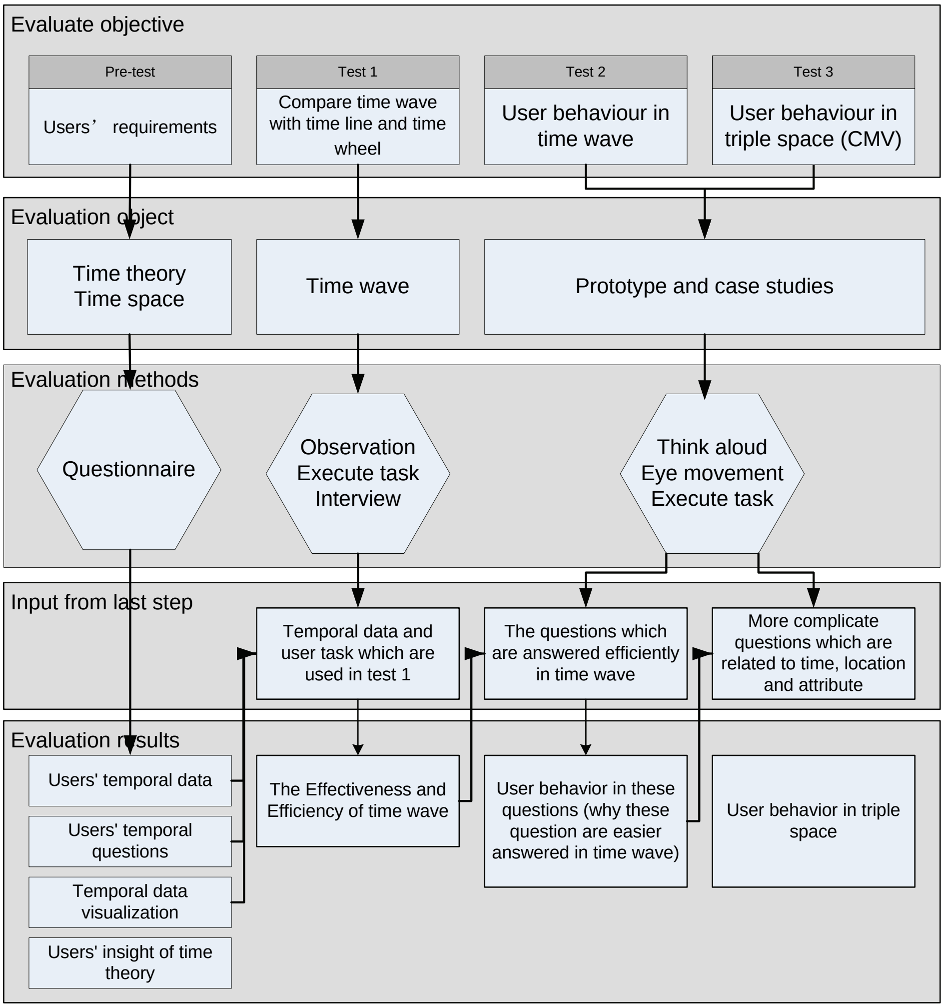



**Figure 7-2. Evaluation plan.**

Following the scheme in Figure 7-2, the evaluation tests 1, 2 and 3 will be described in detail in the following sections.

## *7.3 Selected evaluation methods*

Many different methods for evaluating usability were listed at the beginning of this chapter. This section describes the methods chosen for this research.

Evaluation methods can be classified as qualitative and quantitative. Quantitative evaluation methods are supported by mathematical and statistical analysis to provide a direct result for selected variables, such as how long it takes for users to execute the tasks, and the ratio between correct and incorrect users' answers. The most common evaluation methods for quantitative analysis are probability sampling, surveys and controlled experiments. However, quantitative evaluation methods do not provide any understanding of the users' cognitive processes (Blok, 2005). They supply information on users' reactions, but do not explain the 'how' or 'why' of their actions. Thus, in order to gain insight into users' thinking processes and behavior, qualitative methods are needed that focus on factors that influence the result or observation (Ogao, 2002). Examples of qualitative methods are interviews, focus group discussions, and think-aloud recordings.

In the literature there are many examples and discussions which evaluate the usability of maps or GISs by qualitative methods (Monmonier, 1994; Suchan and Brewer, 2000) or quantitative methods (Brown, 1980; Kumar, 1999) or both (Cornwell and Robinson, 1966; Brewer, 1989; Monmonier, 1991).

The time wave is to be used for temporal exploration in an interactive, visual environment. The question 'does it work' cannot be answered by a single usability method, since we are also interested in its effectiveness, efficiency and the users' satisfaction. In other words, to determine 'how long does it take to find an answer', 'how correct is it', 'how easily does it work', and 'what are the users' thought processes while executing the task' requires a combination of qualitative and quantitative evaluation methods. In the next section, the choice of evaluation methods is explained and justified.

**Questionnaire**

A questionnaire is a traditional and popular method of collecting certain target information from respondents, such as user requirements and feedback (Burkhard and Meier, 2004; Blok, 2005; Mellenbergh, 2008). The questions are structured according to a certain purpose as defined by the person collecting the information, and the answers are collected via a standardized method, such as multiple choice questions, which can be analyzed easily. The advantages of a questionnaire are that is cheap to compile, easy to distribute and to collect.

In the pre-test, the questionnaire was structured according to time theory, to get a systematic overview of users' requirements (see chapter 4).

**Interview**

Compared to a questionnaire, an interview is an interactive and more labor-intensive method of collecting users' requirements and feedback. An interview is a conversation between the interviewer and interviewee conducted to obtain a response with a certain objective. There are structured and unstructured interviews (Kumar, 1999). A structured interview is similar to a questionnaire in that the questions are pre-designed in a certain order so that the answers are structured and easy to process. An unstructured interview is more flexible, although the questions are formulated within a framework (van Elzakker, 2004). The advantages of an interview are its interactive nature and the interviewer can collect the responses of interviewees, including their mood and expression in real time. It is also possible for the interviewer to adjust the content of a question according to the feedback from the interviewee. The disadvantage of an interview is that it demands a lot of time.

In Test 1, the interview was arranged after the users had executed certain tasks. The interviewees could provide direct feedback about their experiences, such as level of satisfaction and comments on the working environment.

**Tasks and observation**

Observing users' performance while executing their tasks is a widely accepted method of evaluating the performance of a graphic representation. The main advantage of observation is that "it is very direct and that memory errors do not occur" (Blok, 2005). What can be observed includes not only the results of the users' answers and their response times, but also their behavior, such as what they say, their actions, etc.

- **Thinking aloud**

With the emphasis on cognitive and perception studies in the geovisualization field, the think-aloud method helps provide understanding of users' thought processes and behavior (Van Sommers, 1984; Ericsson, 1993; van Elzakker, 2004; Blok, 2005). Think aloud is one example of an observation method (Suchan and Brewer, 2000). Think-aloud methods ask the user to speak their thoughts out loud while they execute a series of tasks. This includes thoughts about what they are looking at, thinking, doing and feeling as they go about their prescribed tasks.

In this research, the think-aloud method was used together with eye movement observation to understand the performance of users while working with the time wave. Eye movement methods have similar but complementary objectives to think aloud in usability evaluation. The disadvantages of the think-aloud method is that the participants are somehow disturbed by the requirement to think aloud, and it is possible that their words may differ from their actual thoughts. Using this method in combination with eye movement limits this disadvantage.

- **Eye tracking technology**

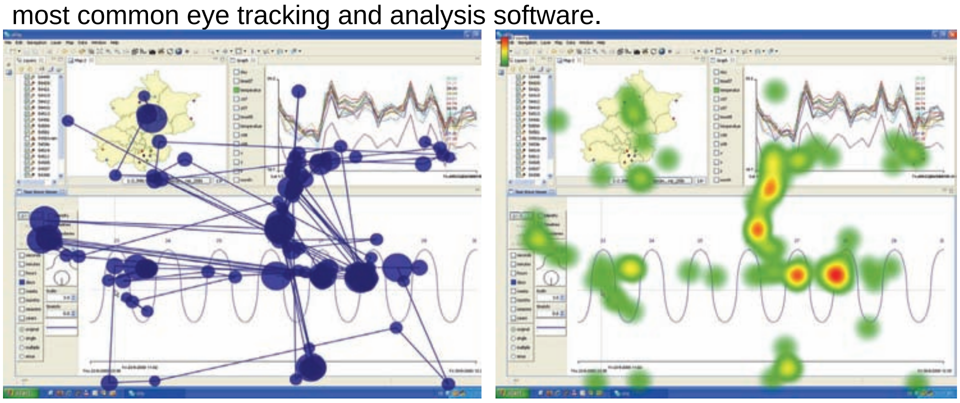
Eye movement studies were conducted long before computers became widely used. According to Jacob (2003), such studies for basic psychological research were being used about 100 years ago, addressing a set of versatile questions, e.g. it has been used when studying language comprehension and production (Henderson and Ferreira, 2004), scene perception (Rayner, 1992; Henderson and Ferreira, 2004), reading (Wade and Tatler, 2005) and spatial reasoning (Keehner, 2008). Eye movement analysis has also been introduced and integrated into usability studies. Goldberg and Kotval (1999) contended that eye movement analysis has been used for at least 70 years in evaluating the performance and usability of spatial displays within information acquisition contexts. Recoding eye movements does not rely on self-reporting; therefore it can be considered an objective method and can enhance traditional performance tests, protocol analysis, and walk-through evaluations of a system (Goldberg and Kotval, 1999).

In geo-visualization, the use of eye movement recording and analysis for evaluating users' performance can be considered both 'old' and 'new'. In this context, 'old' means that many typical evaluation studies supported by eye movement recording and analysis in other disciplines can also be used for geo-visualization. There are such studies, for example, in computer interface evaluation (Mackworth, 1976; Robinson, 1979; Goldberg and Schryver, 1993; Goldberg and Kotval, 1999; Crowe and Narayanan, 2000), human computer interaction (HCI) usability testing (Benel et al., 1991; Jacob, 1991; Ellis et al., 1998; Cowen, 2001) and cognitive processing (Just and Carpenter, 1976; Mackworth, 1976; Loftus, 1978). Early eye movement studies in geo-visualization were driven by cartographic research questions (Steincke, 1987; Brodersen et al., 2002). 'New' refers to developments in technology that enable us to collect more data than ever before and to new methods in geovisual analytics which enable us to design and visualize complex and dynamic processes. Eye tracking technology offers new opportunities and challenges in evaluating and analyzing the cognitive processes of users while working on large, complex, often interactive, data visualizations.

Eye movement recording and analysis may also offer additional tools to enhance usability studies. Several research papers integrating usability studies and eye movement analysis have been published in the geo-visualization domain (Brodersen et al., 2002; Fabrikant et al., 2008; Çöltekin et al., 2009; Garlandini and Fabrikant, 2009; Fabrikant et al., 2010) and continue to attract attention.

Along with the gradually maturing hardware technology to track eye movements, the applications (software) that utilize information derived from eye movements are also becoming more and more comprehensive. Eye tracking research results in an enormous amount of highly detailed data. The tracker typically reports a time stamp (temporal data) and gaze point location within a configured screen coordinate system (spatial data).

Much research has been done to analyze and make use of the huge amounts of eye movement data efficiently (e.g., (Scinto and Barnette, 1986; Belofsky and Lyon, 1988; Krose and Burbeck, 1989; Pillalamarri et al., 1993; Ponsoda et al., 1995; Gitelman, 2002; Fabrikant et al., 2008)). When dealing with traditional eye tracking data, several metrics are reported in usability studies, such as fixation frequency, gaze duration, area of interest (AOI) analysis, and scan path comparisons. These metrics are used to analyze the visual search processes of users as well as to establish the location of their overt attention. For instance, such metrics can be helpful to find out which part of a map attracts most attention at first glance, or to determine the order of user gaze points while observing a map or solving tasks with it. These metrics can be represented as density maps, gaze plots and graphs. Figure 7-3 shows two examples of visualization methods commonly used in representing eye movement data. On the left of the figure, there is a gaze plot which represents saccades, fixations and fixation-durations plotted as a scan path; on the right, there is a density map showing the average fixation-duration of multiple users (density maps can also represent fixation counts). These representations provide a simple and direct, but static, view of eye movement data and, as such, they are found in most common eye tracking and analysis software.



(a) (b)

**Figure 7-3. Two common methods used in visualizing eye movement data (screen view as background) produced in Tobii Studio. a) A gaze plot and b) a fixation density map.**

Eye movement tracking was used together with the think-aloud method to understand user behavior in the CMV environment.

## *7.4 Test 1*

The aim of Test 1 was to compare the performance of the timeline, time wheel and time wave. The test consisted of two parts: one on the role of the graphic representation as temporal visualization and one on their role as an interactive tool. The test set-up allowed the three representations to be judged on their effectiveness (whether the system could answer different temporal questions), efficiency (which method requires the least work/time to answer questions) and satisfaction (how the users feel about the representations).

### 7.4.1 Test preparation

**Test data**

According to the result of the pre-test, the data requirements for further testing had to be of both a linear and cyclic nature. Therefore, meteorology data was selected; it contained daily rainfall statistics for Xi'an and Haikou between the beginning of 2001 and the end of 2002, plus instances of temperature drop, which occur frequently during rainfall. Xi'an is located in a semi-arid area in the center of China, whereas Haikou is located on the coast. For each rainfall event, the date of the rainfall (instant) and the start- and end times (interval) were known.

**Test questions (user tasks)**
Based on the discussions on temporal data and temporal user tasks in chapter 4, the test questions were designed and selected carefully to cover certain aspects of the data characteristics (linear versus cyclic, etc.), the temporal query (if, when, etc.) asked, and the purpose of the graphics (representation and/or interaction). Figure 7-4 summarizes this approach.

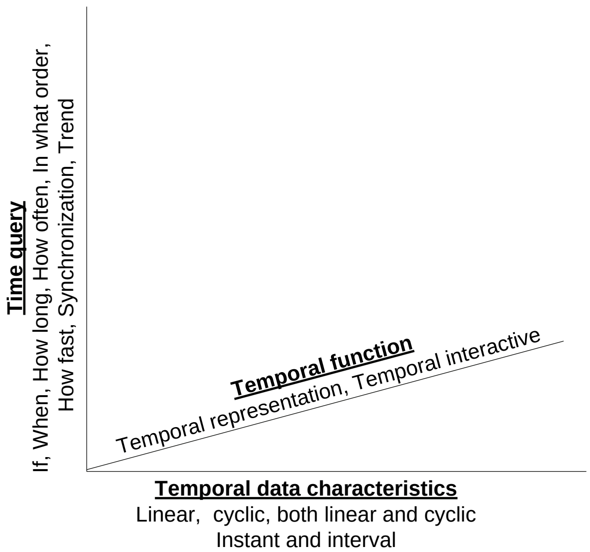



**Figure 7-4. A general view of each the necessary components for designing test questions.**

By combining the temporal data characteristics with the time questions, 19 questions were formulated (Table 7-1).

<table>
<tr><th colspan="2">Representation</th><th colspan="2">View on time</th></tr>
<tr><th></th><th></th><th>Linear</th><th>Cyclic</th></tr>
<tr><td rowspan="10">Time questions</td><td rowspan="1">If</td><td>(1) Did it rain on $2^{nd}$ Feb. 2001 in Haikou?</td><td>(2) Did it rain on the second Tuesday in February in Haikou?</td></tr>
<tr><td rowspan="2">When</td><td>(3) When was the first rain in 2001 in Xi’an?</td><td>(4) Which season had the most frequent rainfall in Xi’an?</td></tr>
<tr><td colspan="2">(16) Which year had the earlier first rain in Xi’an (2001 or 2002)?<br>(17) To compare the rainy Tuesdays of March in 2001 and 2002, which year had the earlier rainfall date?<br>(19) Which month in 2001 or 2002 had the most frequent rain in Xi’an city?</td></tr>
<tr><td>How long</td><td>(6) How long did the second rainfall last in 2001 in Xi’an?</td><td>(5) How many quarters of hours did the rainfall last? (the first rainfall in 2001 Xi’an)</td></tr>
<tr><td rowspan="2">How often</td><td>(7) How often did it rain in Jan. 2002 in Xi’an?</td><td>(15) Was there seldom rain in Xi’an in the winter (from Dec. 2001 to Feb. 2002) (seldom means less than 15 times)?</td></tr>
<tr><td colspan="2">(8) How often did it rain in the second week of Feb. 2001 in Xi’an?<br>(18) How many weekends had rain in Feb. 2001 in Haikou?</td></tr>
<tr><td>In what order</td><td>(9) Which city had the earlier rainfall in 2001?</td><td>(10) Which city had the earlier rain in the spring of 2001?<br>(11) Which city had the earlier rain in the third week of summer in 2001?</td></tr>
<tr><td>Synchronization</td><td>(12) Does the drop in air temperature happen after rainfall in Xi’an?</td><td>(13) Did all the drops in air temperature happen after rainfall in the autumn of 2001?</td></tr>
<tr><td>Trends</td><td>(14) Did it rain more frequently in Haikou than in Xi'an in 2001?</td><td></td></tr>
</table>

**Table 7-1. Temporal questions for visual data representation in Test 1.**

To evaluate the temporal interaction capabilities, 12 temporal tasks covering the selection function were defined (Table 7-2).

<table>
<tr><th></th><th></th><th colspan="2">Instant</th><th colspan="2">Interval</th></tr>
<tr><th></th><th></th><th>Single</th><th>Multiple</th><th>Single</th><th>Multiple</th></tr>
<tr><td rowspan="2">Linear</td><td>Single scale</td><td>(1) 2001</td><td>(5) January and August 2001</td><td></td><td></td></tr>
<tr><td>Multi-scale</td><td>(2) $1^{st}$ Feb. 2001</td><td>(6) $3^{rd}$ Feb. 2001 and $21^{st}$ July 2002</td><td>(9) $2^{nd}$–$5^{th}$ March 2001</td><td></td></tr>
<tr><td rowspan="2">Cyclic</td><td>Single scale</td><td>(3) Spring in 2001 and 2002</td><td>(7) Spring in 2001 and summer in 2002</td><td>(10) The second week in 2001</td><td>(11) The first two days in each month</td></tr>
<tr><td>Multi-scale</td><td>(4) The first month in spring in 2001 and in 2002</td><td>(8) First month in spring 2001 and second month in summer 2002</td><td>(12) All weekend</td><td></td></tr>
</table>

**Table 7-2. Selection of temporal interaction tasks for Test 1.**

### Test working environment

Comparable working environments were designed to compare the performance of the timeline, time wave and time wheel. The timeline and time wheel were realized in the ArcGIS environment, and the time wave in the uDig environment (see discussion in chapter 6). Basic functionality, such as zoom-in/out, overview, selection, and identification, was available in all three environments. An introductory video to both the representations and their functionality was shown to all users before the start of the test. The users were also given time to familiarize themselves with the working environments. Figures 7-5, -6, and -7 show that the environments were designed to have the same look and feel.

In the timeline environment, a timeline starting at 2001-01-01 and ending at 2002-12-31 is shown from left to right. The temporal units available were year, month, week, day, hour and minutes. The rainfall events in Haikou and Xi'an were represented in blue and red, respectively. Depending on the time scale, interval data (the interval of each rainfall) was only visible at a large scale and represented by a line with a start and end point. The temperature drops were symbolized by grey squares. Figure 7-5a shows an overview of the timeline environment. A data layer window is shown on the left and users can switch the different data layers on or off. They can zoom in for more detail. For example, the inset in Figure 7-5a, zoomed in to the beginning of 2001 and with the mouse-over function, revealed the date of the second rainfall event. Figure 7-5b shows a similar detail. The green star indicates the start of each month. An example of a full rainfall event represented by the green line is seen in Figure 7-5c. The start and end times of the event are shown by the points in the city's color. In this case, the user can use the identify function to view the details: the rainfall started at 12:00, ended at 12:45, and lasted 45 minutes. Figure 7-5d shows the temperature drop event (grey squares) together with the rainfall event. The selection function in the timeline working environment used that provided in the ArcGIS software.

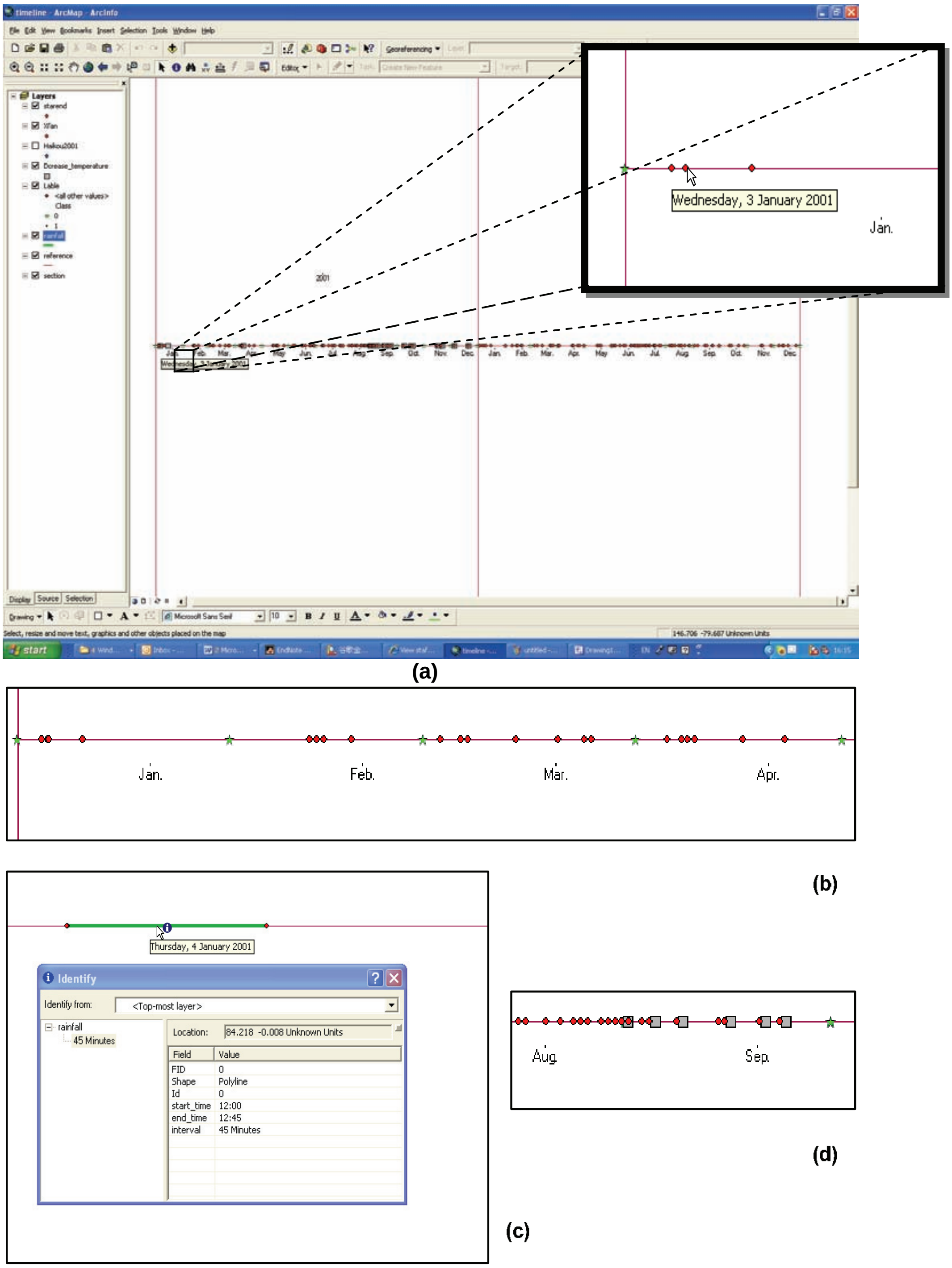
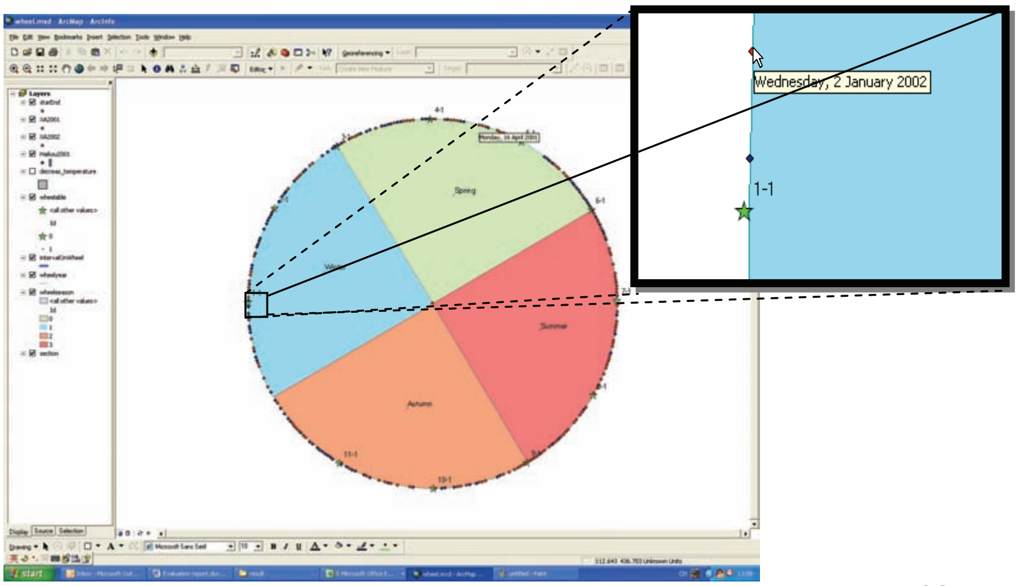
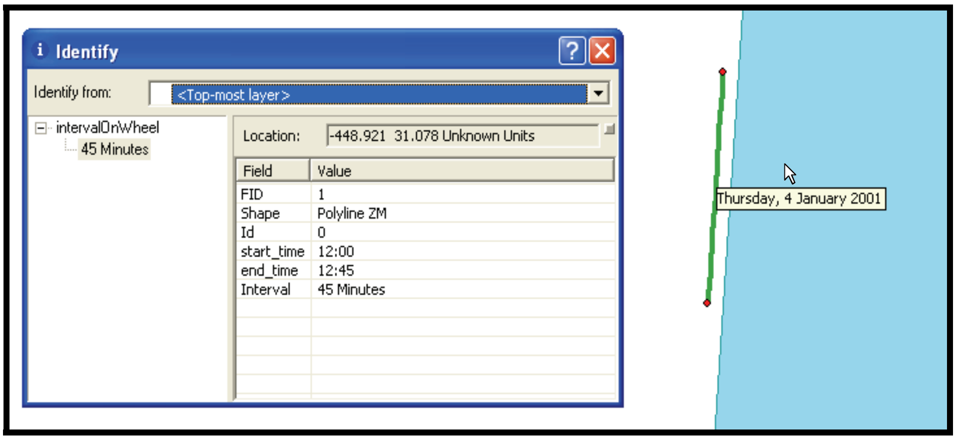



**Figure 7-5. The working environment of the timeline under ArcGIS software: a) overview; b) zoom-in view; c) interval of rainfall representation with identify function window; d) temperature drop events and rainfall events in Xi'an.**

Figure 7-6a gives an overview of the time wheel environment. Similar to the timeline, the left-hand window is a data layer view. The circle represents one year, run clockwise, and starts on the left of the circle. Here the circle is divided into four parts to represent the four seasons. The inset shows some detailed information. Figure 7-6b shows a rainfall event (interval) with a green line, and the identify function reveals the details of the event. Figure 7-6c zoomed in on a month marker (1st April) and Figure 7-6d shows a mouse-over function to obtain details on the event. It should be mentioned that the time wheel representation holds the rainfall event of both 2001 and 2002 on the same circle. This means a red point on the wheel reference could be from 2001 or from 2002. For a question such as ‘did it rain on 2nd July 2001 in Xi’an?’, users have to find 2nd July on the wheel first. If there is a red point (rainfall event in Xi’an city), they then use the mouse-over function or the identify function to see which year the rainfall occurred. The selection function in the time wheel working environment also used that provided by ArcGIS software.




**(a)**

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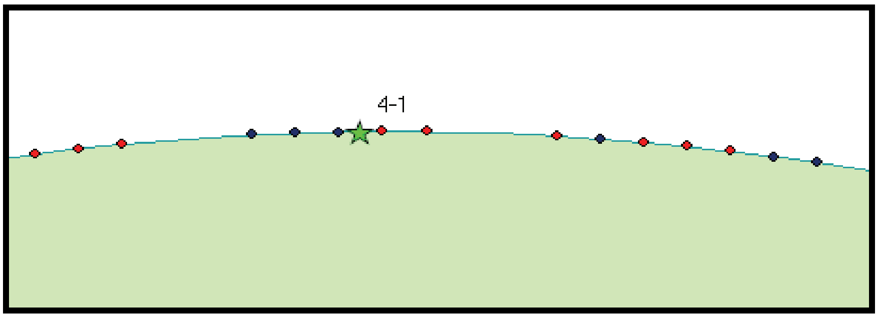
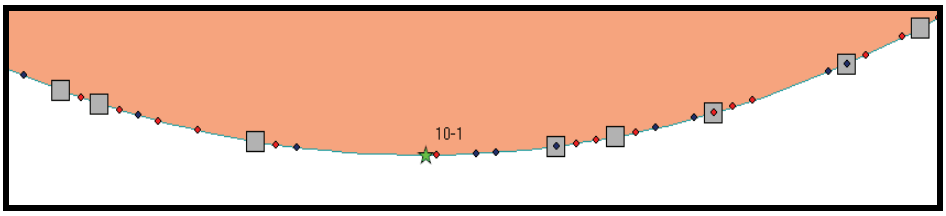



**(c)**




**(d)**

**Figure 7-6. The time wheel working environment: a) overview; b) time interval representation with identify function; 3) zoom-in view; d) temperature drop events (grey squares).**

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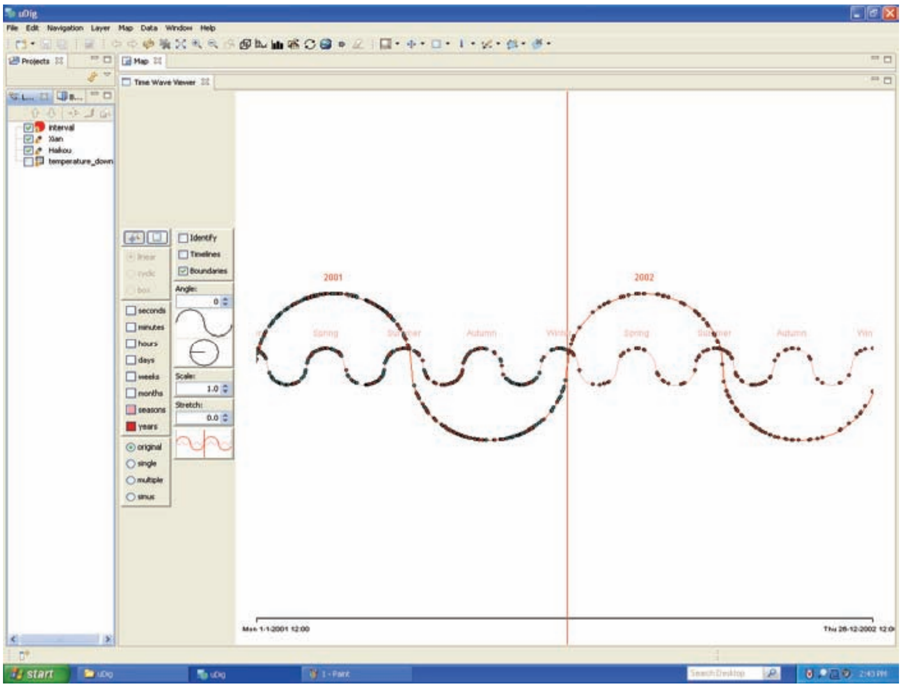
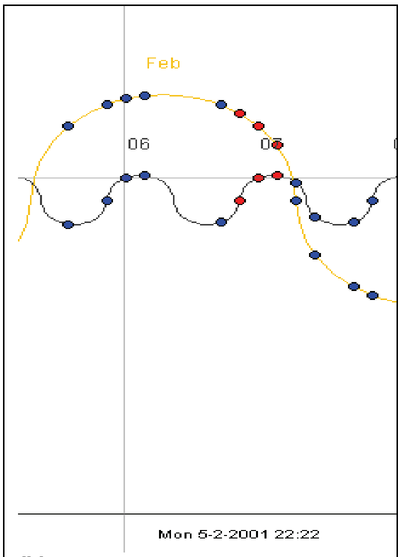
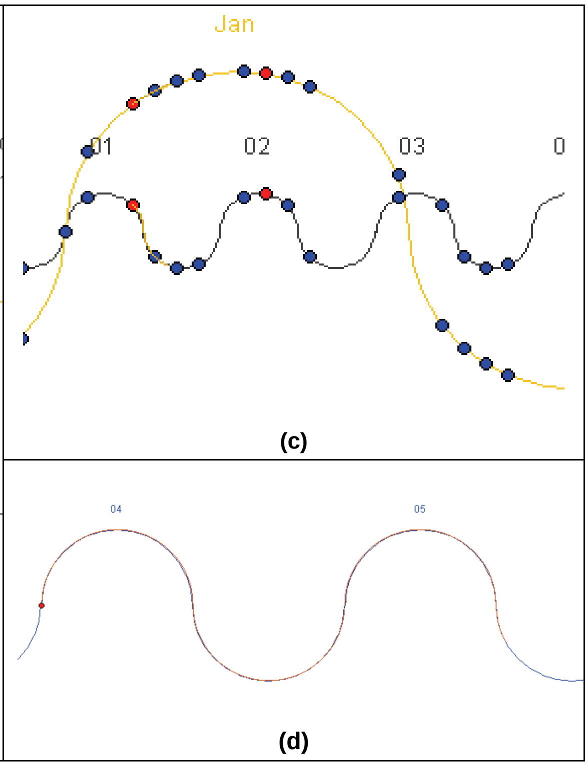
The time wave working environment is shown in Figure 7-7. The time wave window is on the right and it also has a window for the data layers. The time wave functions are shown on the left-hand side of the wave window. In Figure 7-7a, a year and season wave are visible. The wave starts from the left. Figure 7-7c shows a zoom-in result view and Figure 7-7b shows how the timeline function can help the user identify the time. Figure 7-7d shows an interval time of one rainfall (the red line on the green line (hour wave), and in this case the rainfall lasted about 1 hour and 45 minutes. The selection functions were discussed in chapter 6 in detail, including linear selection, cyclic selection, and box selection.




(a)




(b)




(c)

(d)

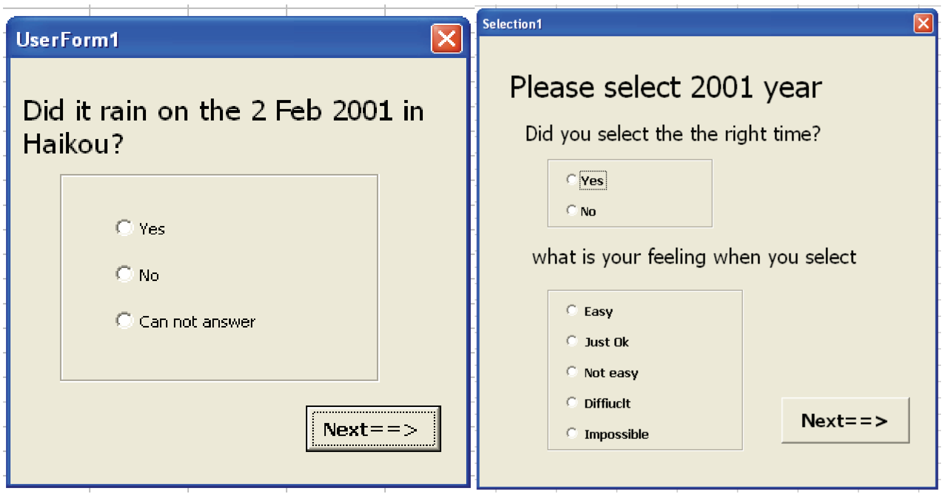
**Figure 7-7. The time wave working environment: a) overview; b) zoom in and timeline function; c) a zoom-in result view with two time scales; d) interval data on time wave.**

### 7.4.2 Test execution

Sixty ITC MSc students participated in the test. They were split into three equal groups, each addressing the same tasks but with a different representation (time wave, timeline and time wheel). All the participants first looked at an introductory video explaining the data, working environment and the tasks they were to perform. They were given some dummy tasks to familiarize themselves with the test environment. The tasks (questions) were given on a separate screen via an Excel interface (Figure 7-9) which automatically registered the users' answers and execution time (see Appendix II). Figure 7-9a shows the interface for a question from Table 7-1, and figure 7-9b shows one for a question in Table 7-2. Here the user's satisfaction was also tested. Figure 7-8 shows a photograph of the test room with participants while taking the test.

**Figure 7-8. Photographs of the test room with participants taking the test.**

After the test, five randomly selected users from each of the three groups were interviewed to collect their general opinions of the working environment.



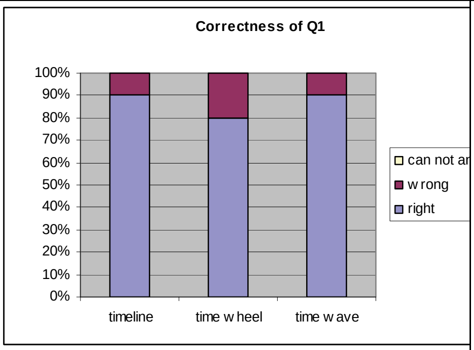
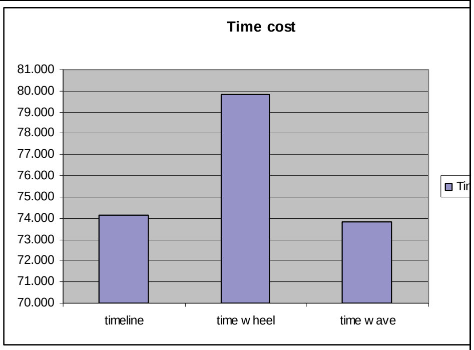

**(a)** **(b)**

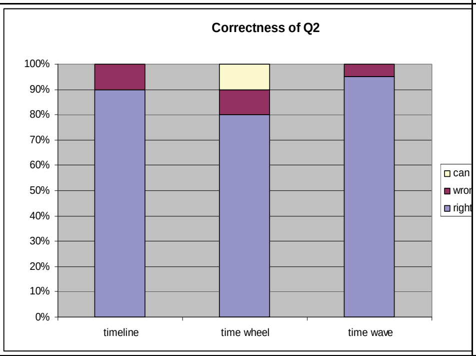
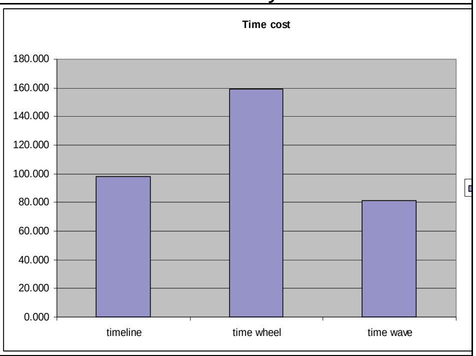
**Figure 7-9. Interface of the task screens. a) An example of the first question in Table 7-1; b) an example of the first question in Table 7-2.**

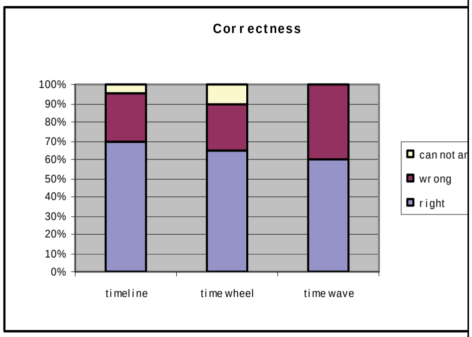
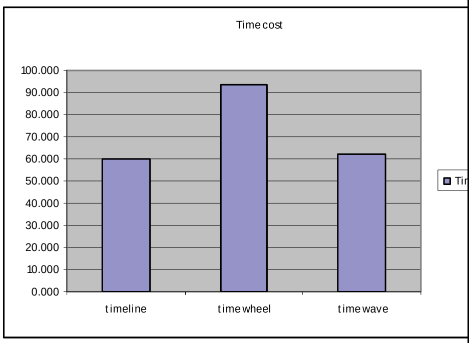
### 7.4.3 Test results analysis

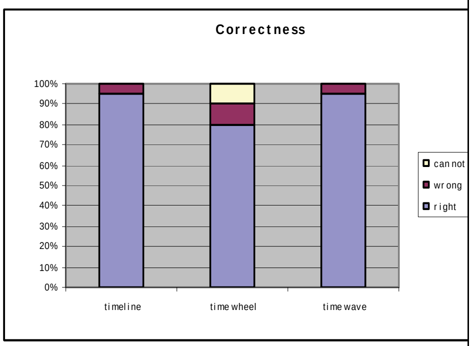
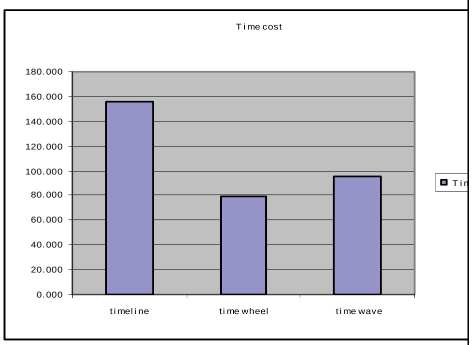
Here, the results of Test 1 are discussed: in the first part the discussion focuses on the comparison of the timeline, time wheel and time wave as temporal representations; in the second part, the three representations as interaction tools are compared. The answers (correctness and response time) for each question of Part 1are shown in diagrams for easy comparison. For Part 2, a diagram of the users' satisfaction has also been added.

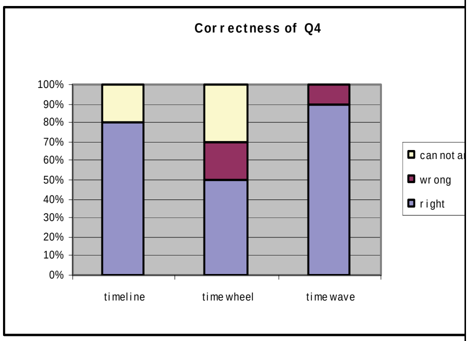
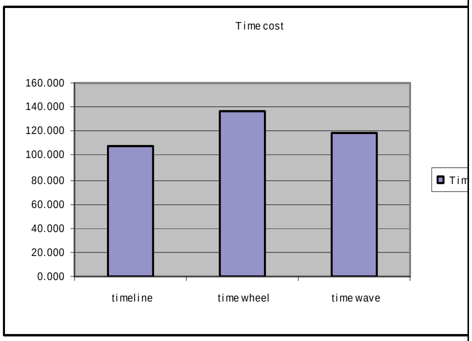
**Part 1. The timeline, time wheel and time wave as temporal representations**

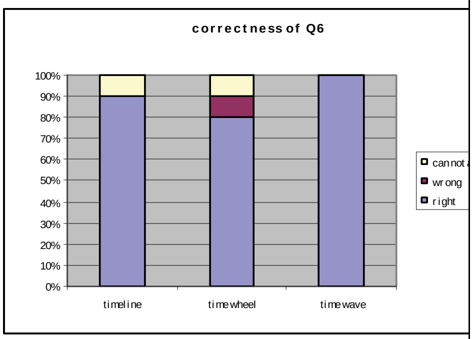
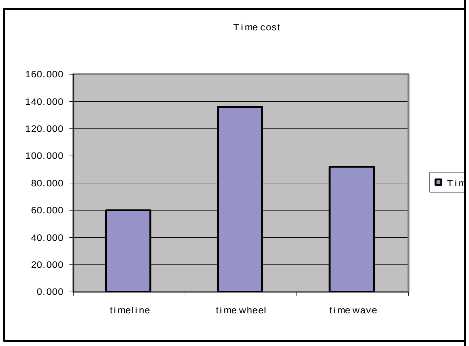
<table>
<tr><td colspan="2">1. Did it rain on the 2nd Feb 2001 in Haikou? (linear + if)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations scored more than 80% correct answers and all the participants thought they could find the answer based on the representation.</td><td>The timeline and time wave are linear in nature, which makes it easy for to find the time instance in both. For the time wheel, it was more difficult because the user had to distinguish between 2001 or 2002 in the same circle before taking a decision. It is obvious that the time wheel scored less for efficiency.</td></tr>
</table>

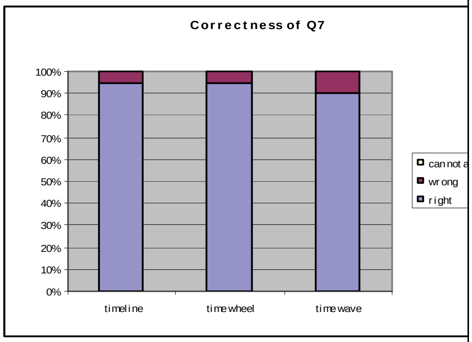
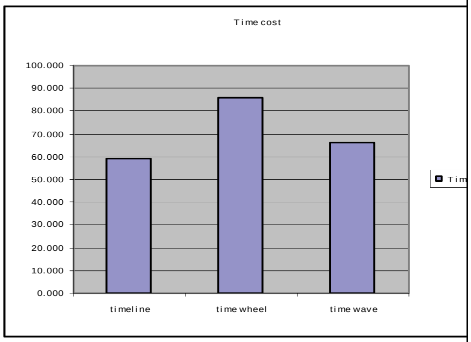
<table>
<tr><td colspan="2">2. Did it rain on the second Tuesday in February in Haikou? (cyclic + if)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations scored over 80% correct answers, but 10% of the users thought they could not answer this question from the time wheel representation. From a theoretical perspective, this problem was not anticipated.</td><td>The time wave showed a better performance in this question, because the week wave can supply additional spatial information to locate Tuesday. Although the time wheel is considered as a cyclic representation, only one cycle can be represented. If the scale of the user task was not on the same scale as the representation, the time wheel performed less well.</td></tr>
</table>

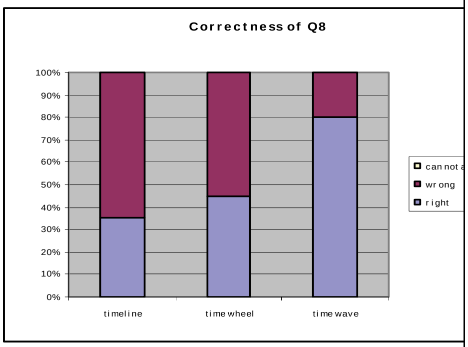
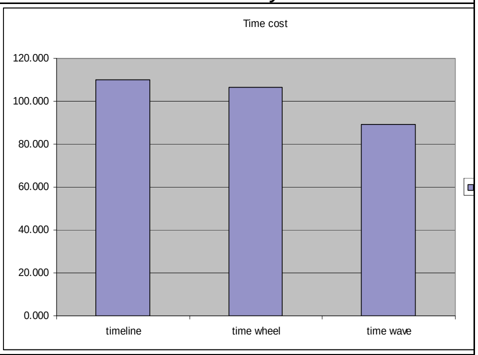
<table>
<tr><th colspan="2">3. When was the first rain in 2001 in Xi’an? (linear + when)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>The correctness of the three representations was 70%, 65% and 60%, respectively.</td><td>This question is of a linear nature. Users can follow the time with the timeline and time wave in order to identify the first rain. With the time wheel, they first had to find 2001, and then the first rain (which was why the time wheel had a longer response time).</td></tr>
</table>

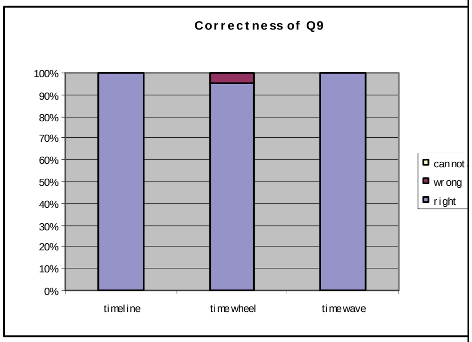
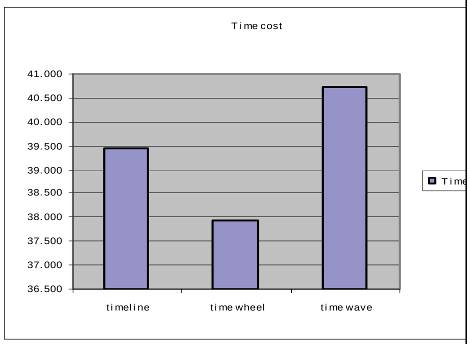
<table>
<tr><th colspan="2">4. Which season had the most frequent rainfall in Xi’an? (cyclic + when)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>The timeline and time wave scored better for this question than the time wheel. The wheel was expected to score better, but the participants found it difficult to select the right year, as revealed during the interviews.</td><td>The response times were as expected, with shorter times for the time wheel and time wave. This is due to the cyclic nature of the data.</td></tr>
</table>

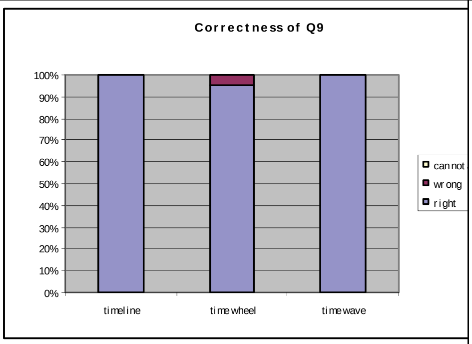
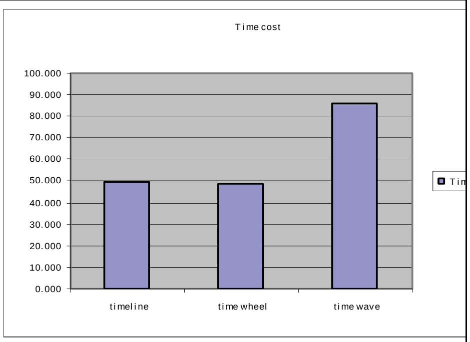
<table>
<tr><th colspan="2">5. How many quarters of hours did the rainfall last (the first rain in 2001 Xi'an? (cyclic + how long)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>When different time scales were involved in a single complex question, the participants were easily lost. This question required starting to search from the year scale and zooming in to the hour and even minute scales. 20% and 30% of the timeline and time wheel participants thought this was not possible. The time wave scored better.</td><td>It was expected that the time wave would perform best here, but the statistics show the timeline did slightly better. A more detailed look at the response data revealed that one of the time wave participants took an extremely long time, thereby influencing the statistics.</td></tr>
</table>

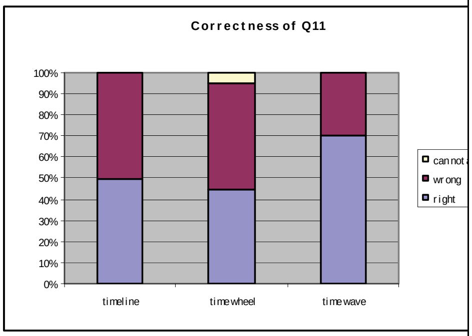
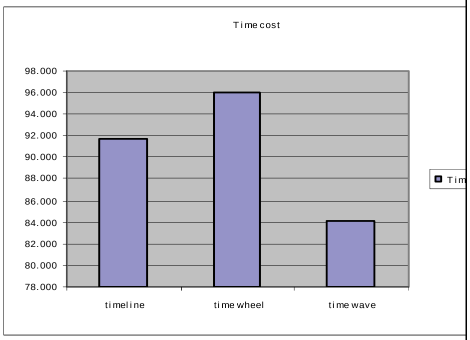
<table>
<tr><th colspan="2">6. How long did the rainfall last (the second rain in 2001 in Xi'an)? (linear + how long)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>The time wave had a 100% score. The appearance of the different wave scales from year, to season, month, week, day and hour, even minutes, in their natural order proved to be of great help for the participants.</td><td>Here the higher response times of the wave were not due to an outlier. It was attributed to the fact that the participants zoomed in to a more detail scale in the time wave than in the timeline.</td></tr>
</table>

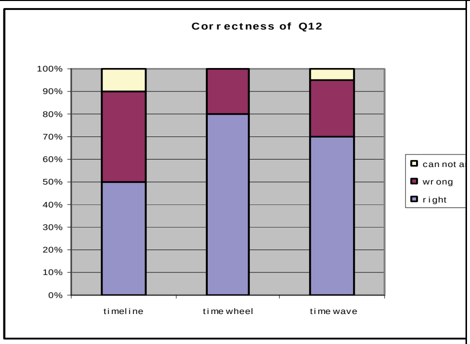
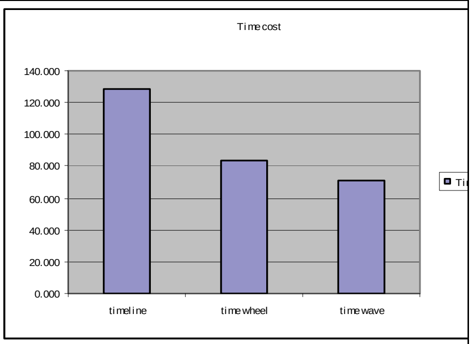
<table>
<tr><td colspan="2">7. How often did it rain in Jan. 2002 Xi'an? (linear + how often)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations scored more than 90% correct. Thus all of them can be used to answer this question.</td><td>The timeline proved to be the most efficient of the three representations, showing that the timeline was good for answering linear time questions.</td></tr>
</table>

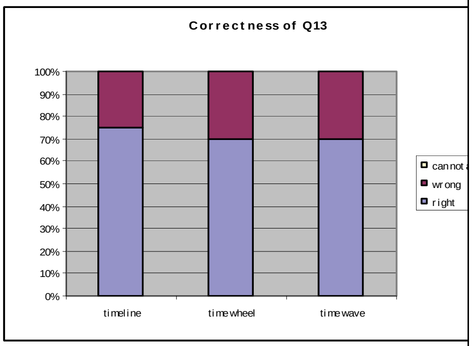
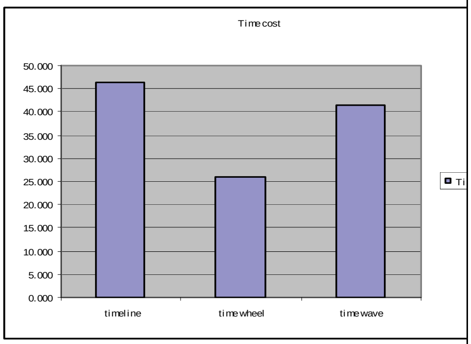
<table>
<tr><td colspan="2">8. How often did it rain in the second week of Feb. 2001 in Xi'an? (both cyclic and linear + how often)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>This is a typical question about both linear and cyclic time. The disadvantage of the timeline and time wheel was obvious (scored less than 50% correct answers). The time wave showed the best performance for both linear and cyclic time questions.</td><td>The time wave showed better efficiency than the timeline or time wheel. However, the difference was not large.</td></tr>
</table>

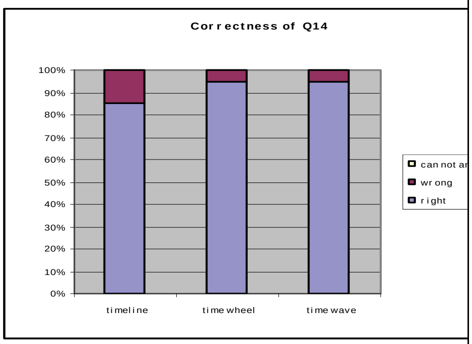
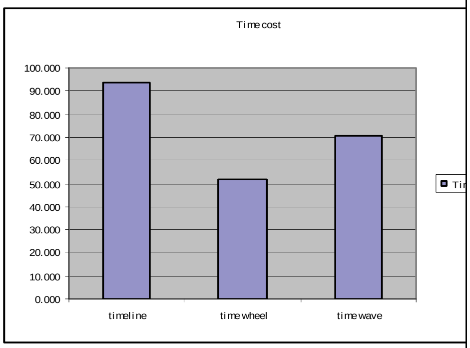
<table>
<tr><td colspan="2">9. Which city had the earlier rain in 2001? (linear + in what order)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations answered this question well (scores of more than 95% correct answers).</td><td>The graph appears to show a significantly short response time, but the vertical scale represents differences of only a few seconds.</td></tr>
</table>

<table>
<tr><td colspan="2">10. Which city had the earlier rain in the spring of 2001? (cyclic + in what order)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations could be used to answer this question.</td><td>The time wave showed the worst performance, due to some confusion about where the season started on the wave, and on which wave (season or month) to look. This revealed a disadvantage of multiple waves representing multiple time scales.</td></tr>
</table>

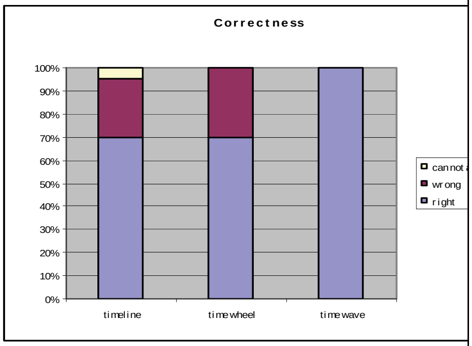
<table>
<tr><td colspan="2">11. Which city had the earlier rain in the third week of summer in 2001? ( both linear and cyclic + multiple scale + in what order)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>The complexity of the question led to low scores.</td><td>This was a question about linear (2001) and multiple cyclic time scales (season and week). The time wave showed the highest efficiency for the three representations.</td></tr>
</table>

<table>
<tr><td colspan="2">12. Did all the drops in air temperature occur after rainfall in Xi'an in 2001? (linear + synchronization)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>The timeline showed the lowest score because of over-plotting on it.</td><td>The graphic representation on the time wave and time wheel had more options to show this data pattern.</td></tr>
</table>

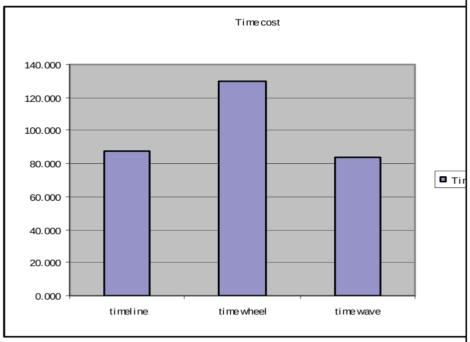
<table>
<tr><td colspan="2">13. Did all the drops in air temperature occur after rainfall in Xi'an in the autumn of 2001? (cyclic + synchronization)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations showed similar scores for this question, and all three methods could answer this question.</td><td>The cyclic nature of the question made it easier to answer with the time wheel.</td></tr>
</table>

<table>
<tr><td colspan="2">14. Did it rain more frequently in Haikou than in Xi'an in 2001? (linear + trends)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>All three representations could answer this question smoothly. They all scored 85% or more.</td><td>The time wheel was the fastest because of the cyclic scale of this question.</td></tr>
</table>

<table>
<tr><th colspan="2">15. it was there seldom rain in Xi'an in the winter (from Dec. 2001 to Feb. 2002) (Seldom means less than 15 times)? (cyclic + how often)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>

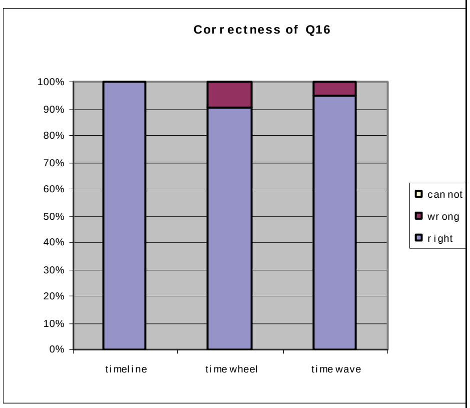



</td><td>

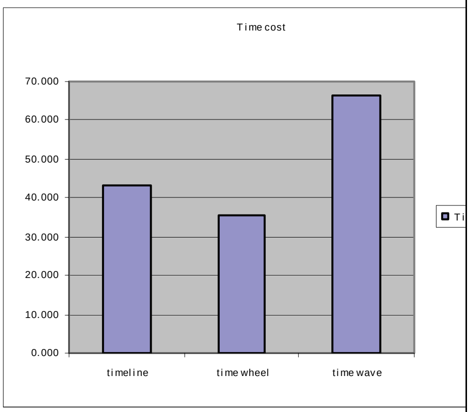



</td></tr>
<tr><td>For this question, the participants had to first locate the winter and count the rainfall events. This question is of both a linear (2001-2002) and cyclic (winter) nature. The better performance of the time wave was because it useful for questions which need both linear and cyclic time.</td><td>The longer response time for the time wheel was due to the fact that users first had to identify the year correctly.</td></tr>
</table>

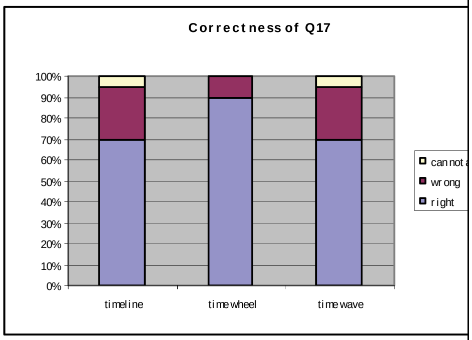
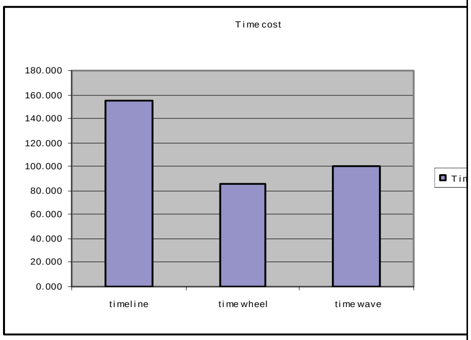
<table>
<tr><th colspan="2">16. Which year had the earlier first rain in Xi'an (2001/2002)? ( both linear and cyclic + when)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th></tr>
<tr><td>

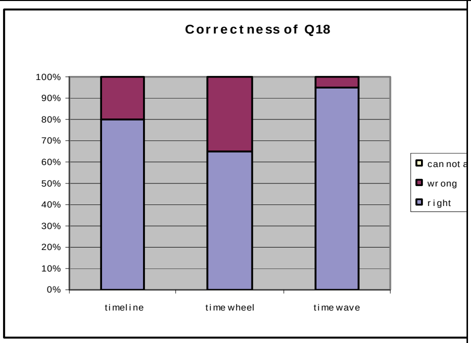
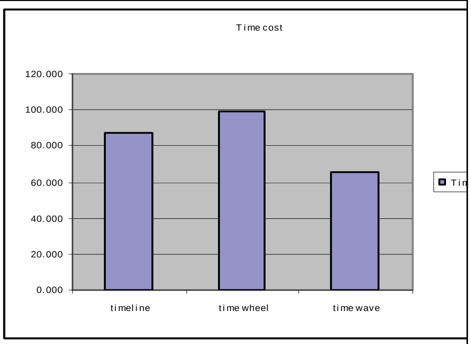


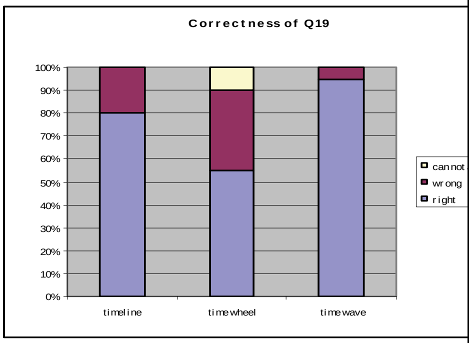
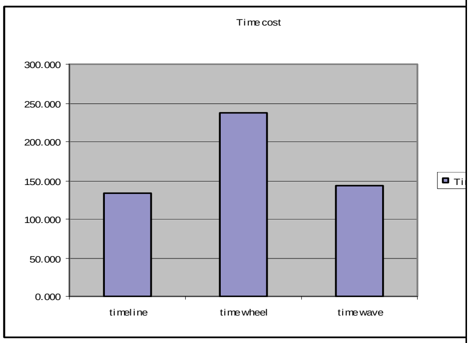

</td><td>



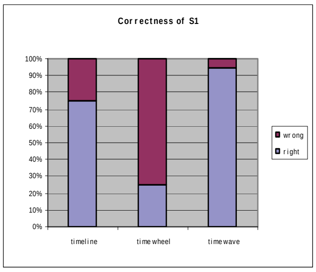
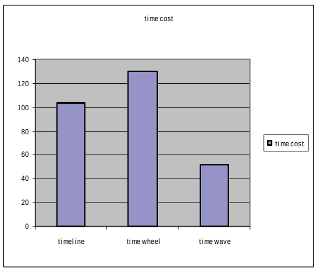
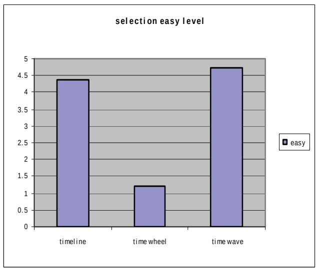

</td></tr>
<tr><td>Here the participants had to find the first rain events in each year, and compare their dates. This question was not difficult to answer.</td><td>This question is on both linear and cyclic time, with the cyclic scale being a year. The unexpectedly slow performance of the time wheel was, again, to do with locating the beginning of an event on the wave.</td></tr>
</table>

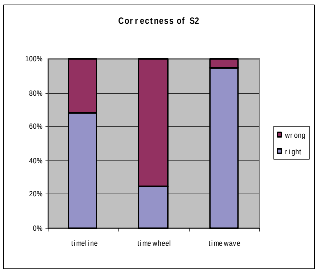
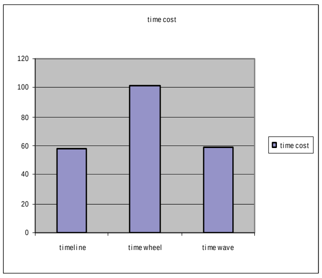
| 17. To compare the rainy Tuesdays of March in 2001 and 2002, which year had the earlier rainy date? (both linear and cyclic + when + multiple scale) | |
|---|---|
| Effectiveness | Efficiency |
|  |  |
| This question includes linear and cyclic time. The scores were close together. | The timeline participants spent the longest in answering this question because it was not easy to find all the Tuesdays in March in each year. |

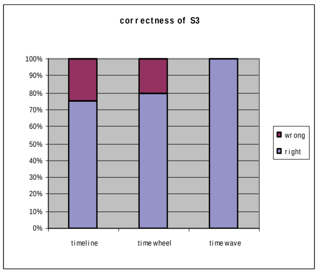
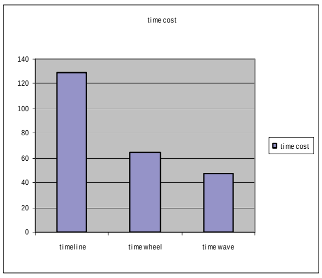
| 18. How many weekends had rain in Feb. 2001 in Haikou? (both linear and cyclic + how often) | |
|---|---|
| Effectiveness | Efficiency |
|  |  |
| Weekends include Saturday and Sunday. To answer, the participants had to first locate Feb. 2001 (linear time), and then count how many rainfall events there were in the weekends. The time wave allowed easy cyclic comparisons which explains its better score. The time wheel showed the worst performance in correctness and efficiency. | The response for the time wave was as expected and it had the best performance. |

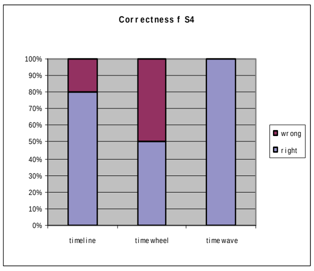
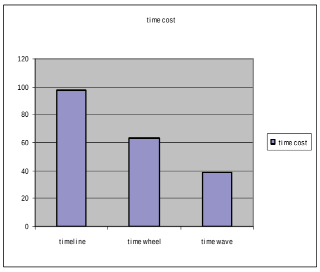
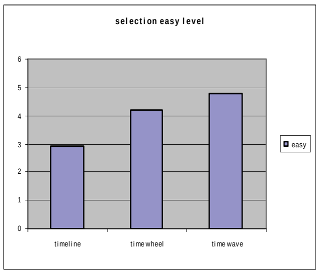
<table>
<tr><td colspan="2">19. Which month in 2001 or 2002 had most frequent rain in Xi'an city? (both linear and cyclic + when)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>This is a typical linear question and both the timeline and time wave showed the better scores.</td><td>The time wave and timeline showed similar response times and were much quicker than the time wheel.</td></tr>
</table>

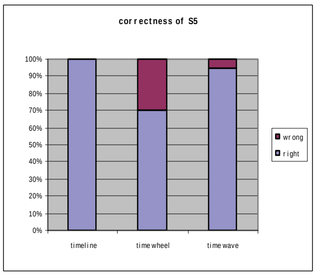
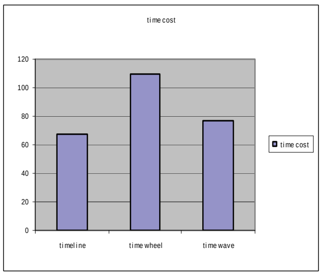
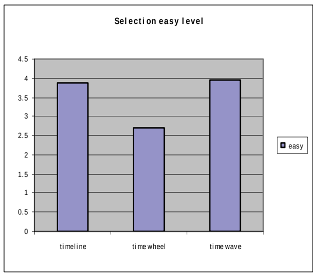
### Part 2. The timeline, time wheel and time wave as interaction tools

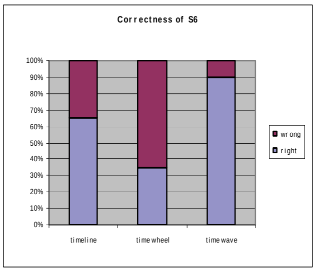
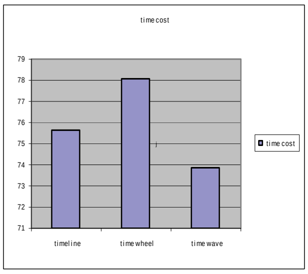
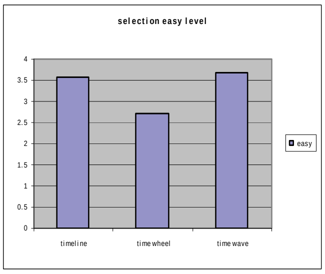
<table>
<tr><td colspan="3">1 Select all the rainfall in 2001 (single scale + single instant + linear time)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td><td>Satisfaction</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>This selection could be based on a linear interval or instant depending on the scale definition. The time wheel's score was very poor because it was very difficult to distinguish 2001.</td><td>Due to the available selection function in the time wave, it had the lowest response times.</td><td>The participants' satisfaction was in line with the results on effectiveness and efficiency.</td></tr>
</table>

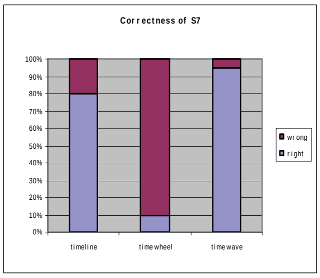
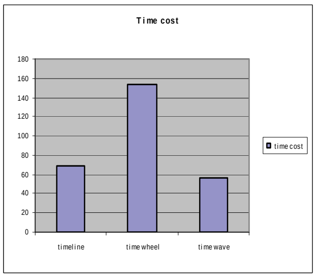
| 2 Select all the rainfall in Feb. 2001 (multiple scale + single instant + linear) | | |
|---|---|---|
| Effectiveness | Efficiency | Satisfaction |
|  |  |  |
| This selection was similar to the last one, but involved an additional time unit (month). The scoring pattern was similar to the previous question. | The response time pattern was similar to the previous question. | The satisfaction for this selection by the different methods further proved that the time wheel was not good at managing linear time. |

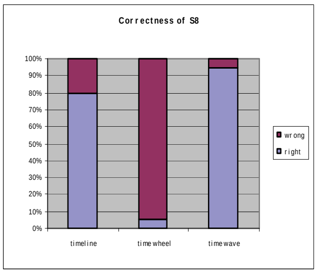
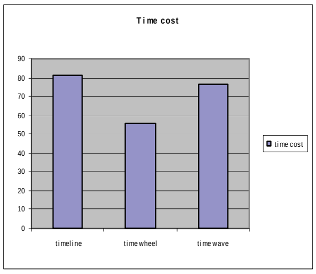
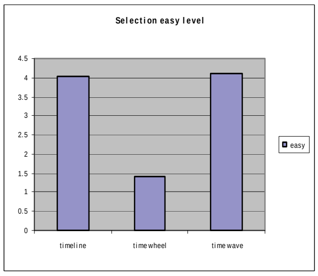
| 3 Select all the rainfall in Spring (single scale + single instant + cyclic) | | |
|---|---|---|
| Effectiveness | Efficiency | Satisfaction |
|  |  |  |
| This was a cyclic time selection. The time wheel here is a year wheel, so the season characteristic was easy to select. In the time wave, cyclic selection functions make the task easy and lead to good scores. | The response time pattern was as expected. | This pattern was also according to expectations. |

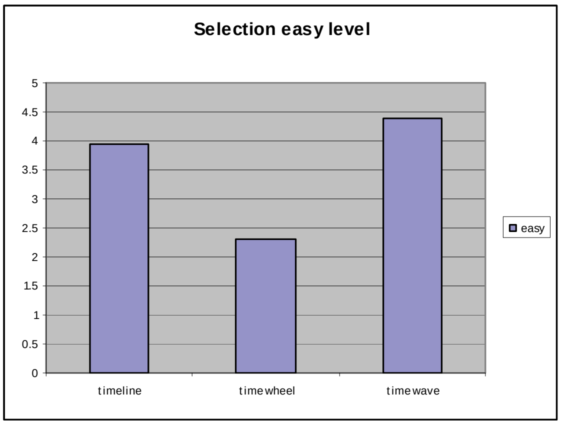
<table>
<tr><th colspan="3">4 Select all the rainfall in the first month of spring (multiple scale + single instant + cyclic)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th><th>Satisfaction</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>This was another cyclic time selection, based on the month as unit. The time wheel got lower scores because the boundary of start and end of the ‘first month’ was not so easy to identify.</td><td>The pattern shows that the timeline was not good at cyclic time selection.</td><td>The satisfaction graph for this task was very similar to that in the previous task. The time wave showed the best performance for cyclic time selection.</td></tr>
</table>

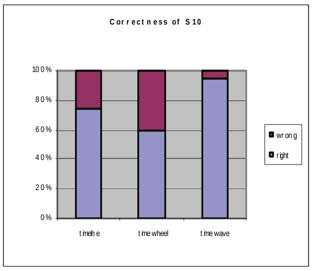
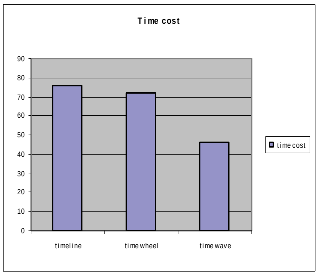
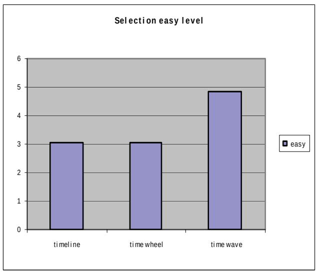
<table>
<tr><th colspan="3">5 Select all the rainfall in Jan. and Aug. 2001 (single scale + multiple instants + linear)</th></tr>
<tr><th>Effectiveness</th><th>Efficiency</th><th>Satisfaction</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>This was a multiple linear time selection.</td><td>The response time pattern was as expected</td><td>The timeline and time wave showed better satisfaction than the time wheel for this multiple, linear time selection.</td></tr>
</table>

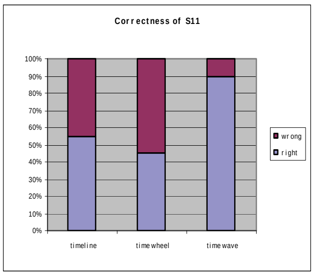
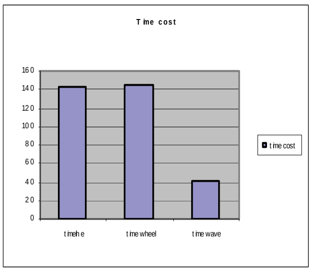
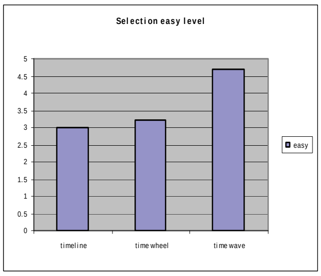
<table>
<tr><td colspan="3">6 Select all the rainfall on 2nd February 2001 and 21st July 2002 (multiple scale + multiple instants + linear)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td><td>Satisfaction</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>This task was a selection of two days. Because the timeline and time wave show the different days from left to right, they were easier to find.</td><td>Due to the explanation in effectiveness, it was understandable that the time wheel took the longest for this task.</td><td>Again, the timeline and time wave showed similar satisfaction for this task. However, the satisfaction of the time wheel was not much lower.</td></tr>
</table>

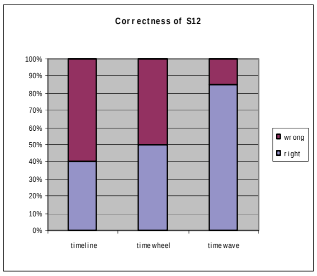
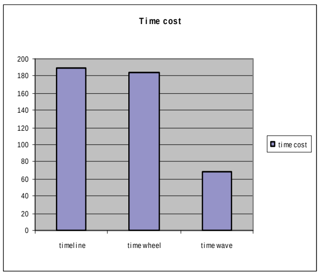
<table>
<tr><td colspan="3">7 Select all the rainfall in spring 2001 and summer 2002 (single scale + multiple instants + cyclic)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td><td>Satisfaction</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>This task looked like a combination of linear (2001 and 2002) and cyclic (season) selection, however, the linear time characteristics played a bigger role, which is why the time wheel scored lowest.</td><td>The response time pattern was as expected. The time wheel took the longest.</td><td>The users' satisfaction in this task proved, again, that the time wheel was not good for interacting with linear time data.</td></tr>
</table>

<table>
<tr><td colspan="3">8 Select all the rainfall in the first month of spring 2001 and second month of summer 2002 (multiple scale + multiple instants + linear)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td><td>Satisfaction</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Compared to the previous task, an additional time unit was involved. The time wheel showed even poorer scores because of the increased complexity.</td><td>Surprisingly, the above graph shows no extreme differences in response times. However, if the quality of the answers is included (effectiveness), there is a dramatic change.</td><td>The satisfaction proved again that the time wheel was not good at managing linear time. The time wave and timeline showed a similar performance in dealing with linear time.</td></tr>
</table>

<table>
<tr><td colspan="3">9 Select all the rainfall on the 2nd- 5th Feb. 2001 (single interval + linear + multiple scale)</td></tr>
<tr><td>Effectiveness</td><td>Efficiency</td><td>Satisfaction</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">This question could not be judged because of a technical error. Only the selection ‘easy level’ showed that the timeline and time wave were better than the time wheel in dealing with linear time data.</td></tr>
</table>

| 10 Select all the rainfall in the second week of 2001 (single interval + single scale + cyclic) | | |
|---|---|---|
| Effectiveness | Efficiency | Satisfaction |
|  |  |  |
| This task was a linear (2001) and cyclic (week) selection. It required the participant to identify the second week of 2001. In the time wave, the week boundary simplified the identification process, so the time wave showed the best performance. | It is understandable that the time wave took least time due to the reason explained for the effectiveness of this task. | The satisfaction pattern was in line with the findings for effectiveness and efficiency. |

| 11 Select all the rainfall events in the first two days in each month (multiple intervals + single scale + cyclic) | | |
|---|---|---|
| Effectiveness | Efficiency | Satisfaction |
|  |  |  |
| This was multiple linear and cyclic selections. The time wave outperforms the other representations in this task and had better scores. | With this complex question including both linear and cyclic time, the time wave had the fastest response times. | The satisfaction patterns were not surprising. |

| 12 Select the rainfall in all weekends (single interval + multiple scales + cyclic) | | |
|---|---|---|
| Effectiveness | Efficiency | Satisfaction |
|  |  |  |
| This task is similar to the previous one, but on a different time scale. The result further proved that the time wave was good at managing a complicated linear and cyclic time task. | The graph of time taken in this task was quite similar to the last task. As expected, the time wave's response times were fastest. | Here the satisfaction with the time wave was even larger than for the previous question. |

## 7.5 Test 2

The aim of this test was to study the participants' behavior while working with the time wave. Eye tracking and think-aloud methods were used to gather information.

### 7.5.1 Test preparation

**Test data**

The dataset which was used in Test 2 comprised rainfall data from a single meteorological station (D1007) in July 2002. Only the starting time of each rainfall period was considered in this test.

**User tasks**

The nature of the questions in Test 2 were based on the nature of temporal data (linear, cyclic, or both) as discussed in chapter 4. The questions were also based on the results of Test 1, because they were all similar to questions in which the time wave performed best. The results of test 2 should give an impression of how users reach their answers while working with the time wave, and should provide information about how and why the time wave is more efficient than the other methods for specific questions. The test questions are given below and discussed.

1. Did it rain on 2$^{nd}$ July 2002?

The question is of linear nature and asks about 'if'. This question is similar to question 1 in Test 1, where the time wave performance was best, both in correctness and response time.

2. How often did it rain in July?

This question asks ‘how often’ and is similar to question 7 in Test 1.The time wave’s performance was slightly less than the timeline’s but far better than the time wheel.

3. Did it rain on the second Tuesday in July?

This question focuses on cyclic time (week) and includes linear time (second Tuesday) as well. It was similar to question 2 in Test 1, where the time wave outperformed the timeline and time wheel both on correctness and response time.

4. Which week had the most frequent rainfall in July 2000? How often did it rain at that week?

This question combined linear (July 2000) and cyclic (week) time and asked for ‘which’ and ‘how often’. It is similar to questions 8 and 19 in Test 1. For both questions, the time wave performed best.

5. How many Fridays did it rain?

This is a cyclic time question and asks about frequency. It is similar to question 18 in Test 2. Again, the time wave performed best on both correctness and response time.

6. How often did it rain at midnight?

This is similar to the previous question, but on a different scale. A ‘day wave’ can be used to answer this question.

7. On which dates did it rain on an afternoon in the third week of July 2000?
8. On Tuesdays, did all the rain fall in the afternoon?

Both questions 7 and 8 combine linear and cyclic time and use multiple scales. The purpose of these questions is to learn about the users’ behavior in the time wave environment when they have to switch on many waves with different scales and work with them together.

**Working environment**

The time wave plug-in for the uDig environment was used in this test. However, as in Test 1, only the time wave window was as shown in Figure 7-10. For each question, the time scale, wave scale and stretch were fixed before the participant started answering to make sure that the view was completely the same for all of the participants. To answer the question, the functionalities of the time wave were limited and it was not necessary for participants to interact with the working environment. In the time wave window, the time when it was raining is located on the time wave reference.

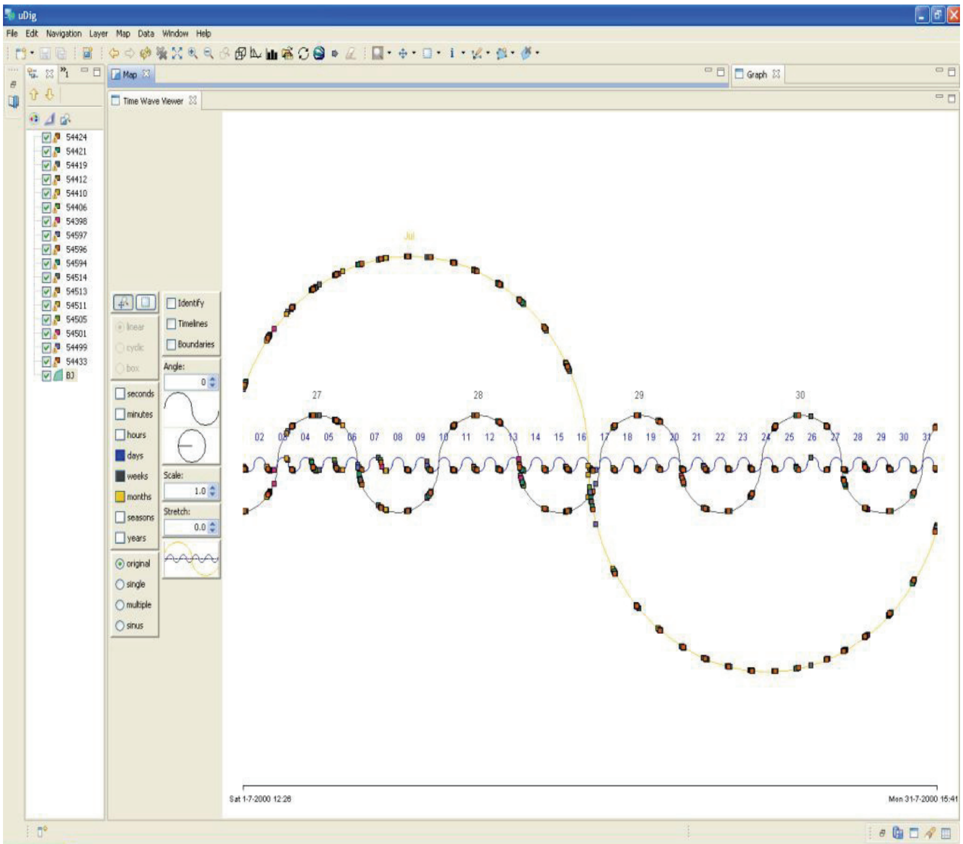



**Figure 7-10. Working environment for Test 2.**

### 7.5.2 Test execution

Eye movement data was collected in a controlled laboratory setting at GIVA's (Geographic Information Visualization and Analysis) Eye Movement Lab in the Department of Geography, University of Zurich, Switzerland. It was equipped with an active, near-infrared-enabled remote video eye tracker (Tobii X120). For this study, the tracker was configured to record at a sampling rate of 60 Hz. The fixation threshold value was set to 100 milliseconds, screen resolution to 1280*1024 pixels, and the system was calibrated for each participant. A project file was built on the software of the eye movement machine and this helped structure the test process. In this project file, the eight questions were set on eight interfaces and each one followed by an eye tracking section. This meant that the project file was run for each participant when the test started in order to control the test process. The participants read the question on the interface and pushed the start button for the eye tracking for that question.

The data post-processing stage involved creating scenes, segments and AOI (are of interest) visualizations. The post-processing phase was supported by the thinking aloud. The think-aloud results not only showed when the participants started searching for the answer, but also supplied clues to explain their eye movements.

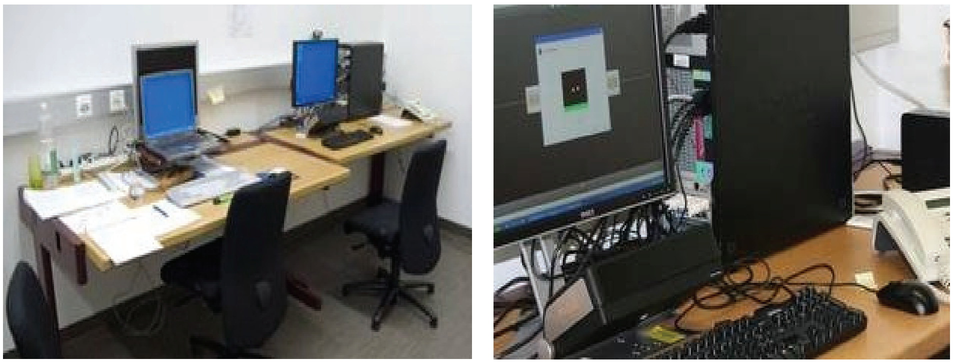


**Figure 7-11. Lab environment and eye tracker machine**

There were eight participants in this test, comprising MSc and PhD students, males and females, of different cultural backgrounds. Some had no geosciences background. Each participant had to sign an information statement and consent form giving their permission to the test with eye tracking equipment. They all watched an introduction video about the time wave, think-aloud method, about how to answer the questions, and were shown examples of questions. They all had time to familiarize themselves with the working environment. Before the start of the test, the eye tracking system executed a calibration process. The questions were read in the question interface and after the participants were asked if they understood the question properly, they switched to time wave view. The eye tracker started to record all their gaze points and paths from the moment the time wave view was switched on. After answering a question, the participant moved automatically on to the question interface to read the next question. During the answering process, they were asked to think aloud.

### 7.5.3 Analysis of the test results

An example of the raw data which was collected by the tracking system is shown in Figure 7-12. For each record, several attributes were stored, such as time stamp, GazePointX, GazePointY, and StimuliName. The Tobbi software included many visualization functions, such as gaze plots (Figure 7-3a), density maps (Figure 7-3b), and statistical graphs for AOI.

The gaze points of each participant are represented as circles; the size indicates how long the point was fixed. The line represents the path of the eye movement and the density map visualizes the fixation density. The density variable could be relative time, absolute time or fix frequency. For the statistical graph for AOI, the areas of interest should be defined first. The statistical result for each AOI can be a fixation length, observation length, or fixation count.

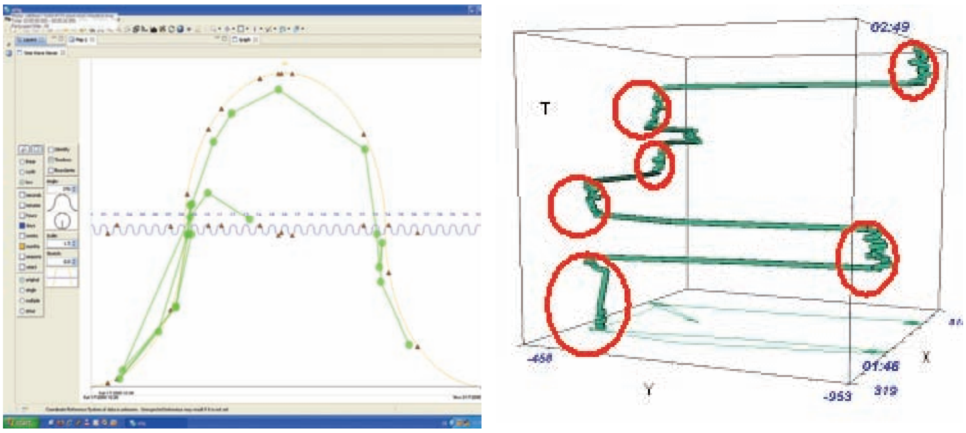
| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | | | | | | | | | | | | | | | | | |
| 25 | Timestamp | DateTimeS | DateTimeS | Number | GazePoint | GazePoint | CamXLeft | CamYLeft | DistanceLe | PupilLeft | ValidityLef | GazePoint | GazePoint | CamXRigh | CamYRigh | DistanceR | PupilRigh |
| 26 | 0 | | | | | | | | | | | | | | | | |
| 27 | 25 | 35:11.0 | 00:00.0 | 0 | 654.4712 | 583.2638 | 0.543718 | 0.477618 | 549.1342 | 3.233968 | 0 | 647.436 | 577.0726 | 0.34625 | 0.470269 | 545.1095 | 3.19032 |
| 28 | 41 | 35:11.0 | 00:00.0 | 1 | 656.4716 | 583.2542 | 0.543694 | 0.477502 | 549.1514 | 3.249114 | 0 | 644.8998 | 574.6387 | 0.346228 | 0.470164 | 545.1476 | 3.19357 |
| 29 | 58 | 35:11.1 | 00:00.1 | 2 | 654.9207 | 577.9441 | 0.543684 | 0.477471 | 549.1706 | 3.236611 | 0 | 646.1209 | 575.385 | 0.346198 | 0.470143 | 545.1903 | 3.18335 |
| 30 | 75 | 35:11.1 | 00:00.1 | 3 | 658.5046 | 576.8575 | 0.543676 | 0.477465 | 549.1783 | 3.242279 | 0 | 647.9658 | 580.4432 | 0.346189 | 0.470103 | 545.198 | 3.20082 |
| 31 | 91 | 35:11.1 | 00:00.1 | 4 | 657.2526 | 580.2762 | 0.543664 | 0.477428 | 549.1635 | 3.24158 | 0 | 647.3184 | 574.8751 | 0.346183 | 0.470036 | 545.1985 | 3.18951 |
| 32 | 108 | 35:11.1 | 00:00.1 | 5 | 654.5379 | 578.3836 | 0.543654 | 0.477344 | 549.1484 | 3.255178 | 0 | 647.865 | 569.33 | 0.346184 | 0.469917 | 545.177 | 3.17430 |
| 33 | 125 | 35:11.1 | 00:00.1 | 6 | 655.493 | 585.4182 | 0.543647 | 0.47712 | 549.0754 | 3.237803 | 0 | 646.849 | 562.8158 | 0.346182 | 0.469761 | 545.196 | 3.16270 |
| 34 | 141 | 35:11.1 | 00:00.1 | 7 | 659.1487 | 588.5155 | 0.543639 | 0.476991 | 549.0294 | 3.238387 | 0 | 647.1252 | 567.0452 | 0.346152 | 0.469571 | 545.1923 | 3.15561 |
| 35 | 158 | 35:11.2 | 00:00.2 | 8 | 659.6146 | 587.3704 | 0.543605 | 0.476944 | 549.0037 | 3.243576 | 0 | 635.6585 | 576.3729 | 0.346075 | 0.46952 | 544.8521 | 3.16746 |
| 36 | 175 | 35:11.2 | 00:00.2 | 9 | 613.3249 | 552.6999 | 0.54394 | 0.476794 | 549.4329 | 3.242611 | 0 | 613.691 | 550.1854 | 0.346486 | 0.469239 | 545.2092 | 3.17031 |
| 37 | 191 | 35:11.2 | 00:00.2 | 10 | 612.7201 | 545.1376 | 0.54413 | 0.476512 | 549.3345 | 3.235704 | 0 | 599.9885 | 538.9264 | 0.34668 | 0.469022 | 545.1237 | 3.17836 |
| 38 | 208 | 35:11.2 | 00:00.2 | 11 | 614.1143 | 547.389 | 0.544025 | 0.476448 | 549.2162 | 3.253922 | 0 | 597.7756 | 544.6567 | 0.346582 | 0.469064 | 545.179 | 3.19946 |
| 39 | 224 | 35:11.2 | 00:00.2 | 12 | 610.8263 | 548.983 | 0.543981 | 0.47644 | 549.1697 | 3.248766 | 0 | 597.8942 | 541.7313 | 0.346545 | 0.46911 | 545.166 | 3.18013 |
| 40 | 241 | 35:11.2 | 00:00.2 | 13 | 610.0194 | 546.1318 | 0.543884 | 0.476409 | 549.27 | 3.22037 | 0 | 597.1889 | 553.2359 | 0.346474 | 0.469147 | 545.1486 | 3.21296 |

**Figure 7-12. A table view of raw eye movement data.**

However, since eye movement datasets are almost always quite large, there were obvious limitations to the above visualization methods. Overlaps (e.g. Figure 7-3) may lead to misunderstanding of the data. For example, if the viewer tries to identify the number of gaze points within a certain area, this may not be possible because larger fixations may occlude smaller ones entirely. Furthermore, temporal information (such as the order of fixations on a scan path) is potentially lost at overlapping scan paths and this makes it difficult to establish when the fixation was directed to a certain area. For smaller datasets, design choices such as using transparency, or numbering the fixation points can partly solve the problem, but in large datasets this approach may not be feasible.

In addition to the traditional eye movement visualization methods, this research also used the space-time-cube (STC) to analyze the eye movement data. This is a visualization method from the time geography domain (Hägerstrand, 1970) and it combines time and space in a natural way. Time can be represented as continuous or discrete. The *X* and *Y* axes indicate the 2D space, while the time units along the *Z*-axis can be in years, days, hours, etc. In the STC, the space-time-path (STP) shows the object's trajectory through time and space. The record's time stamp (or start time) for one gaze point corresponds to the time component; the *X* and *Y* of a gaze point (screen coordinates) represent the location component, and attributes can be recorded, e.g. validity, event data, gaze point content, or AOI metadata. Hence, eye movement recordings have many similarities with spatio-temporal data and can be visualized as such. In an STC, the *X, Y* plane of the cube represents the user's screen view. The eye movement (space-time-path) is along the *Z*-axis. The movement's attributes can, for instance, be represented by the color or size (volume) of the path.

Figure 7-13 shows a simple example of eye movement data visualized in a gaze plot (Figure 7-13a) and STC (Figure 7-13b). In the gaze plots, the overview of the trajectory can be shown clearly, however, the overlap is obvious and temporal order is missed. In STC, the trajectory of eye movements is displayed as a space-time-path, which immediately reveals spatio-temporal patterns. The vertical 'lines' (the ellipses in Figure 7-13a) indicate an eye fixation at a particular location. The fixations still include micro-movements as seen in the ellipses. This is not surprising, because human eyes have continuous micro-saccadic movements and fixations are typically defined with temporal as well as spatial thresholds. In the STC, the fixation points can be easily identified by the approximate vertical line. The length of the approximate vertical line shows the duration of one fixation (fixation length). The nearly horizontal lines indicate (uncontrolled) eye movements (saccades). The slope of the line shows the speed of the eye movement. The space-time-path can be projected on to a two-dimensional surface (screen view as background of the eye movement path), resulting in the familiar gaze plot representation with a scan path.




**(a) (b)**

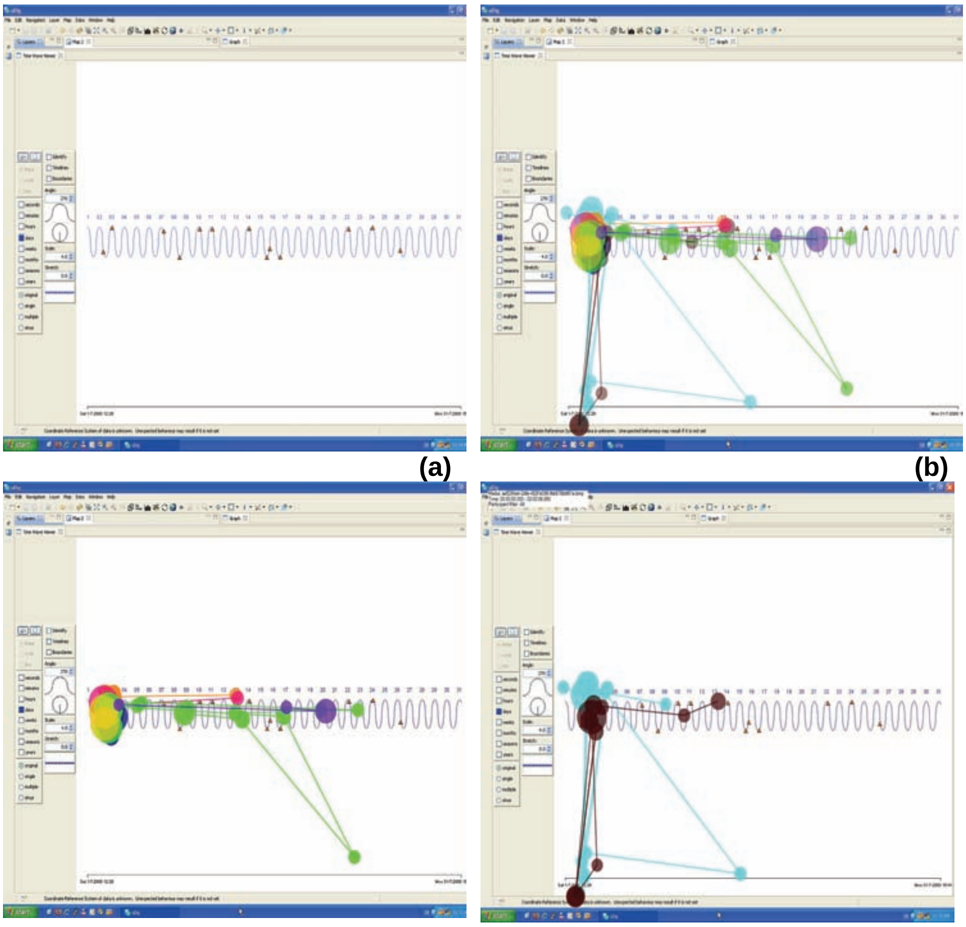
**Figure 7-13. An example of eye movement data in the space-time-cube (STC).**

Below, the results of the eight questions are discussed.

*1. Did it rain on 2nd July 2002 in the yellow station?*

Figure 7-14 tells the story of this task. Figure 7-14a shows the view users see when they start with the question, a time wave with the day as the basic unit. Figure 7-14b shows the gaze plots of all eight participants (each in a different color). All their gaze points moved to the left side of the wave to identify 2nd July. This proves that time is spatialized from left to right in the human mind but it should be noticed that, in the gaze plots, the information from left to right cannot be discovered. Animation of gaze plots also supports the understanding of the user's behavior.

The gaze plots can be grouped into two categories as shown in figures 7-14c and 7-14d. In Figure 7-14c, six participants checked the wave only to identify 2nd July and derive the answer. In Figure 7-14d, two participants not only identified the second peak of the day wave, but also went to the labeled timeline at the bottom of the view to confirm their identification. This means that most of the participants could depend on the wave as a reference to identify the linear time for instant and interval without needing to refer to the timeline. A few participants liked to have assistance from the timeline for confirmation.

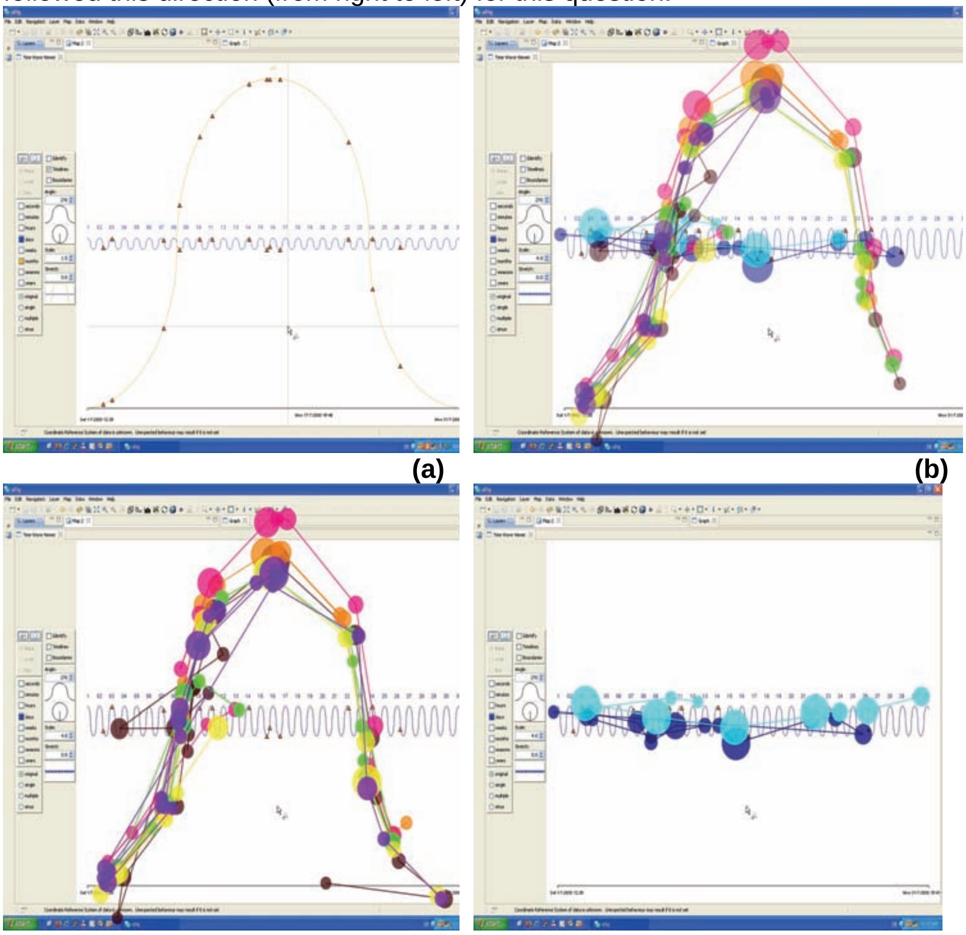


(a) (b) (c) (d)

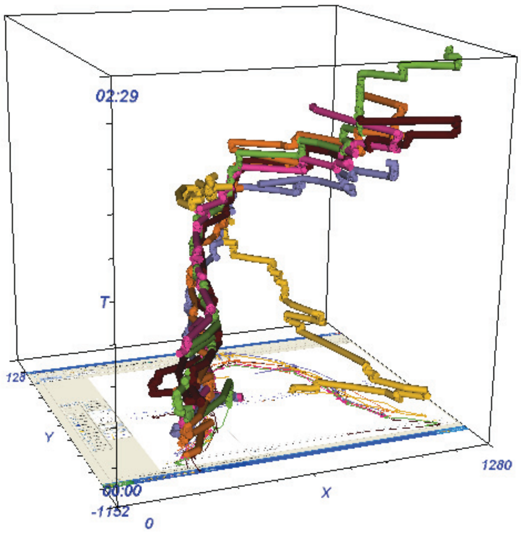
**Figure 7-14. 'Did it rain on 2nd July 2002 in station yellow?' a) time wave at start; b) gaze plots of all participants; c) gaze plots of time wave 'lookers' only; d) gaze plots of time wave and timeline 'lookers'.**

*2. How often did it rain in July?*

For this question, two waves were shown in the start view, one with the day as the basic unit and one with the month. Figure 7-15a shows an interesting feature of the time wave as a reference: when there are many waves, like the day waves here, the wave almost becomes a line. The aim of this question was to find out whether, when the question is oriented towards a month (cyclic time) scale, the user would prefer this wave, or would prefer to use the 'line' of the day waves? Figure 7-15b shows the gaze plots of all eight participants, in which there are clearly two patterns. The eyes of one group (six participants) followed the month wave reference (Figure 7-15c) and the other group followed the linear nature of the day waves (Figure 7-15d). In Figure 7-15c, it looks as if all the participants followed a similar path along the wave. However, this proved not to be true, as revealed in Figure 7-15e which shows the same gaze paths in the STC. This shows that one participant (yellow path) started from right to left; comparing this path with his paths taken in other questions showed that he only followed this direction (from right to left) for this question.



(a) (b) (c) (d)




**(e)**

**Figure 7-15. Results for question 2: a) user view; b) gaze plots for all participants; c) gaze plots of group 1 (6 participants); d) gaze plots of other group (2 participants); e) result of group 1 in the space-time-cube (STC).**

*3. Did it rain on the second Tuesday in July?*

This is a typical cyclic question. Figure 7-16a shows the time wave with the week as the basic unit. It is obvious that the first week of July did not have a Tuesday. Red circles on the time wave show the position of Tuesday on the week wave. The users first had to identify the position of Tuesdays in the wave and then find the second Tuesday. Figure 7-16b shows all the gaze plots from the eight participants; most gaze points are located at the yellow triangles (rainfall symbol) and the labels on the timeline. It looks as if the users first identify rainfall events and then check whether it was on a Tuesday. However, when the pattern is viewed more closely, some interesting details can be discovered. In Figure 7-16c, the blue participant focused long on the position of the first Tuesday even though was no rainfall symbol. Then his focus moved to rainfall events (yellow triangles), went directly to the position of the second Tuesday, and verified this on the timeline. The orange participant focused on the second Tuesday directly and only briefly visited other points. In Figure 7-16d, the three participants shown immediately look for the position of the first Tuesday and verified this via the timeline. After that they moved to the same position in the next wave. This is shown more clearly in figures 7-16e and 7-16f. Figure 7-16e shows part of the gaze plot of the blue participant. Numbers and the application of transparency identify the path's order. Figure 7-16f shows similar patterns from other participants. The analysis of these patterns reveals an important advantage of using the time wave. It perfectly combines cyclic time information (*Y*-direction) with linear time (*X* direction). The shape of the wave helped users to identity and compare repetitive events in a more efficient way.

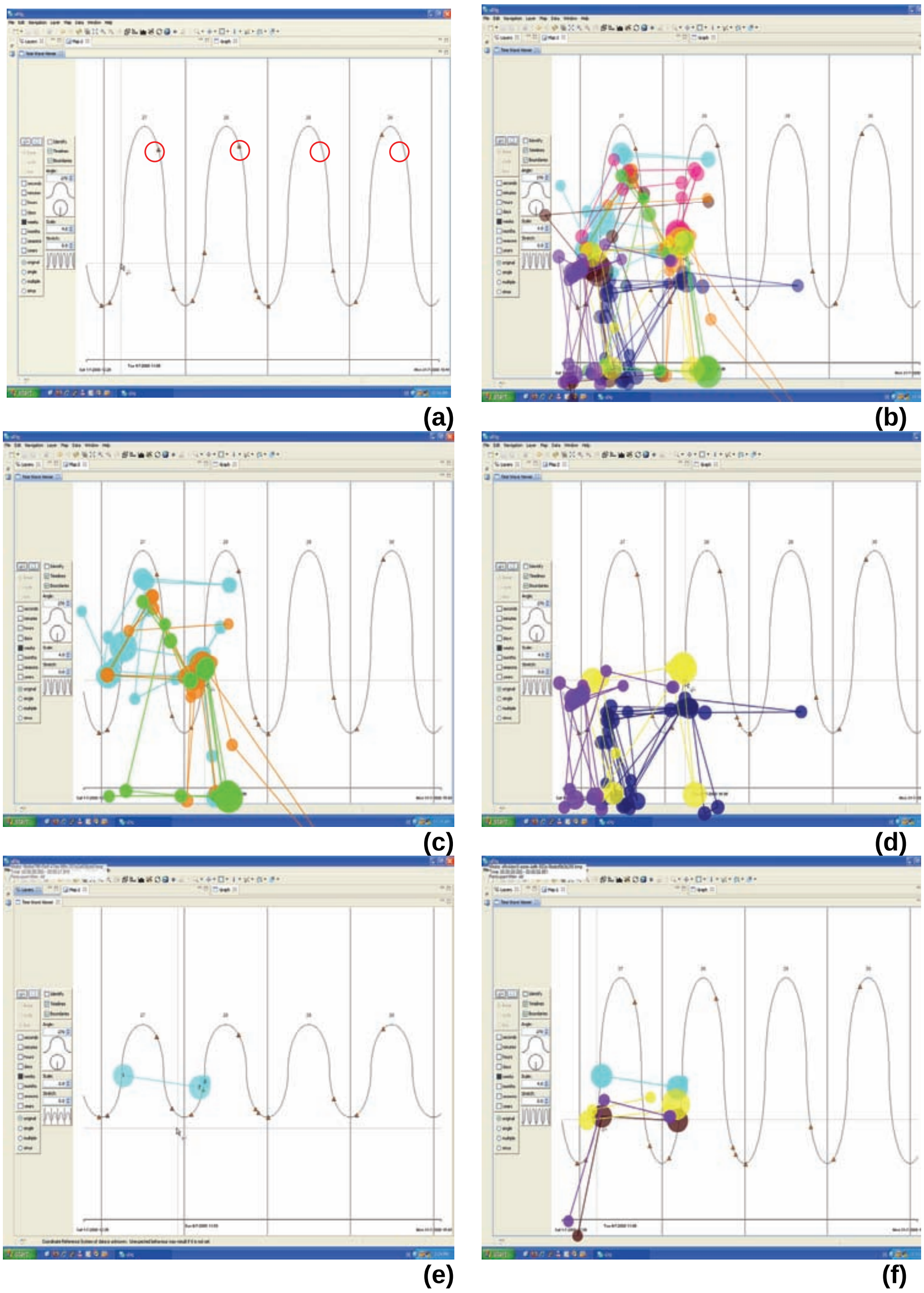
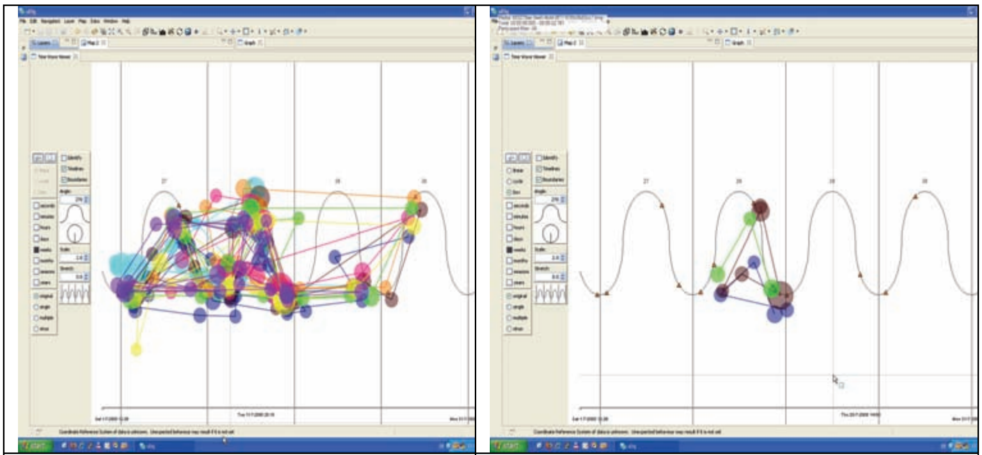



**Figure 7-16. Result for question 3, did it rain on the second Tuesday in July? a) User view (red circles show the position of Tuesday on week wave; b) gaze plots from the 8 participants; c) gaze plots of group 1; d) gaze plots of group 2; e) part of the gaze plot of the blue participant; f) similar patterns to e) from the other participants.**

*4. Which week had the most frequent rainfall in July 2000? How often did it rain in that week?*

This question is about comparing cyclic events. The users have to identify each of the weeks first and then compare them. They do not have to go into detail, but need to glance at the wave to determine if it rained. Figure 7-17a shows an overview of the participants' gaze plots on a wave with weeks as the temporal unit. The second and third weeks were given the most attention. The gaze plots show that the users started from overview and then identified more density patterns. Next they compared these patterns by moving their eyes up and down the patterns. In this case, the aim was to distinguish and identify the different weeks. Based on the gaze plots, it looks as if the wave alone was enough to answer the questions. For the second question, Figure 7-17b shows a selected result from three participants who showed similar visual behavior within one week. Their fixation points were only placed on the rainfall (yellow triangles) on the wave.

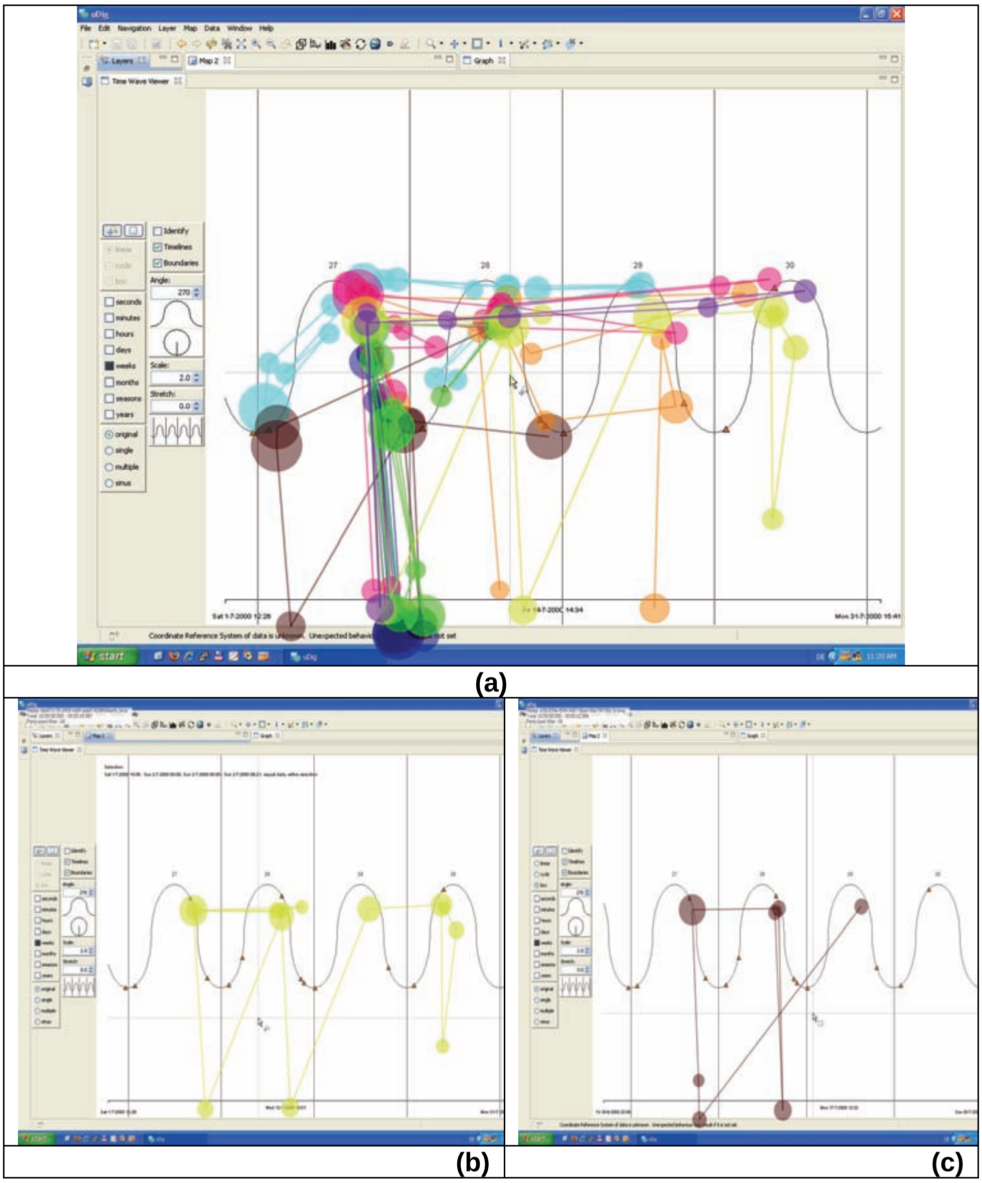


(a) (b)

**Figure 7-17. Gaze plots for question 4, Which week had the most frequent rainfall in July 2000? How often did it rain in that week? a) An overview of gaze plots of the 8 participants on a wave; b) similar patterns from 3 participants in one week.**

*5. On how many Fridays did it rain?*

This question is about identifying cyclic time instances with a linear order. It is similar to question 2 but slightly more complicated. In the overview (figure 7-18a), the pattern reveals that some of the participants identified the Friday in the first week and verified this on the timeline. After that, they just checked the 'position' of Fridays on each wave unit and drew their conclusions. They did not go back to the timeline to confirm the second week. This means that the wave shape helped the users to identify the cyclic time without any additional support. Figures 7-18b and 7-18c give the detailed paths of the yellow and brown participants, respectively, who rechecked with the timeline after they had identified Friday in the wave. Figures 7-18d, e, f and j show patterns of users who only checked the timeline for the first week and those who did not check at all.


Identify
Timelines
Boundaries
Angle:
Scale:
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seconds
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hours
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weeks
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seasons
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28
29
30
Sat 1-7-2000 12:26
Mon 31-7-2000 15:41
(a)
(b)
(c)

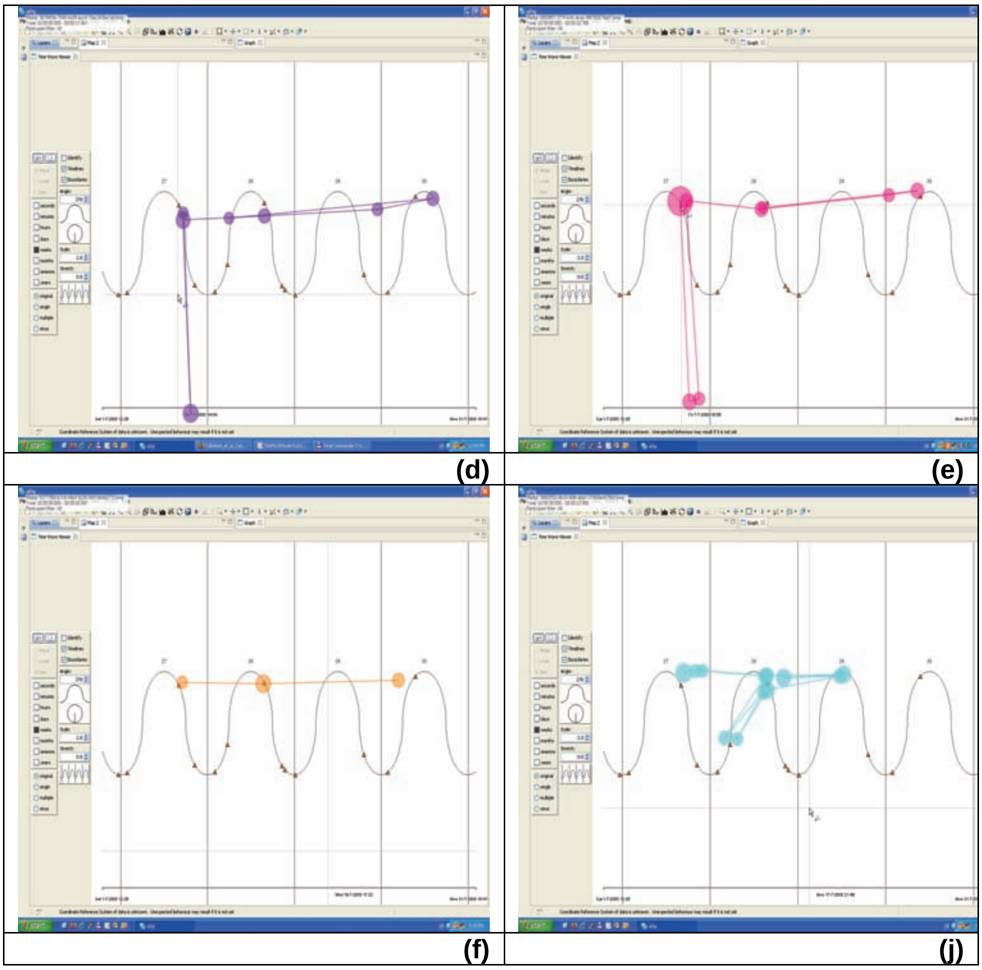


**Figure 7-18. Gaze plots for question 5, On how many Fridays did it rain? a) Overview of gaze plots for all participants; b) and c) gaze plots of two participants who checked the timeline more than once; d) and e) gaze plots of two participants who checked the timeline only once for the first week; f) and j) gaze plots of two participants who never checked the timeline.**

*6. How often did it rain at midnight?*

Although this question is similar to the previous one, the time scale is different. The aim was to see whether users had problems with more dense time scales. The overview in Figure 7-19a shows the 31 days in July. The wave was somewhat compressed along the horizontal axis and midnight was located at the bottom of wave. Figure 7-19b shows gaze plots for all the participants. It was interesting to observe that all the participants focused on the triangles at the bottom of wave without verifying the timeline to make sure it was 'midnight'. They nearly all read the wave from left to right.

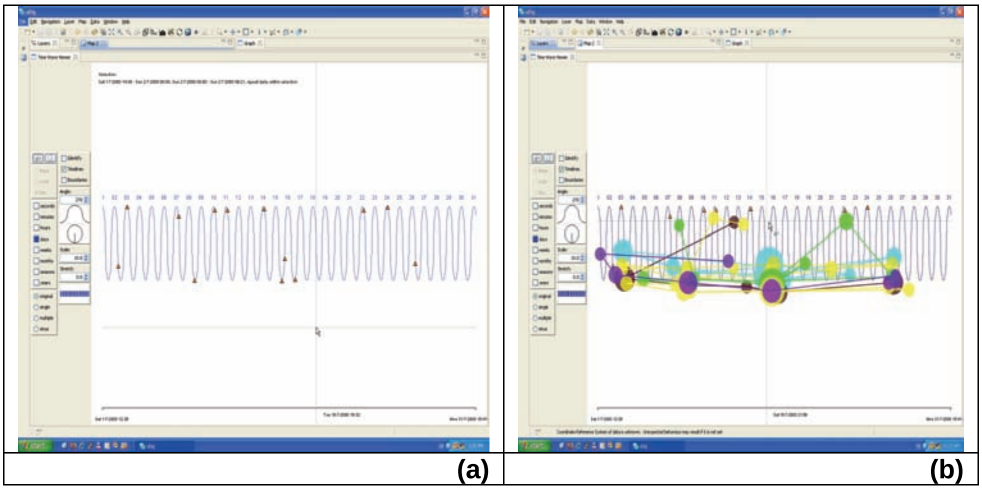



**Figure 7-19. Result for question 6, How often did it rain at midnight? a) User view; b) overview of gaze plots for several participants.**

*7. On which dates did it rain in the third week of July 2000 in the afternoon?*
Questions 7 and 8 are about multiple time scales. Figure 7-20a shows the start view of users for this question. It shows both the week and day as the wave's time units. This combination is required to be able to identify the 'third week' and 'afternoon'. Figure 7-20b gives an overview of the participants' gaze plots. They started at the beginning of the month and then identified the 'third week'. They followed the wave for a while to check for rainfall symbols and seemed to realize they should move to the day wave to find 'afternoon' within this week. It can also be seen that the rainfall symbols in the fourth and fifth weeks were not looked at. Figure 7-20c shows the behavior of users to identify the 'afternoon' in each day of the third week. Figure 7-20d shows an example of the blue participant, who focused on each rainfall symbol and tried to distinguish whether it was at an afternoon.

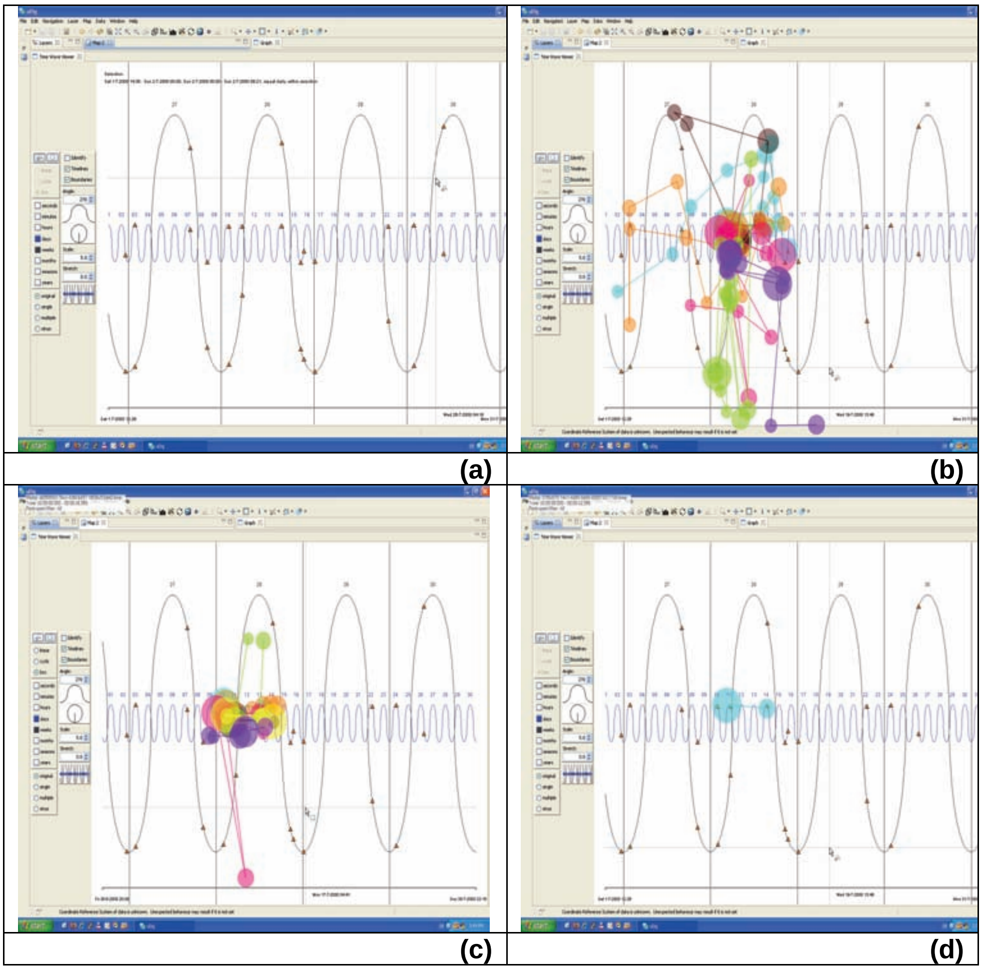
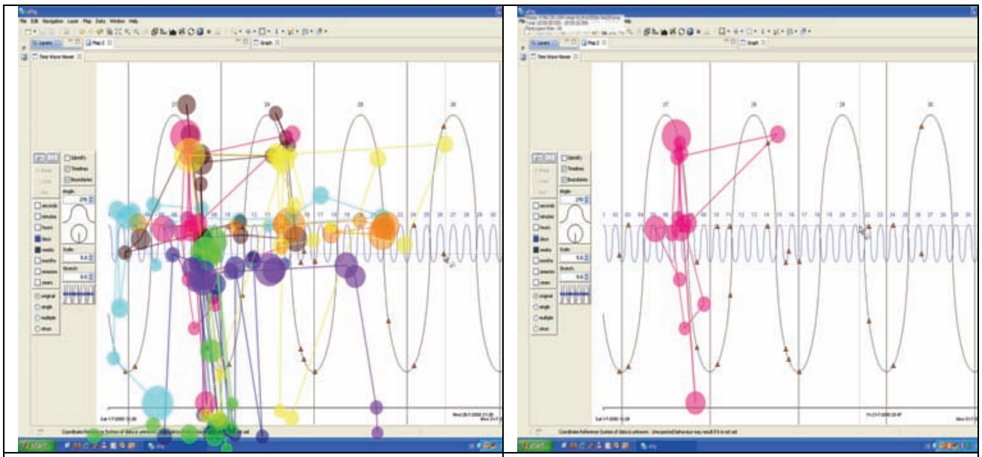



**Figure 7-20. Result for question 7, On which dates did it rain in the third week of July 2000 in the afternoon? a) User view; b) overview of gaze plots; c) similar pattern within the third week; d) the gaze plots of one participant who searched directly for the rainfall on the day wave in the third week.**

*8. On Tuesdays, did all the rain fall in the afternoon?*

For this question, users had to identify the rainfall on Tuesdays and check whether it fell during the ‘afternoon’. This question is slightly different to question 7. In that question, after identifying the third week (cyclic), each day (linear) within the week had to be checked. With this question, each Tuesday acts as both a cyclic and linear time identifier while the ‘afternoon’ (cyclic) also had to be checked. Figure 7-21a shows an overview of gaze plots for all the participants. It can be seen that they first identified the first Tuesday in the week and verified this with the timeline. Then they focused on Tuesday rainfall to identify whether it was in the afternoon. Next they moved directly to the following Tuesday with rainfall. Figure 7-21b shows a gaze path for one participant.



(a) (b)

**Figure 7-21. Result for question 8, On Tuesdays, did all the rain fall in the afternoon? a) Overview of gaze plots for all participants; b) gaze path of one participants.**

## *7.6 Test 3*

The aim of Test 3 was to study the users' behavior in the triple space environment. Eye tracking and the think-aloud method was used to gather information about their behavior. The hypothesis was that the nature of the questions will drive user behavior, i.e. switching between location-, attribute- or time-space will be based on the user task.

There are six basic questions according to Peuquet's work (see also chapter 3):

- When ➔ where
- When ➔ what
- What ➔ when
- Where ➔ when
- What ➔ where
- Where ➔ what

As mentioned earlier, the **arrows** in the above questions are expected to drive eye movements in triple space.

### 7.6.1 Test preparation

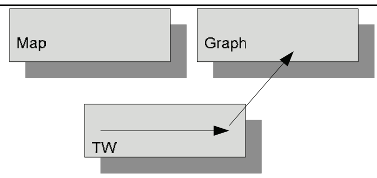
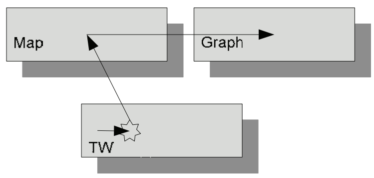
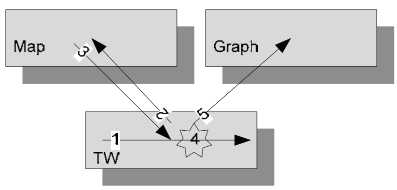
**Test data**

The dataset used in Test 3 was the same as used with the case study described in chapter 6. It contains daily observations of when the highest temperature was reached at a group of metrological stations in the Beijing area (China).

**Test user tasks**

The questions which were used in this test were formulated with two goals in mind. One was related to the exploration process in which the graphics act as both data representation and interaction tool. The other was related to the complexity of the questions including time, location and attribute.

Four tasks, each of them with several subtasks, were designed. They are summarized in Table 7-3 and the hypothesis on the expected eye movement patterns in triple space is also shown.

| | Subtasks | Question formula | Expected eye movement pattern |
|---|---|---|---|
| T1 | 1. Which date shows a clear anomaly for all stations?<br>2. Compared with the other dates in the month, is it earlier or later?<br>3. What is the temperature range on that day? | When (overview)<br>When➔when<br>When➔what |  |
| T2 | 1. Which station reached its highest temperature first on 2nd July?<br>2. Where is it? (south, north or east west)<br>3. What is the highest temperature of that day for the station?<br>4. Compared to the other stations, what is the temperature characteristic of this station? | When➔object<br>when ➔where<br>when➔what<br>what (overview) |  |
| T3 | 1. Comparing the stations yellow 54501 and green 54594, which one reached its highest temperature first on most of the days?<br>2. What is the spatial relationship between the yellow and green stations?<br>3. On which day did the yellow station reach its highest temperature much later than the green station?<br>4. What were the highest temperature values of the two stations that day? | Object➔when<br>Object➔where<br>Object➔when<br>When➔what |  |

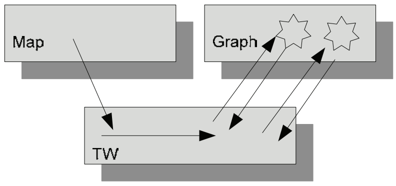
| | | | |
|---|---|---|---|
| T4 | 1. Are stations 54424 (blue) and 54421 (pink) the most eastern stations?<br>2. Which of those two stations reached its highest temperature first on most of the days?<br>3. What is the temperature range of the two stations?<br>4. On which day did the blue station reach its highest temperature?<br>5. On that day, did the pink or blue station reach its highest temperature first?<br>6. On which day did the pink station reach its highest temperature?<br>7. On that day, did the blue station or the pink station reach its highest temperature first? | Object➔where<br>Where➔when➔obje ct<br>Object➔what<br>What➔when<br>What+when➔object<br>What➔when<br>What+when➔object |  |

**Table 7-3. User tasks and expected eye movement patterns in triple space.**

**Working environment**

In this test, the view of the time wave (time-space) is extended with location space and attribute space as shown in Figure 7-22. In location space, a map is used to show the spatial distribution of the 19 meteorological stations. The users could use some basic interactive functions such as zoom in/out, overview and selection. A graph showing the change in temperature over time was available in attribute space, in which the users could select any point on the time axis to display the temperatures of all the stations. In time-space, all the time wave functions (introduced in chapter 6) were available. These three spaces are coordinated each with other, e.g. if a user identifies a station in the map, the corresponding line in the graph and symbol on the wave will be highlighted.

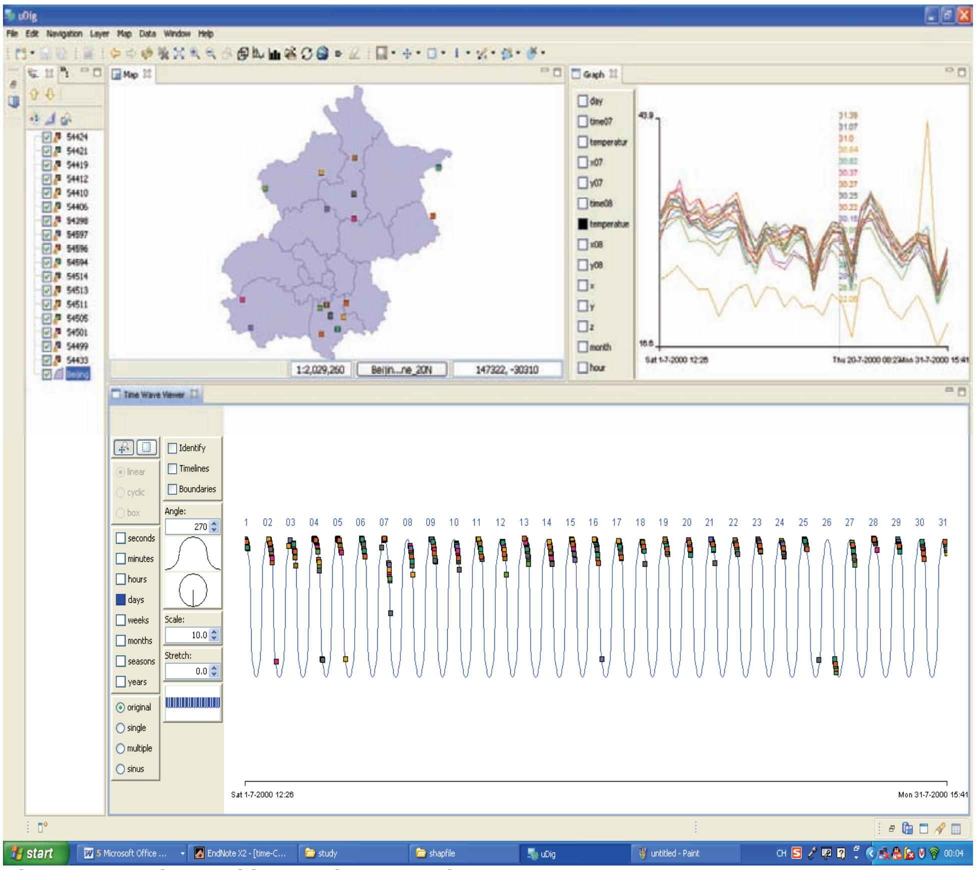


**Figure 7-22. The working environment for Test 3.**

### 7.6.2 Execution of the test

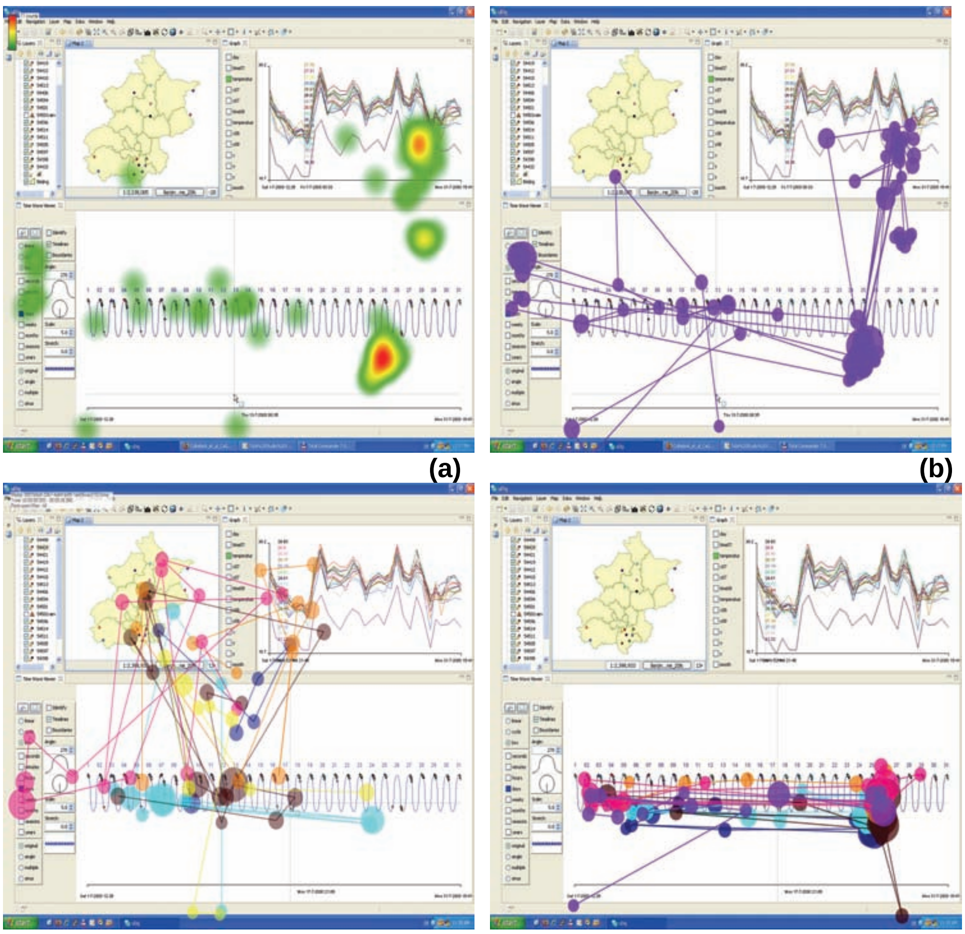
Test 3 was executed immediately after Test 2 with the same eight participants. Again they were shown an introductory video and had some time to familiarize themselves with the extended working environment. They started by reading the user tasks and had the opportunity to ask for clarification before the start of the test. The test was executed subtask by subtask, following the same protocol as Test 2. The eye tracking equipment (Figure 7-11) was used and the participants were asked to think aloud while they performed the tasks.

### 7.6.3 Analysis of the test results

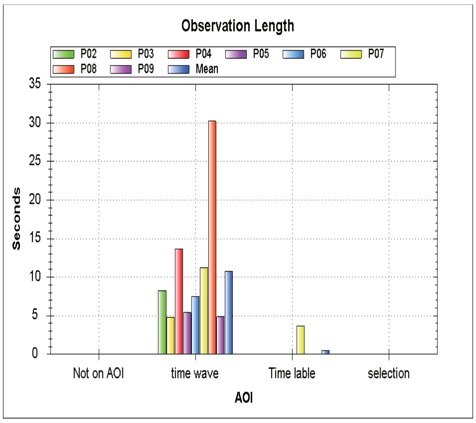
1. Task 1

This task contained three subtasks. The hypothesis was that the users start from the overview in time-space and looks for the anomalies in the time wave, and compares these with the other days to see the magnitude of the anomaly. Then they identify the particular day in time-space and find the value range in attribute space for that day.

Figure 7-23a shows a density map of the absolute gaze duration for the whole task for one participant. This map was calculated based on the distribution of the absolute duration of all the users' gazes. Red represents the locations with the longest gaze time during the test. From red to green, the absolute duration of gaze decreases, and the blank part means there were no gaze points or the gaze duration was less than the minimum threshold. On the map, the red areas are around the day with the anomaly in time-space and the corresponding temperature range at that day in attribute space. The selection and time scale functions also attracted some user attention. There are also some gaze points located on the time wave; this is probably related to the users looking for anomalies along the wave. Figure 7-23b shows the gaze plots of one participant during Task 1. He started from an overview of the environment and searched for anomalies on the time wave. He then focused on 26th July, which deviated from the other days. Finally, his gaze moved to the same day in attribute space several times, to find the value range in time-space.



(a) (b) (c) (d)



Observation Length
P02
P03
P04
P05
P06
P07
P08
P09
Mean
35
30
25
20
15
10
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Seconds
Not on AOI
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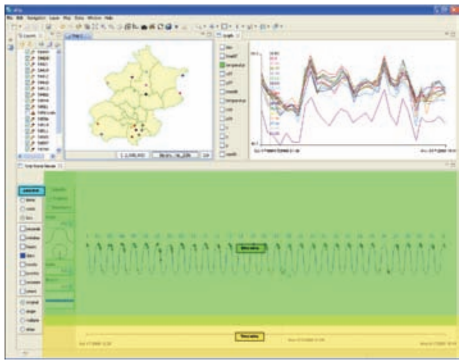
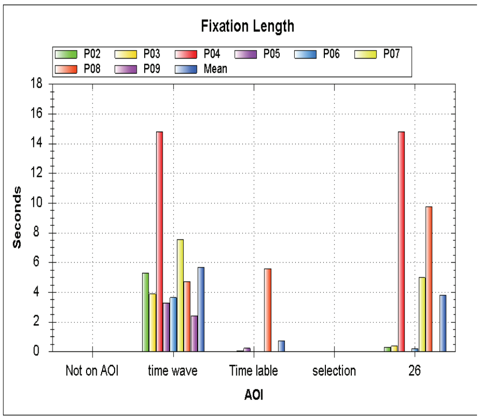
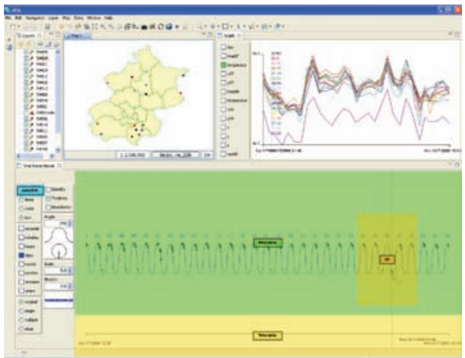
Time lable
selection
AOI

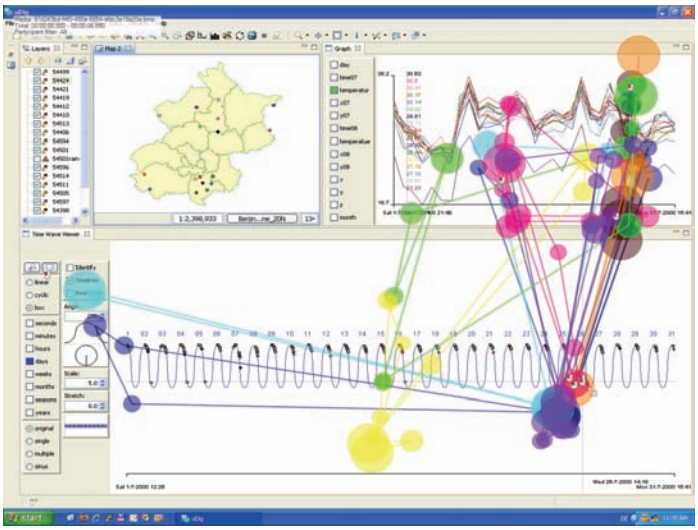
(e)



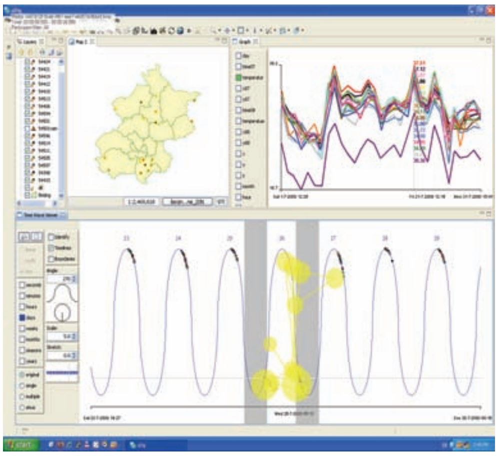
Fixation Length
P02
P03
P04
P05
P06
P07
P08
P09
Mean
18
16
14
12
10
8
6
4
2
0
Seconds
Not on AOI
time wave
Time lable
selection
26
AOI

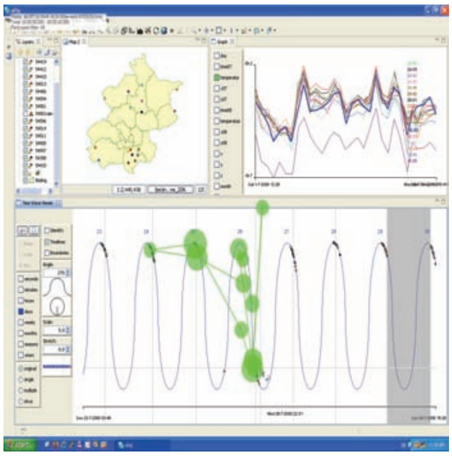



(f)

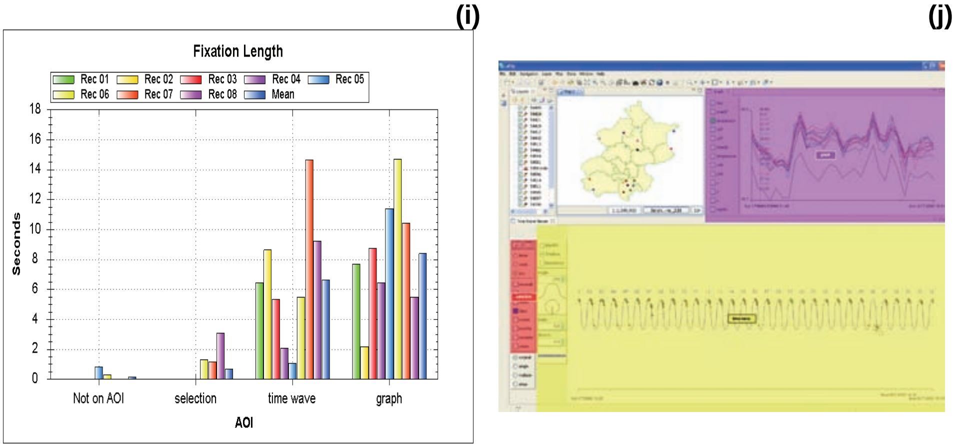


(h)





**(i)** **(j)**




**(k)**

**Figure 7-23. Task 1 of Test 3. a) A density map of the absolute gaze duration for the whole task for one participant; b) gaze plots for one participant; c) gaze plots of users when they had just started executing the tasks; d) gaze plots for subtasks 1 and 2; e) diagram of AOI statistics of subtask 1; f) diagram of AOI statistics of subtask 2; h) gaze plots for subtasks 3; i) and j) explanations for abnormal plots in 7-23h (green and yellow plots); k) AOI statistics on fixation length for subtask 3.**

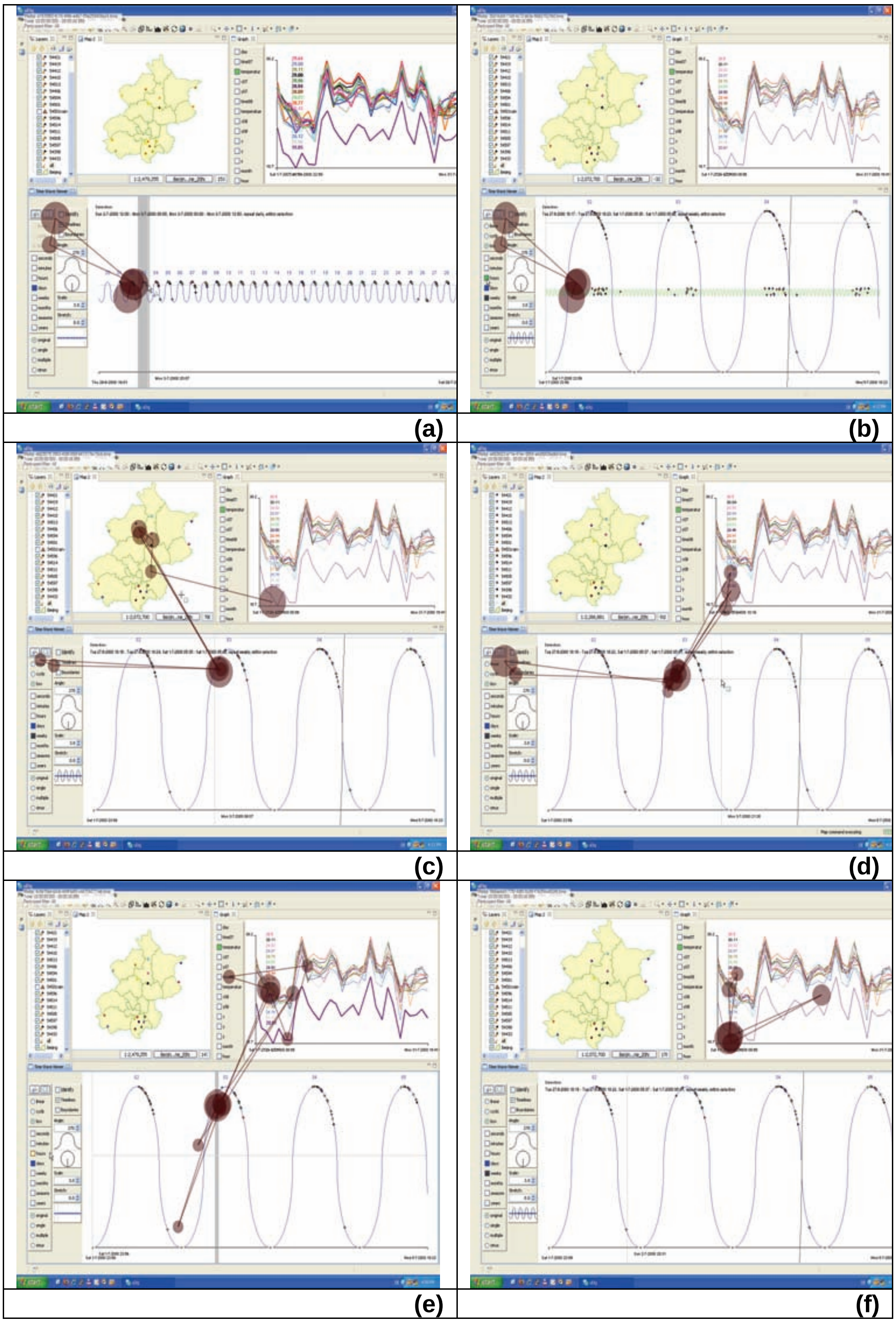
Figures 7-23c, d and h give some details of the gaze plots of all the participants for the subtasks. Figure 7-23c shows users' gaze plots when they had just started executing the tasks. In this phase, users glance over the whole environment to get an overview. Figure 7-23d shows the gaze plots of all the users while executing subtasks 1 and 2. They looked at the time wave in a horizontal direction to identify the anomaly, and moved left-right to establish its magnitude. It is obvious that for these two temporal questions the users' focus was in time-space. Since the nature of the question was about the temporal distribution, most gaze plots were on the time wave itself, and seldom on the timeline. Figure 7-23e shows a diagram of AOI statistics for subtask 1. For all participants (each represented by a color), it displays the observation length for the defined AOI. The AOI are defined in the right of Figure 7-23e (the green rectangle corresponds to the time wave AOI). It is evident that most observation time was spent on the time wave. This means users can get all the temporal information needed from the time wave. Figure 7-23f shows the AOI analysis for subtask 2. In the AOI diagram on the right of the figure, an area for the anomaly was added.

Figure 7-23h gives the gaze plots of all the participants on subtask 3. It can be seen that the users' gaze moves several times between time-space and attribute space. The selection function in the time wave was used to identify the date. Figures 7-23i and j highlight a typical problem faced in the analysis. When following the green and yellow gaze plots in 7-23h, it looks as if those plots are anomalies themselves. In fact, this was not true, because they used the zoom function (compare time wave view in 7-23h with i and j). Here they also looked at 26$^{th}$ July, but because of the zoom it moved location. It is easy to misinterpret results like these.

Figure 7-23k shows the AOI statistics on fixation length for subtask 3. It can be seen that most fixation points are distributed over the time wave and graph (time-space and attribute space).
In summary, it could be concluded that the eye movement patterns expected for Task 1 matched the observed patterns.

2. Task 2

As shown in Table 7-3, the hypothesis for Task 2 assumed the users would start from time-space, identify one day on the time wave, move to the geographic map to find the station's spatial location, and then move to attribute space to find the temperature for that day. Finally, in attribute space they would compare this temperature with those of the other stations. Figure 7-24a-f show the behavior of one particular user step-by-step. This user started in time-space with the overview of July, and moved to the function bar to activate the zoom function (Figure 7-24a). He moved back to the time wave and zoomed in to 2$^{nd}$ July, to identify which station first reached its highest temperature (details-on-demand). After that, he moved to the function bar again to activate the selection function (Figure 7-24b). From there, he moved on to location space to answer the 'where' question (Figure 7-24c) and then directly to attribute space to answer the 'what' question. However, it seems he wanted to check having the correct day and went back to time-space and activated the selection function (Figure 7-24e). In this figure, the corresponding graph is highlighted and the temperature values are listed to allow reading the temperature of the station on that day after looking to find the characteristic of temperature value range for this station.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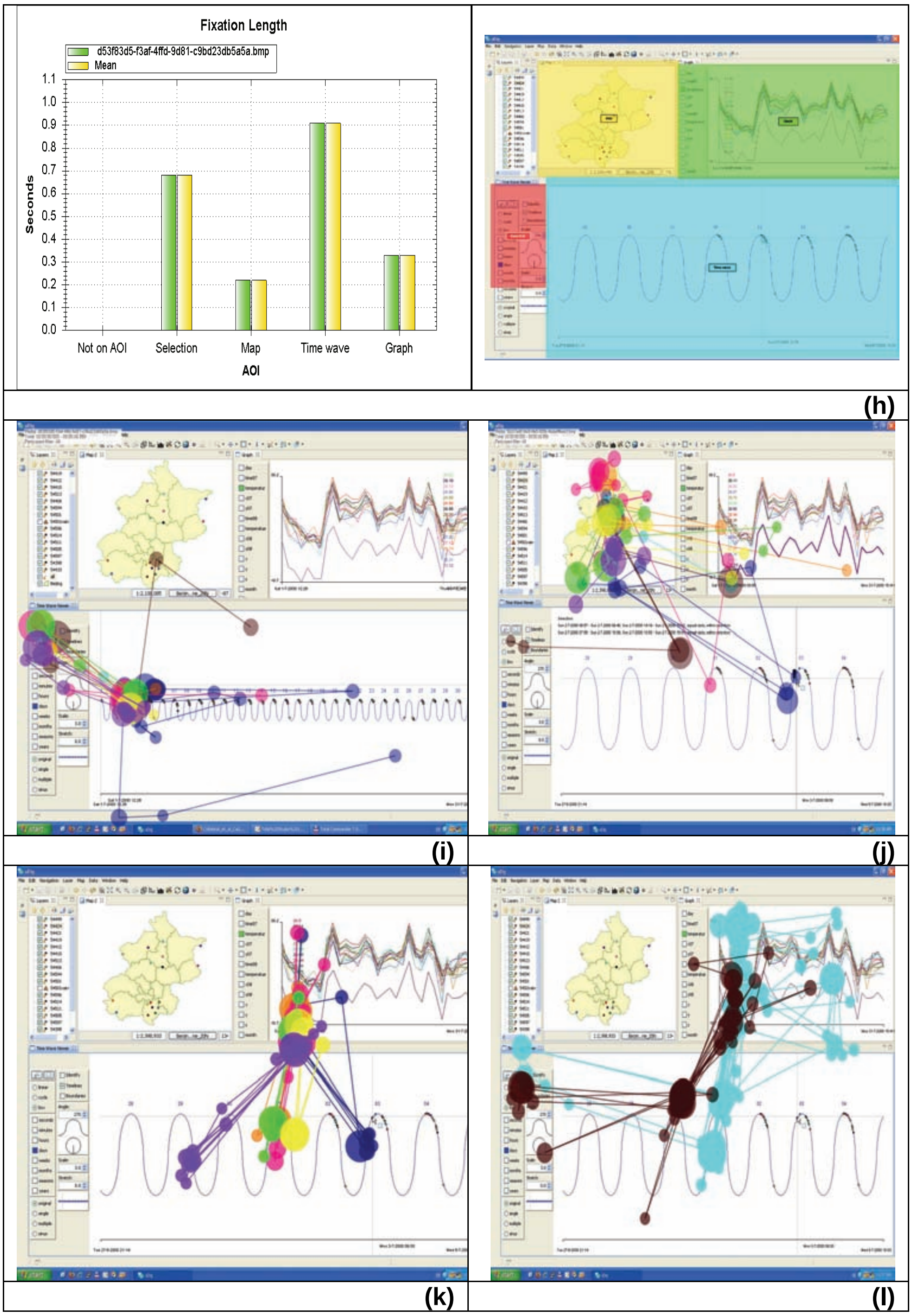
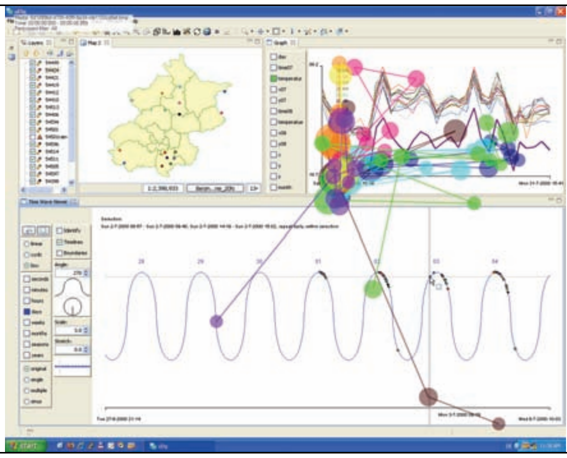

Fixation Length
d53f83d5-f3af-4ffd-9d81-c9bd23db5a5a.bmp
Mean
Seconds
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Not on AOI
Selection
Map
Time wave
Graph
AOI
(h)
(i)
(j)
(k)
(l)



**(m)**

**Figure 7-24. The result of Task 2 in Part 2. a)—f): Gaze plots show a user's behavior for this task; h) task's AOI analysis of fixation time; i)—m) show the gaze plots of all participants for each of the subtasks.**

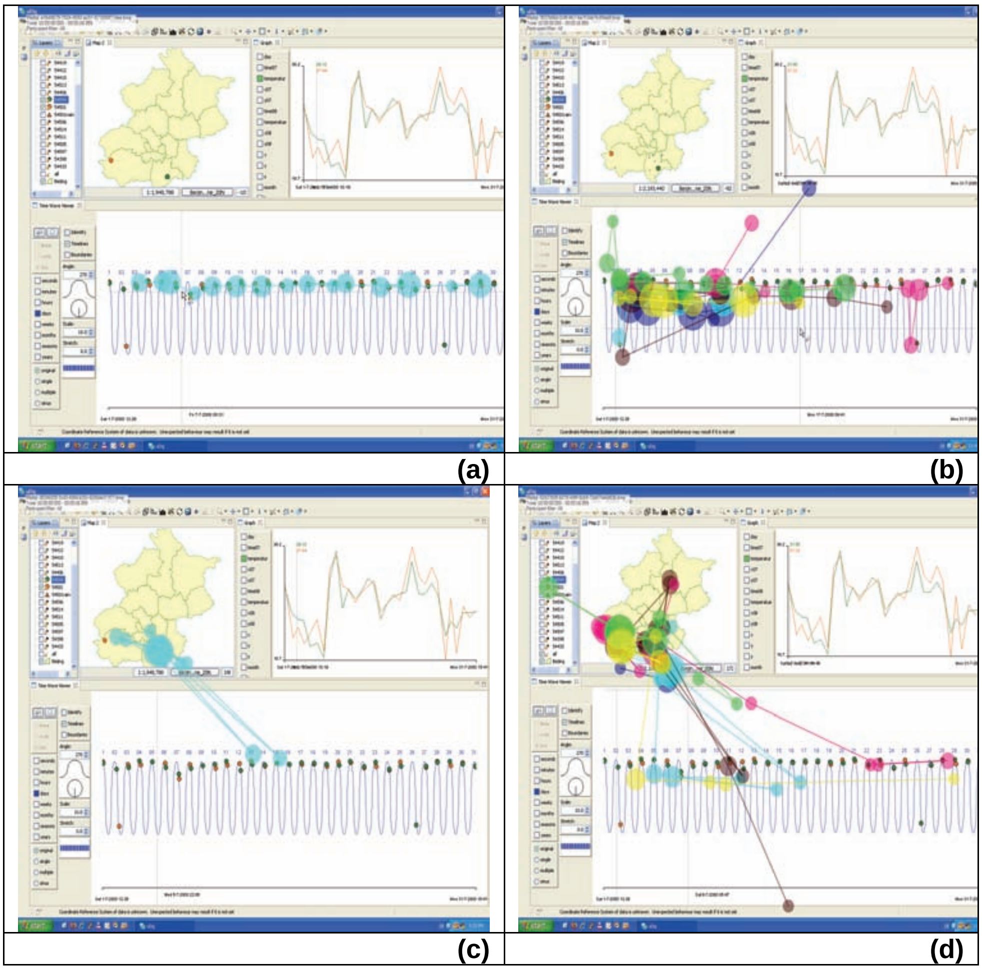
Figure 7-24h shows the task's AOI analysis of fixation time. The definition of AOI is given in the right of the figure. The time wave and function bar got most fixation time. Figures 7-24i-m shows the gaze plots of all the participants for each subtask. Figure 7-24i shows the participants trying to zoom-in from the overview to find 2$^{nd}$ July. This is followed by moving to the map view to find the location of the station (Figure 7-24j). For subtask 3, two patterns can be distinguished (figure 7-24k and l): users identified the station and the time point by viewing the time wave and time axis in the time graph (attribute space) only. Then they used the function bar to select the station and time point. It should be noticed that, in Figure 7-24k, the purple points and blue points are located at the wrong place (not 2$^{nd}$ July). This is because the stimuli for these two participants are different from the others due to their using the 'pan' function. Figure 7-24m shows users concentrating on attribute space to answer questions 3 and 4. They first focused on 2$^{nd}$ July to establish the temperature and then had a look at the whole value range for the station.

The results show the users' processes confirm the hypothesis. The questions drive the user interactive action in triple space to find the answers. Misunderstanding of the users' process can happen easily and result in the dynamic stimulus (user view), with more work involved to process the data and explain the reason. Thinking aloud and replaying the gaze plots animation is necessary to help process the tracking data.

3. Task 3

In Table 7-3, we predicted that user behavior for this task would cover all three spaces. The gaze plots confirm this; the patterns from all the participants are similar. Figures 7-25a, c, e and h show the gaze plots for the four subtasks done by one participant. Figures 7-25-b, d, f and i show the gaze plots from all the participants. For subtask 1 (figures 7-25a and b), the users identified the order of the stations from left to right. Then they moved to the map to find the spatial relationship of the two stations (figures 7-25c and d). For subtask 2, their gaze moved back to time-space to look for the day on which the yellow station reached its highest temperature much later than the green station (Figure 7-25-e and f) and subsequently to identify that day (figures 7-25h and i). Finally, they focused on attribute space to establish the temperature values of the two stations for that day.

The process revealed in the gaze plots matches the predicted eye-movement pattern in Table 7-3.



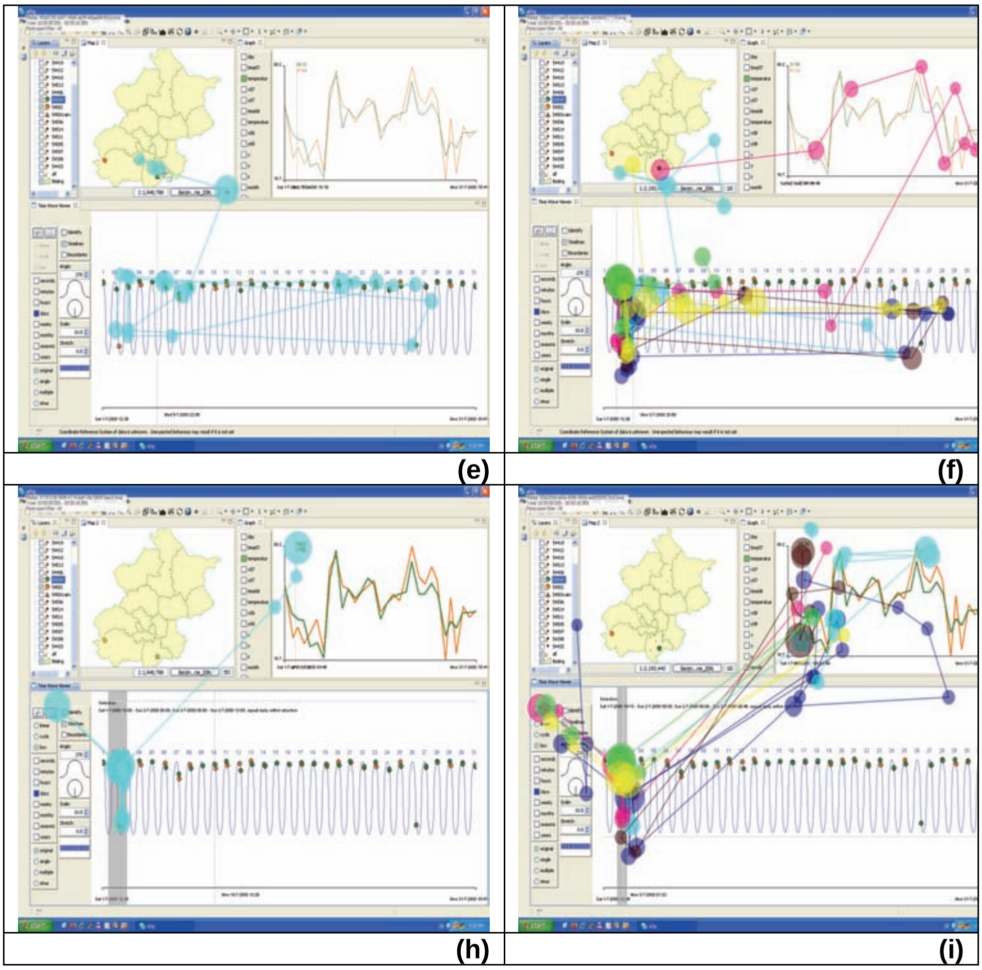
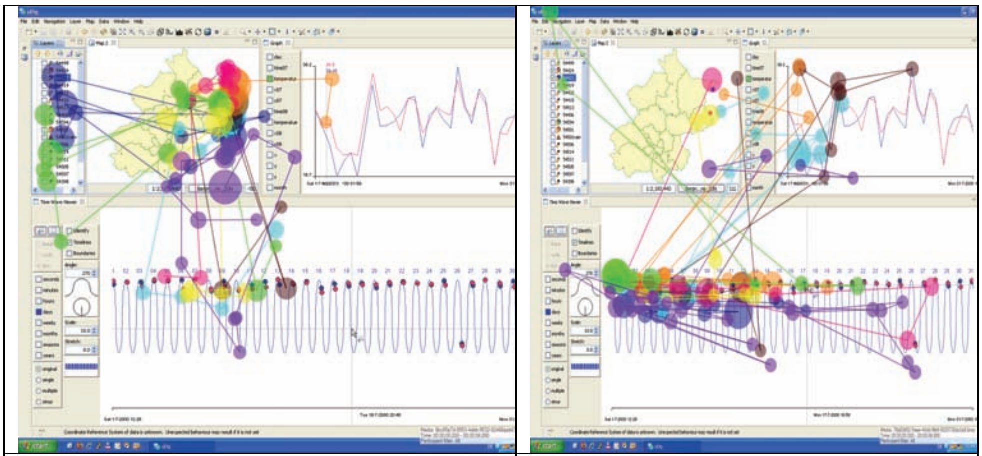


**Figure 7-25. Task 4 results. a), c), e) and h) show the gaze plots of the four subtasks done by one participant; b), d), f) and i) show the gaze plots for all the participants.**

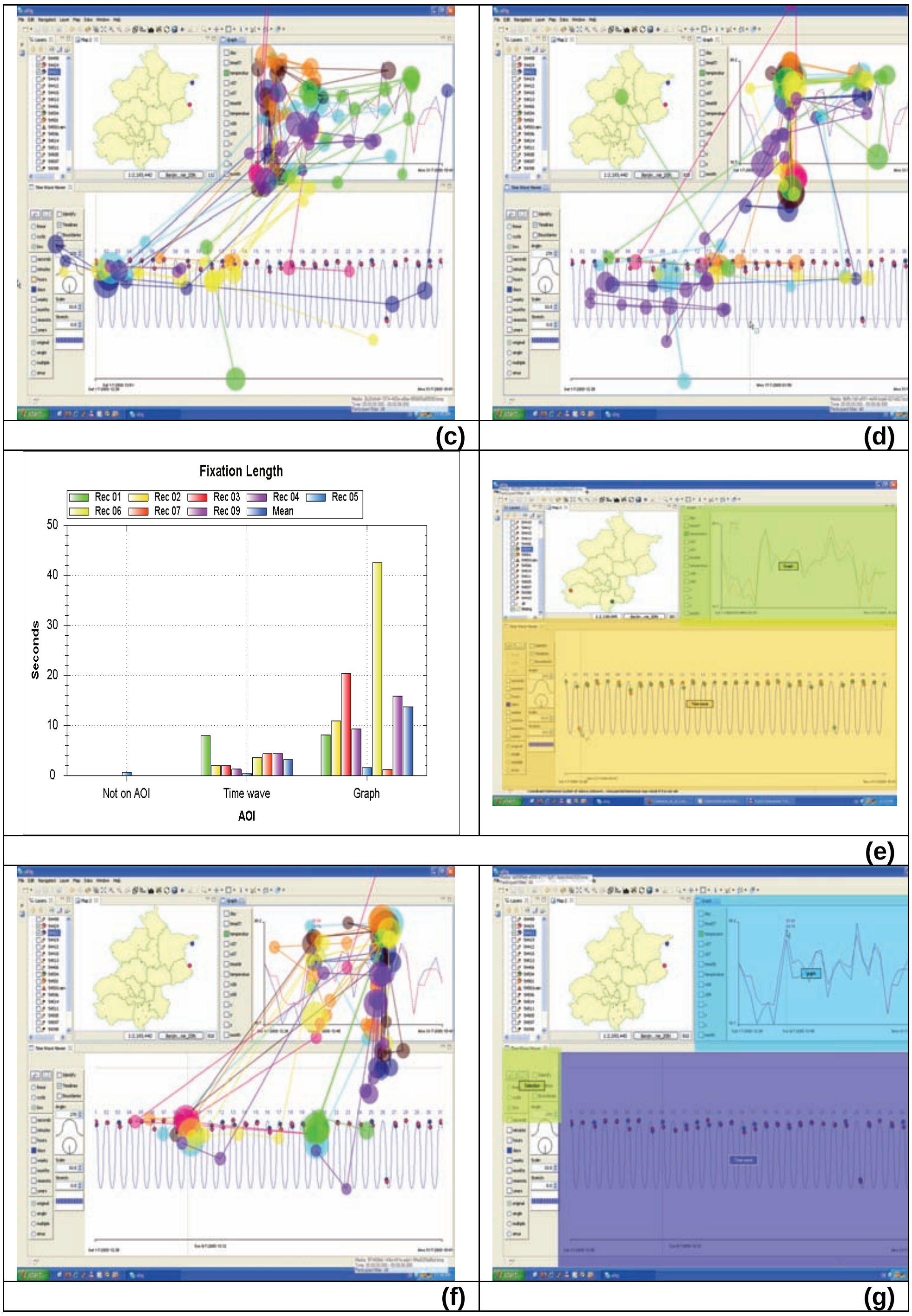
4. Task 4

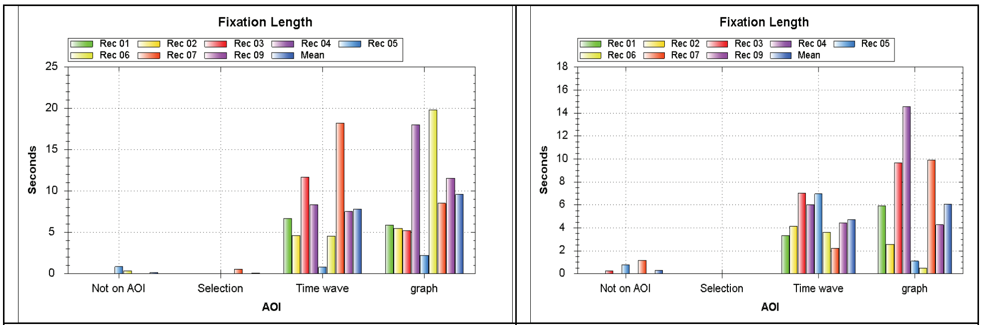
This task again required the users to use all three spaces in alternating ways. The recorded gaze plots show similar behavior by all the participants. This time the users started in location space and used the map to find both stations (Figure 7-26a). It is interesting that the behavior of the blue and green participants also focused on the layer window. They tried to identify the two stations by their names which were shown there. Next, most users moved from location space to time-space to answer the question about where→when (Figure 7-26a). For subtask 2, each day in July was observed in the day wave to find the station which reached its highest temperature first (Figure 7-26b). The vertical axis of the graph in attribute space, representing the temperature, was studied to find the temperature ranges of the two stations (Figure 7-26c). It is unclear why some participants moved between the time-spaces and attribute space at this stage of the task. After checking the video recordings with the think-aloud recordings, it proved to be an anomaly. Paths like this can arise during the user's thinking process before reaching the answer. In the meantime, their eyes wander over the screen and are recorded. Figure 7-26e shows AOI statistics of fixation length in relation to subtask 3. Although several users were not sure where to find the answers, as shown in 7-26c, they put most of their focus on to attribute space for this 'what' question. This implies that the triple space supplies a clue for the user about where to find the answer.

For subtasks 4 and 5, users searched for the highest temperature of the blue station in July (this is the vertical cluster of gaze points in attribute space in Figure 7-26d). After identifying the day, they moved back to time-space to answer the question 'in what order' (Figure 7-26d). A similar process is shown in Figure 7-26f as well. The vertical cluster of gaze points in attribute space shows that the users looked for the day in July when the pink station reached its highest temperature. The AOI statistics about fixation length for subtask 4 and 5 are shown in figures 7-26h and I, while the definition of the AOI is given in Figure 7-26g. It can be noted that the participants were busy moving between time-space and attribute space to answer these two questions. This matches the hypothesis for this task as formulated in Table 7-3.



**(a)** **(b)**


(c)
(d)
Fixation Length
Rec 01
Rec 02
Rec 03
Rec 04
Rec 05
Rec 06
Rec 07
Rec 09
Mean
Seconds
50
40
30
20
10
0
Not on AOI
Time wave
Graph
AOI
(e)
(f)
(g)




(h) (i)

**Figure 7-26. Task 4 result. a) Gaze plots for subtask 1; b) gaze plots for subtasks 2; c) gaze plots for subtask 3; d) gaze plots for subtask 5; e) AOI statistics of fixation length in relation to subtask 3; f) gaze plots for subtask 5; g) AOI definition for subtasks 4 and 5; h) AOI statistics for fixation length for subtask 4; i) AOI statistics for fixation length for subtask 5.**

## *7.7 Summary*

This chapter describes the design, execution and analysis of three tests. Here they are summarized in turn:

In Test 1, three representations were evaluated to gain insight into their function as visual temporal representation and as interaction tools. The results revealed the following characteristics of each method.

- The timeline as a typical linear representation is good in showing linear data. Questions 1, 3, 6, 7, 9, 12 and 14 were linear temporal questions. The timeline performed better than the time wheel, both on correctness and response time. Only for question 12 did the timeline not perform well. This was due to over-plotting, e.g. too much data on a single line. However, in the other cases, the simple one-dimensional nature of the timeline is in favor of using this method. The timeline was also good for selecting linear time. In linear tasks 1, 2, 5, 6 and 9, the timeline showed a better performance than the time wheel. There are no obvious differences between the performances of the timeline and time wave as a linear representation. For some linear questions, such as questions 1, 12 and 14, the time wave performed better than the timeline, because it has more space to locate data (in 2 dimension) than timeline. For linear selection, the shape of the wave provides a hint to help identify the selection point on the wave, so the time wave also showed a better performance than the timeline.
- The time wheel is good at managing certain cyclic time problems, but the test proved it was not flexible enough (this might be partly due to the way the time wheel was implemented here). Questions 2, 4, 5, 10, 13 and 16 are cyclic time questions. However, the time wheel performed better than the other representations only in questions 4, 10, 13 and 16. This because there was only one time unit in these four questions which fitted the single wheel in the representation. For questions 2 and 5, the time wave performed best. This indicates that the time wave is good at managing

cyclic time at different scales. For cyclic time selection, the time wheel functions well, such as in tasks 3 and 4. However, for linear time tasks or both linear and cyclic time, the time wheel appears to be unsuitable.

- Test 1 revealed that the capability of the time wave to manage both linear and cyclic time problems was good. Questions 8, 11, 15, 17, 18, 19 were typical questions that included both linear and cyclic time, and here the time wave outperformed the other methods. For the other tasks, it performed just as well as the timeline and time wheel.
- When it came to selecting time, the time wave had an advantage over the other methods. The time wave not only showed the best performance on both linear and cyclic time tasks (such as tasks 10, 11, 12), on multiple intervals in many temporal scales (such as 7 and 8), but it also performed better than the timeline on some linear time selections (such as 1, 2, 6 and 9), and better than the time wheel on some cyclic time tasks (such as 3 and 4).

Based on interviews with 15 participants after the test, the timeline users did not show the positive attitude towards the timeline we had expected. The single dimension of the line made it difficult to locate data. The users of the time wheel thought there were too many limitations in its use, in relation to different time scales, working with linear time, and for interaction options. The users of the time wave were happy and confirmed the flexibility of the interactive tools integrated into the time wave.

It should be noted that it is impossible to give an absolutely fair evaluation condition for these three methods, because they are affected by many factors, such as working environment and the participants' experience and background. In this study, I considered as many factors as possible and tried to find a good balance for each method.
In Test 2, the users' behavior while working with the time wave was tested. It lead to several conclusions:

- For linear questions (such as questions 1 and 5), users followed the wave from left to right. In question 1, users followed the day wave which is an approximate, horizontal line, to identify the data. In this case, the wave's ups and downs were ignored. For question 5, the month was shown as a curved shape and most users followed this curve to find the answer. These results show that the time wave retains a linear representation.
- For questions 3, 5 and 6, cyclic time was required. For question 3, users needed to identify the third Tuesday. Most of them checked the label on the timeline to make sure their identification was correct. This shows the label and timeline are a more familiar method to use for checking. For questions 5 and 6, users needed to identify several cyclic time periods, Friday and midnight. Here the advantage of the time wave was evident. After users had learnt the position and how cyclic time is represented on the time wave, they did not go back to check the timeline. Instead they just went directly to a certain place on the time wave to answer the questions.
- Questions 7 and 8 dealt with both linear and cyclic time on multiple scales. The results show how the users followed the different paths on the time

wave for linear and cyclic time. For linear time, users followed the horizontal line to find the answer, whereas for cyclic time, the wave shape provided the cyclic information to support direct identification.

In Test 3, the time wave worked with the map and graph together to support the users' interactive and iterative processes. For each of the four tasks, the results confirmed the hypotheses. This means that the triple space concept helped users to find the answers efficiently, because each data type had its own space. Supported by the CMV technique, different perspectives of the data could be linked to each other. In this test, the users' view changed often because of interactive searching like zooming and panning. This caused a problem in the post-processing phase, especially when users wanted to make comparisons. Think-aloud recordings or replaying the gaze plot videos were needed to avoid misinterpreting the results.

# Chapter 8 Conclusions and discussion

***Summary***

The need for advanced visual analytical methods and techniques to study multivariate spatio-temporal data from a temporal perspective initiated this research. This need grew from the availability of huge amounts of diverse multi-scale and multi-resolution spatio-temporal data and from the GIScience domain wanting to contribute to solving global problems.

Looking back to the beginning of this thesis, the problem definition was '*Does the use of visualization methods during the exploration of spatio-temporal data contribute to a better understanding of the data if their temporal characteristics are also considered?'* With respect to this problem, six research questions have been discussed in the various chapters. The questions are numbered in the pink circles in the research scheme shown in Figure 8-1. The questions are summarized and answered below.

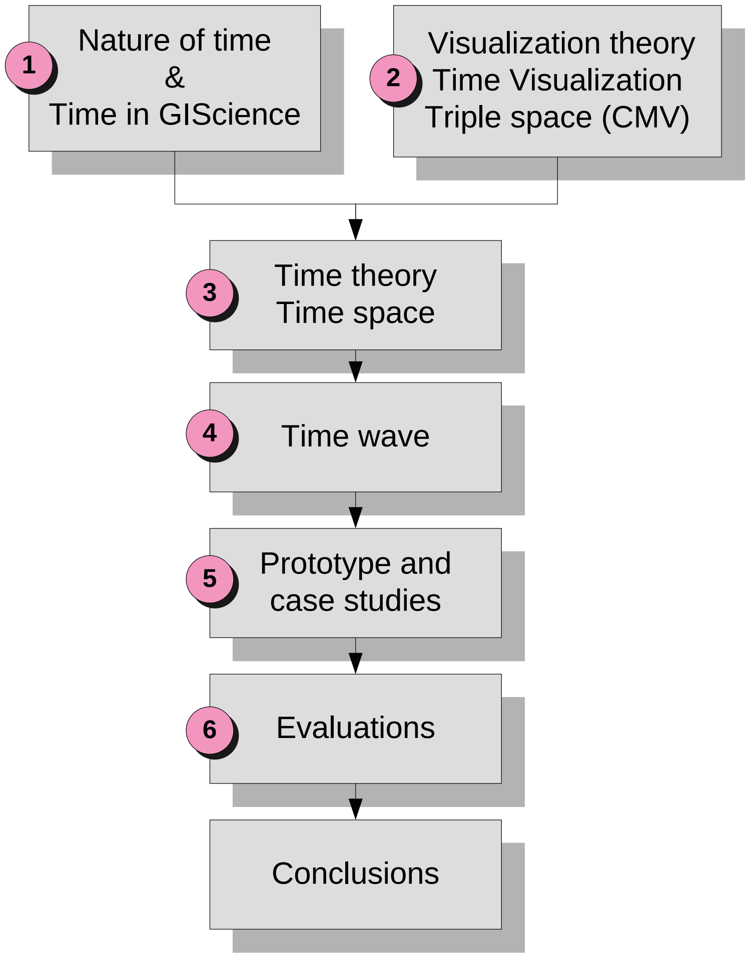



**Figure 8-1. The research and research questions (the numbers in the circles)**

7. What is the nature of time and specifically time in GIScience?

In chapter 2, the time issue was discussed from the perspective of various disciplines such as philosophy, physics, cognition and GIScience. These discussions on both the nature and the visualization of time revealed different perspectives on time, each with a particular application in mind. However, there were also notable similarities among all the viewpoints. Particularly the notions of linear and cyclic time, discrete and continuous time, and absolute and relative time. These notions were taken into consideration in the time visualization environment and in developing the time wave and its functionality to be able to answer different temporal questions. It was shown how these notions describe the nature of time and are closely linked to the human cognition of time.

8. What are the existing visualization options for exploring time?

In chapter 3, the common visualization-based approach to problem solving in the geo-visualization domain was discussed and used to structure this research work (Figure 2-1). Three important keywords are applied in most visualization research: user tasks, data framework and visualization framework. These were used to discuss the basic visualization theories of Bertin, Peuquet, MacEachren and Andrienko to derive a systematic view on visualization.

Based on the character of spatio-temporal data, the visual working environment is composed of three main views that represent location space, attribute space and time-space, each with a focus on its data component (location, time and attribute), and the user tasks (where, when and what). Representation and interaction tools were introduced for each space. The link between the individual views of the triple space, and the iterative process of problem solving are supported via the Coordinated Multiple View (CMV) technique. Based on the three keywords, taxonomies of time visualizations have been reviewed to discuss and evaluate the existing time visualization methods.

9. Based on visualization theory, how can time-space be structured?

To define the requirements for time-space, in chapter 4 I have discussed temporal data, temporal user tasks, and temporal visualization from both temporal visualization theory and the users' perspective (derived from the results of a questionnaire). From the theoretical viewpoint, a temporal visualization concept was discussed based on the integration of several visualization theories (in chapter 3), research on time (chapter 2), GIScience and the information visualization domains considered in this research. The nature of the temporal data and the user tasks (temporal tasks space (TTC)) at hand are the driving forces in selecting a suitable graphic representation. From a user requirements perspective, potential users were questioned to see if my ideas about the temporal visualization concept would match users' applications in their research. According to the analysis of the answers to the questionnaire, most of the temporal data and the temporal user tasks in applications can be included and structured according to my temporal visualization concept. Thus, this concept, can be used to explain how to structure a time-space based on temporal data, temporal user tasks, and temporal visualization. However, the user requirements study revealed a gap between the theories and available applications in time visualization. This gap was characterized by four points:

1. A combined approach for linear and cyclic time is missing.
2. Relative time should also be considered in time-space.
3. A close combination of temporal representation and interaction tools in time-space is required.
4. Coordinating time-space with location space and attribute space has to be realized.

10. What graphic representation can be used and how can this be realized (in a prototype)?

Chapter 5 introduced an alternative approach for working with spatio-temporal data, based on the requirements of time-space and the gap between theories and applications. This new time-wave approach not only combines linear and cyclic time (gap 1), but also temporal data representations and interaction (gap 3), and it allows a limited representation of attribute and locational data (gap 4). The time wave can be used not only as a temporal reference, a representation to show the temporal patterns, but also as temporal interaction tools to support temporal actions, such as locating, identifying, zooming in/out, and comparing time instances or intervals. Via the CMV technique, the time wave can also be used to further interact with location space and attribute space to support interactive and iterative exploration processes. The exploratory activities are guided by Shneiderman's visual information seeking mantra. Depending on the task, users can switch from one space to another and into any of the information-seeking modes (overview, zoom/filter, and details-on-demand). The time wave can be extended as an event wave to solve the problem of considering relative time (gap 2) and as multiple waves to support tasks needing to make comparisons.

11. How can time-space be used to explore spatio-temporal data (a case study)?

In chapter 6, the working environment of the time wave, together with a map for location space and a graph for attribute space, was designed and realized in uDig. Based on the time wave reference, several functions can be defined, such as time scale selection, identification, time selection, etc. A case study based on data observed at meteorological stations in Beijing was used to demonstrate the time-space framework and the capabilities of the time wave. Temporal patterns and distributions were studied from time-space, switching to location space (maps) and attribute space (diagrams) when required.

12. Does this concept of time-space and the new graphic representation work (usability testing)?

The time wave was designed (chapter 5) and a prototype made and tested with a case study (chapter 6) according to the requirements of time-space (chapter 4). The usability of the time wave was discussed in chapter 7. Its evaluation in this research comprised four steps. The first step was discussed in chapter 4 and involved collecting the users' requirements and analyzing their current understanding of time theory. It identified a gap between theory and application. In the second step, the time wave was compared with other visualization methods – the timeline and time wheel – to evaluate and compare their effectiveness, efficiency and user satisfaction. The advantages and disadvantages of the time wave were discussed based on analysis of the evaluation results. In step 3, eye-tracking technology was used to study users' behavior while working in the time wave environment. Step 4 explored users' thinking processes while working in triple space with the time wave; for this step eye-tracking technology and think-aloud recordings were used.

***Conclusions***

The reason for developing the time wave was to have a graphic representation that would allow access to the large amounts of spatio-temporal data now available and a means of exploring it. The time wave stimulates users to tackle the problem at hand via the time-space approach and supports the geovisual analytical process. The time wave, which simultaneously incorporates the best of the timeline and time wheel, has different roles to play: it can be used as a temporal reference, a temporal data representation system, and a temporal interaction tool. It can be used to answer important time-related questions, and in combination with graphic representations in location space and attribute space, it can tackle complex questions relating to temporal geodata. As such, it supports users in discovering spatio-temporal patterns and relations in their data. The time wave showed a better performance than either the timeline or time wheel in representing and interacting with combined linear and cyclic time.

The time wave is a good example of how an alternative view on the data might reveal patterns that are not always obvious from traditional graphic representations. In overview mode, it has a suitable visualization to provide an impression of the nature of the data, whether linear or cyclic. We do not argue that the time wave is the only visual representation in time–space, since graphics based only on the timeline or time wheel might be preferred in certain situations. This will very much depend on the nature of the data and the task at hand.

So far, based on the evaluation results, it is also evident that the time wave also has some disadvantages. Even though the time wave can display different granularities of the same data set, or different data sets of the same granularity in a single representation, there are limitations to the number of wave periods or the number of temporal granularities that can be displayed at the same time, especially if the time scales differ greatly. With a very large amount of data, the time wave will, like many other graphic representations, suffer from overplotting.

It is claimed that the optimal solution space is time-space interactively linked with location and attribute space. This allows users to tackle problems flexibly and from many different perspectives. Triple space structures the data, visualizations and users' interaction in an efficient way. It supports users in finding answers and orders their thinking process systematically. To deal with the temporal user tasks, a temporal link is necessary and useful. Defining the temporal link in time-space could help users to identify or select the time instant and/or interval at different granularities and show the spatial and attribute characteristics in the other spaces. To define a useful temporal link, different views of time have to be considered, such as linear versus cyclic, continuous versus discrete, instant versus interval, and granularities.

Since exploratory tasks are executed as an iterative process, the temporal representation and temporal interactive function should work together in time-space to interact with the other spaces. The combination of representation and interactive tools are necessary in location and attribute space as well, supporting the interactive and iterative process of exploration. This means that the feature of interest can be identified, selected and compared further, based on the data patterns in any part of the representation.

The temporal visualization concept helps users to structure their problem such that they can find the most appropriate visualization for the temporal problem at hand. The results from the questionnaire sent to sixty students gave support to our approach and will prove helpful in the further development of useful visualizations based on users' needs. However, users need to be trained in working with the time wave and they need to learn more about TTS.

***Future work***

The temporal visualization concept can be elaborated by analyzing existing temporal visualization methods for their strengths and weaknesses in the context of users' actual temporal problems. If successful, this could lead to a kind of advisory system that could assist users in selecting a suitable graphic representation dedicated to their specific temporal data and tasks. However, more case studies are needed to be able to further discuss the usability of the time wave in different applications.

Most of the existing studies on relative time are based on absolute time. Their focus on relative time in studying the relative temporal relationships of events may result in a different view on how to discover regularities or irregularities in the data. I have shown how the time wave could be extended with the event wave to further investigate how GI scientists can deal with relative time. The role of the time wave as a time legend for animation control needs to be further explored through case studies and usability evaluations, and by comparing the use of the time wave with the timeline and time wheel.

# References


Abrams, M., N. Doraswamy, et al. (1992). Chitra: visual analysis of parallel and distributed programs in the time, event, and frequency domains. IEEE Transactions on Parallel and Distributed Systems IEEE Computer Society. **3:** 672-685.

Ahlberg, C. and B. Shneiderman (1994). Visual Information Seeking: Tight Coupling of Dynamic Query Filters with Starfield Displays. ACM CHI, ACM.

Aigner, W., S. Miksch, et al. (2005). PlanningLines: Novel Glyphs for Representing Temporal Uncertainties and their Evaluation. Proceedings of the Ninth International Conference on Information Visualization Washington DC, USA, IEEE Computer Society

Aigner, W., S. Miksch, et al. (2007). "Visualization Time-oriented Data--- A Systematic View." Computers and Graphics **31**: 401-409.

Allen, R.B. (1995). Interactive Timelines as Information System Interfaces. Symposium Libraties, Japan.

Andrienko, G., N. Andrienko, et al. (2003). "Interactive maps for visual exploration of grid and vector geodata." ISPRS Journal of Photogrammetry and Remote Sensing **57**(5-6): 380-389.

Andrienko, N., G. Andrienko, et al. (2003). "Exploratory spatio-temporal visualization: an analytical review." Journal of Visual Languages & Computing **14**(6): 503-541.

Andrienko, G. and N. Andrienko (2006). Exploratory Analysis of Spatial and Temporal Data. Berlin, Germany, Springer.

Augustine, S. (1963). The Confessions of St. Augustine New York.

Augustine, S. (398). "Confessions."

Barnicle, K. (2000). Usability testing with screen reading technology in a Windows environment. Proceedings on the 2000 conference on Universal Usability Arlington, Virginia, United States ACM New York.

Beard, D., M. Palaniappan, et al. (1990). A visual calendar for scheduling group meetings. ACM conference on Computer-supported cooperative work Proceedings of the 1990 ACM conference on Computer-supported cooperative work ACM.

Belofsky, M.S. and D.R. Lyon (1988). Modeling eye movement sequences using conceptual clustering techniques. Air Force Systems. Brooks Air Force Base, Air Force Human Resources Laboratory.

Benel, D.C.R., D. Ottens, et al. (1991). Use of an eye tracking system in the usability laboratory. Human Factors Society 35th Annual Meeting, Santa Monica, Human Factors and Ergonomics Society.

Berker, R. and W. Cleveland (1987). "Brushing scatterplots." Technometrics **29**(22): 127-142.

Bertin, J. (1983). Semiology of graphics : diagrams, networks, maps. Madison, University of Wisconsin Press.

Bevan, N. (1994). "DRAFT INTERNATIONAL ISO DIS 9241-11 STANDARD." Retrieved 26/01, 2005, from http://usability.ru/sources/iso9241-11.htm#5.3.1.

Blok, C. (2005). Dynamic visualization variables in animation to support monitoring of spatial phenomena. Utrecht University, ITC. Enschede, Universities Utrecht, ITC**:** 188.
Boren, T. and J. Ramey (2000). "Thinking aloud: Reconciling theory and practice." IEEE Transactions on Professional Communication **43**(33): 261-278.
Brewer, C. (1989). "Color chart use in map design." Cartographic perspective **4**: 3-10.
Brewer, I., Alan M. MacEachren, Hadi Abdo, Jack Gundrum, George Otto, (2000). Collaborative Geographic Visualization: Enabling Shared Understanding of Environmental Processes. IEEE Symposium on Information Visualization 2000.
Brian, F. and J. Pritchard (1997). Visualization of historical events using Lexis pencils. Centre for Applied Statistics Fylde College, Lancaster University.
Brodbeck, D. and L. Girardin (2003). Design Study: Using Multiple Coordinated Views to Analyze Geo-referenced High-dimensional Datasets. International Conference on Coordinated & Multiple Views in Exploratory Visualization, London, England, IEEE Computer Society.
Brodersen, L., H.H.K. Anderson, et al. (2002). Applying Eye-Movement Tracking for the Study of Map Perception and Map Design. Denmark, Kort & Matrikelstyrelsen.
Brown, A. (1980). "The use of densitometry in determining equal-interval screened value scales for maps and color charts." ITC Journal **1**: 103-126.
Brown, I.M. (1998). A 3D Interface for Visualization of Serial Periodic Data. ACM GIS'98, Washington DC USA.
Buja, A., D. Cook, et al. (1996). "Interactive high-dimensional data visualization." Journal of Computational and Graphical Statistics, **5**: 78-99.
Burkhard, R.A. and M. Meier (2004). Tube Map: Evaluation of a Visual Metaphor for Interfunctional Communication of Complex Projects. Proceedings of I-KNOW '04. Graz, Austria.
Butterfield, I.C. (2003). Spacetime and the philosophical challenge of quantum gravity. Physics Meets Philosophy at the Planck Scale: Contemporary Theories, in Quantum Gravity, Callender C. Cambridge, Britain, Cambridge University Press**:** 33-89.
Card, S.K., J.D. Mackinlay, et al. (1999). Readings in information visualization: using vision to think. San Francisco, California, Morgan-Kaufmann.
Carlis, J.V. and J.A. Konstan (1998). Interactive Visualization of Serial Periodic Data. ACM UIST'98, San Francisco.
Carpendale, T., M.sheelagh, A. Fall, D.J. Cowperthwaite, J. Fall, F.D. Fracchia (1996). Visual Access for Landscape Event based Temporal Data. visulization'96.
Carr, D.B., R.J. Littlefield, et al. (1986). Scatterplots Matrix techniques for large n. Proceeding of the Seventeenth Symposium on the Interface of Computer Sciences and Statistics, New York, Elsevier North-Holland.
Chen, T. (2005). Modeling and Visualizing Linear and Cyclic Changes. Re-presenting GIS. P. Fisher and D. J. Unwin. London, John Wiley & Sons, Ltd. **15:** 205-211.

Chi, E.H., et al. (1998). Visualizing the Evolution of Web Ecologies. ACM CHI'98, CA USA.

Chi, E.H. (2000). A Taxonomy of Visualization Techniques using the Data State Reference Model. IEEE Symposium on Information Visualization, Salt Lake, IEEE computer Society.

Cleveland, W.S. (1993). Visualizing data. Murray Hill, AT&T.

Çöltekin, A.,B. Heil, et al. (2009). "Evaluating the Effectiveness of Interactive Map Interface Designs: A Case Study Integrating Usability Metrics with Eye-Movement Analysis " Cartography and Geographic Information Science **36**(1): 5-17.

Cornwell, B. and A. Robinson (1966). "Possibilities for Computer Animation Films in Cartography." Cartographic Journal **3**(2): 79-82.

Cowen, L. (2001). An Eye Movement Analysis of Web-Page Usability. UK, Lancaster University. **Master**.

Crowe, E.C. and N.H. Narayanan (2000). Comparing interfaces based on what users watch and do. Proceedings Eye Tracking Research and Applications Symposium, New York, Association for Computing Machinery.

Chi, E.H., et al. (1998). Visualizing the Evolution of Web Ecologies. ACM CHI'98, CA USA.

Daassi, C., M. Dumas, et al. (2000). Visual exploration of temporal object databases. proc. of BDA00 Conference, Blois, France.

Daassi, C., M.-C. Fauvet, et al. (2002). Multiple Visual Representation of Temporal Data. Proceedings of the 13th International Conference on Database and Expert Systems Applications Springer-Verlag.

Daassi, C., L. Nigay, et al. (2004). Visualization Process of Temporal Data 15th International Conference, DEXA 2004, Zaragoza, Spain,, Springer Berlin / Heidelberg.

Daly, M.T. (1972). Techniques and concepts in geography: a review. Melbourne, Nelson.

Damasio, A.R. (2006). "Remembering When

Davis, M. (1993). Media Streams: an iconic visual language for video annotation. Proceedings 1993 IEEE Symposium on Visual Languages, Bergen, Norway, IEEE.

Dowden, B. (2009). "Time." The internet Encyclopedia of Philosophy.

Dragicevic, P. and S. Huot (2002). SpiraClock: A Continuous and Non-Intrusive Display for Upcoming Events. Conference on Human Factors in Computing Systems, Minnesota, USA

Dykes, J., A.M. MacEachren, et al., Eds. (2005). Exploring Geovisualization, Elsevier Science & Technology Books.

Edsall, R., M.-J. Kraak, et al. (1997). Assessing the Effectiveness of Temporal Legends in Environmental Visualization GIS/LIS '97 Annual Conference and Exposition Cincinnati, Ohio

Edsall, R.M., M. Harrower, et al. (2000). "Tools for visualizing properties of spatial and temporal periodicity in geographic data." Computers & Geosciences **26**(1): 109-118.

Edsall, R.M. (2003). "The parallel coordinate plot in action: Design and use for geographic visualization." Computational Statistics and Data Analysis **43**(4): 605-619.

Ellis, S., R. Candrea, et al. (1998). Windows to the soul? What eye movements tell us about software usability. Usability Professionals' Association Conference 1998.
Elmasri, R. and J.Y. Lee (1998). Implementation Options for Time-Series Data. Temporal databases: research and practice. O. Etzion, S. Jajodia and S. S. (Eds.), Springer. **1:** 115-128.
Ericsson, K.A., and H.A. Simon (1993). Protocol analysis: Verbal reports as data., Cambridge, MA: MIT Press.
Fabrikant, S.I., S.R. Hespanaha, et al. (2008). A visual analytics approach to evaluate inference affordance from animated map displays. GIScience 2008 Pre-Conference workshop on Geospatial Visual Analytics, Park City, UT.
Fabrikant, S.I., S. Rebich-Hespanaba, et al. (2008). "Novel Method to Measure Inference Affordance in Static Small-Multiple Map Displays Representating Dynamic Process." The Cartographic Journal **45**(3): 201-215.
Fabrikant, S.I., S. Rebich-Hespanha, et al. (2010). "Cognitively inspired and perceptually salient graphic displays for efficient spatial inference making" Annals of the Association of American Geographers **100**(1): 13-29.
Flaherty, P. (1991). "Transaction logging systems: a descriptive summary." Library Hi Tech **11**(2): 67-78.
Frank, A. (1994). Different Types of "Times" in GIS. GIS and Computational Science Perspectives.
Fuhrmann, S., P.Ahonen-Rainio, R. Edsall, S.I. Fabricant, E.L. Koua, (2004). "Making useful and useable geovisualization: design and evaluation issues." Exploring Geovisualization.
Gahegan, M. (2000). "On the application of inductive machine learning tools to geographical analysis." Geographical Analysis **32**(113-139).
Gahegan, M., M. Harrover, T.M. Rhyne and M. Wachowicz (2001). "The integration of geographic visualization with databases, data mining, knowledge construction and geocomputation." Cartography and Geographic Information Science **28**(1): 29-44.
Garlandini, S. and S.I. Fabrikant (2009). Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization. Spatial Information Theory: 9th International Conference, COSIT 2009, Berlin, Germany, Springer Berlin / Heidelberg.
Garnett, H. (1903). Statistical Atlas- Twelfth Census of the United States, take in the year 1900. Wasington, United States Census Office.
Gitelman, D.R. (2002). "ILAB: A prog ram for postexperimental eye movement analysis." Behavior Research Methods, Instruments, & Computers **34**(4): 605-612.
GIVA's Eye Movement Lab. from http://www.geo.uzh.ch/en/units/gisience-giva/services/eye-movement-lab/.
Gleick, J. (1999). Faster: The Acceleration of Just About Everything, New York Pantheon Books.
Goldberg, J.H. and J.C. Schryver, Eds. (1993). Eye-gaze determination of user intent at the computer interface. Eye Movement Research: Mechanisms, Processes and Applications. Amsterdam, North-Holland Press.

Goldberg, J.H. and X.P. Kotval (1999). "Computer interface evaluation using eye movements:methods and constructs". International Journal of Industrial Ergonomics **24**: 631-645.
Goldhaber, M. H. (1997). "Attention Shoppers! wired."
Goralwalla, I.A., M.T. Ozsu, et al. (1998). An Object-Oriented Framework for Temporal Data Models. Temporal Database-Research and Practice. O. Etzion, S. Jajodia and S. Sripada. Berlin Heidenberg, Springer. **1:** 1-35.
Green, M. (1998). Toward a Perceptual Science of Multidimensional Data Visualization: Bertin and Beyond, ERGO/GERO Human Factors Science.
Hägerstrand, T. (1970). "How about People in Regional Science?" Papers of the Regional Science Association **24**: 7-21.
Haklay, M. and A. Zafiri (2008). "Usability engineering for GIS: Learning from a screenshot." Special Issue on Use and User Issues The Cartographic Journal **45**(2): 87-97.
Hannah, S. (2008). Sorting Out Card Sorting: Comparing Methods for Information Architects, Usability Specialists, and Other Practitioners. Aim Capstone 2005.
Harris, R.L. (1999). Information graphics: a comprehensive illustrated reference New York Oxford University Press US
Harris, S., B. Hetzler, et al. (2000). ThemeRiver: Visualization Theme Changes Over Time. IEEE Symposium on Information Visualization, USA, IEEE Computer Society.
Harrison, B.L., R. Owen, R.M. Baecker (1994). Timelines: An Interactive System for the Collection of Visualization of Temporal Data. Graphics Interface' 1994, Canadian.
Havre, S., B. Hetzler, et al. (2000). ThemeRiver: Visualizing theme changes over time. IEEE Symposium on Information Visualization, Los Alamitos, USA, IEEE Computer Society.
Hawking, S., Penrose R. (2001). The nature of space and time. International-Studies-in-Philosophy. **4:** 126.
Heath, M.T. and J.A. Etheridge (1991). "Visualizing the Performance of Parallel Programs." IEEE Software **8**: 29-39.
Helman, C.G. (2005). "Cultural aspects of time and ageing." Science & Society **6**(Special issue): 54-58.
Henderson, J.M. and F. Ferreira (2004). Scene Perception for Psycholinguists. The Integration of Language, Vision, and Action: Eye Movements and the Visual World. J. M. Henderson and F. Ferreira. New York, NY, Psychology Press.
Hibino, S. and E.A. Rundensteiner (1997). MMVIS: Design and Implementation of a Multimedia Visual Information Seeking Environment. the fourth ACM international conference on Multimedia, Boston, Massachusetts, United States ACM.
Hinneburg, A., D.A. Keim, et al. (1999). "HD-Eye: Visual Mining of High-Dimensional Data." IEEE Comput. Graph. Appl. **19**(5): 22-31.
Hoeber, O. and X.D. Yang (2006). Exploring Web Search Results Using Coordinated Views. International Conference on Coordinated & Multiple Views in Exploratory Visualization London, England, IEEE Computer Society.

Hoover, K. (2003). "Nonstationary time series, cointegration, and the principle of the common cause." The British Journal for the Philosophy of Science **54**: 126.
Hornsby, K. and M.J. Egenhofer (2002). "Modeling Moving Objects over Multiple Granularities." Annals of Mathematics and Artificial Intelligence **36**: 177-194.
Isard, W. (1970). "On notions and models of time " Papers in Regional Science **25**: 7-32.
Jacob, R.J.K. (1991). "The use of eye movements in human-computer interaction techniques: what you look at is what you get." computer—human interaction **9**(2): 152-169.
Jacob, R., and K. Karn, Ed. (2003). Eye tracking in human computer interaction and usability research: Ready to deliver the promises. The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research. Amsterdam, The Netherlands, Elsevier Ltd.
Jaynes, J. (1976). The origin of consciousness in the breakdown of the Bicameral mind. Boston, Houghton Mifflin Co.
Jones, L.A. and J.H. Wearden (2004). "Double standards: Memory loading in temporal reference memory." Quarterly Journal of Experimental Psychology **57**(B): 55-77.
Just, M.A. and P.A. Carpenter (1976). "Eye fixations and cognitive processes." Cognitive Psychology **8**: 211-222.
Karam, J.M. (1994). Visualization Using Timelines. Intl Symposium on software Testing and Analysis (ISSTA).
Keehner, M.H., M., Cohen, C.A., Khooshabeh, P. & Montello, D. R. (2008). "Spatial reasoning with external visualizations: What matters is what you see, not whether you interact." Cognitive Science **32**: 1099-1132.
Keim, D. (1996). "Pixel-Oriented Database Visualizations." SIGMOD Record, Special Issue on Information Visualization: 35-39.
Keim, D. (1997). Visual Techniques for Exploration Databases. Knowledge Discovery in Databased, Newport Beach.
Keim, D., M. Hao, et al. (2002). Pixel bar charts: a visualization technique for very large multi-attribute data sets. Information Visualization, USA.
Keim, D.A. (2003). CircleView-A new approach for visualizing time-related multidimension data sets, konstanz.
Kilman, D. and D. Forslund (1997). "An International Collaboratory Based on Virtual Patient Records." Communications of ACM **40**(8): 110-117.
Kincade, C.M., P.B. Dupont, et al. (1985). "Electronic Calendars in the office: An Assessment of User Needs and Current Technology." ACM Transactions on Office Information Systems **3**(2): 89-102.
Koike, Y., A. Sugiura, et al. (1997). TimeSlider: An Interface to Specify Time Point Proceedings of UIST '97.
Koussoulakou, A. and M.-J. Kraak (1992). "Spatio-temporal maps and cartographic communication." The Cartographic Journal **29**: 101-108.
Kraak, M.-J. (1996). Cartography: Visualization of geospatial data.
Kraak, M.-J., E. R., et al. (1997). Cartographic animation and legends for temporal maps: exploration and or interaction. 18th ICA/ACI International Cartographic Conference, Stockholm, Sweden.

Kraak, M.-J., R. Edsall, et al. (1997). Cartographic animation and legends for temporal maps: exploration and/or interaction. 18th ICC Stockholm Sweden
Kraak, M.-J. and D. v.d. Vlag (2007). "Understanding Spatiotemporal Patterns: Visual Ordering of Space and Time." Cartographica **42**(2): 153-162.
Krose, B.J.A. and C.A. Burbeck (1989). "Spatial interactions in rapid pattern discrimination." Spatial Vision **4**: 211-222.
Kullberg, R.L. (1995). Dynamic Timelines: Visualizing Historical Information in Three Dimensions. Science in Media Arts and Sciences. Cambridge, Massachusetts Institute of Technology. **Master**.
Kullberg, R.L. (1996). Dynamic Timelines: Visualizing the History of Photography. ACM CHI'96.
Kumar, R. (1999). Research methodology. A step-by-step guide for beginners. London, New Delhi: SAGE Publications.
Kumar, R. (2005). Research methodology: A step-by-step guide for beginners. London, SAGE Publications.
Kumar, R.F., R.B. Allen (1998). Metadata visualization for Digital Libraries: Interactive Timeline Editing and Review. Proc. of ACM Digital Libraries,, Pittsburgh, USA.
Lakoff, G. and M. Johnson (1980). Metaphors we live by. Chicago, The University of Chicago Press.
Lamirel, J.-C. and S.A. Shehabi (2006). MultiSOM: a Multiview Neural Model for Accurately Analyzing and Mining Complex Data. International Conference on Coordinated & Multiple Views in Exploratory Visualization London, England, IEEE Computer Society.
Langran, G. (1992). Time in Geographic Information Systems. London, Taylor & Francis.
Larkin, J.H. and H.A. Simon (1987). "Why a diagrame is (sometimes) worth ten thousand words." Cognitive Science **11**: 65-99.
Lawrence, M. and E.-K. Lee (2006). exploRase: Exploratory Data Analysis of System Biology Data. International Conference on Coordinated & Multiple Views in Exploratory Visualization London, England, IEEE Computer Society.
Li, X. and M.-J. Kraak (2008). "The Time Wave. A New Method of Visual Exploration of Geo-data in Time–space." The Cartographic Journal **45**(3): 1-9.
Liu, L.Y., J.J. Wang, et al. (2006). "Predicting winter wheat condition, grain yield and protein content using multi-temporal EnviSat-ASAR and Landsat TM satellite images." International Journal of Remote Sensing **27**(4): 737-753.
Loftus, G.R., Mackworth, N.H., (1978). "Cognitive determinants of fixation location during picture viewing." Journal of Experimental Psychology: Human Perception and Performance **4**(4): 565-572.
London, Computer Society.
Luttermann, H., M. Grauer. (1999). VRML History: storing and Browsing Temporal 3D-worlds. ACM VRML'99, Paderborn Germany.
Ma, H. (2003). "The Nature of Time and Space." Nature and Science **1**: 1-11.
MacEachren, A.M. (1995). How Maps Work: Representation, Visualization, and Design. New York, USA, Guilford press.

Mackinlay, J.D., G.G. Robertson, et al. (1991). The Perspective Wall: Detail and Context Smoothly Integrated. ACM CHI'91, New York.

Mackinlay, J., G. Robertson, et al. (1994). Developing calendar visualizers for the information visualizer. Proceedings of the 1990 ACM conference on Computer-supported cooperative work, Los Angeles,.

Mackworth, N. H., Ed. (1976). Stimulus density limits the useful field of view. Eye Movements and Psychological Processes Erlbaum Hillsdale, NJ.

Marphetia, T. (2001). "Brain Areas Critical To Human Time Sense Identified." UniSci - Daily University Science News, 2009.

Matthews, G. and M. Roze (1997). "Worm plots." IEEE Computer Graphics and Applications **17**(6): 17-20.

McDermott, P. and J. Sinnott (2006). An Architecture for Visualization and Interactive Analysis of Proteins. International Conference on Coordinated & Multiple Views in Exploratory Visualization, London, England, IEEE Computer Society.

McFarlane, T.J. (1998, 2004). "The Nature of Time." Retrieved 27/09, 2009, from http://www.integralscience.org/abouttime.html.

Mellenbergh, G.J. (2008). Tests and Questionnaires: Construction and administration. Advising on Research Methods: A consultant's companion. H.J. Adèr and G.J. Mellenbergh. Huizen, The Netherlands, Johannes van Kessel Publishing**:** 211-236.

Mennis, J.L., D.J. Peuquet, et al. (2000). "A conceptual framework for incorporating cognitive principles into geographical database representation." International Journal of Geographical Information Science **14**(6): 501-520.

Moere, A. (2004). Time-varying data visualization using information flocking boids. Proceedings of IEEE symposium on information visualization, Austin, USA.

Monmonier, M. (1989). "Geographic brushing: Enhancing exploratory analysis of the scatterplot matrix." Geographical analysis **21**(1): 81-84.

Monmonier, M., Johnson, B.B. (1991). Using qualitative data gathering techniques to improve the design of environment maps. 15th International Cartographic Association Conference, Bournemouth.

Monmonier, M., Gluck, M. (1994). "Focus Groups for Design Improvement in Dynamic Cartography." Cartography and Geographic Information Systems **21**(1): 37-47.

Morris, K. and D.H.B., A. Moore (2000). "Mapping the environment through three-dimensional space and time." Computers, Environment and Urban Systems **24**: 435-450.

Morrison, A. and P. Tennent (2006). Coordinated Visualization of Video and System Log Data. International Conference on Coordinated & Multiple Views in Exploratory Visualization, London, England, IEEE Computer Society.

Morriston, W. (1999). "Must the past have a beginning?" Philo **2**: 5-19.

Muller, W., Hetdrun Schumann (2003). Visualization Methods for Time-dependent data-Overview. Winter simulation conference 2003, New Orleans USA.

Myrvold, W. (2003). "Relativistic quantum becoming." The British Journal for the Philosophy of Science **54**: 475-50.
Nielsen, J. (2004). Card Sorting: How Many Users to Test. Jakob Nielsen's Alertbox.
Nielsen, J., T. Clemmensen, et al. (2002). Getting access to what goes on in people's heads?: reflections on the think-aloud technique. Nordic Conference on Human-Computer Interaction, Aarhus, Denmark ACM New York.
Ning, S.K., N.B. Chang, et al. (2006). "Soil erosion and non-point source pollution impacts assessment with the aid of multi-temporal remote sensing images." Journal of Environmental Management **79**(1): 88-101.
Norton, W. (1984). History Analysis in Geography. London and New York, Longman.
Ogao, P.J. (2002). Exploratory Visualization of Temporal Geospatial Data Using Animation. Geoinformation Processing. Utrecht, University of Utrecht. **Ph.D**.
Oliver. (1997). "On-line Library of Information Visualization Environments." 2009, from http://otal.umd.edu/olive/.
Palen, L. (1999). Social, individual and technological issues for groupware calendar systems. the SIGCHI conference on Human factors in computing systems: the CHI is the limit Pittsburgh, Pennsylvania, United States ACM.
Paul, C.L. (2008). "A modified delphi approach to a new card sorting methodology." Journal of Usability Studies **4**(1): 7-30.
Peuquet, D.J. (1984). "A Conceptual Framework and Comparison of Spatial Data Models." Cartographic Journal **2**(4): 66-113.
Peuquet, D.J. (1994). "It's about Time: A Conceptual Framework for the Representation of Temporal Dynamics in Geographic Information Systems." Annals of the Association of American Geographers **84**(3): 441-461.
Peuquet, D.J. (1998). Time in GIS and Geographic database.
Peuquet, D.J. (2002). Representations of Space and Time. New York, Guilford.
Pillalamarri, R.S., B.D. Barnette, et al. (1993). "Cluster: a program for the identification of eye-fixation-cluster characteristics." Behavior Research Methods, Instruments, and Computers **25**(1): 9-15.
Plaisant, C., B. Milash, et al. (1996). LifeLines: visualizing personal histories. Conference on Human Factors in Computing Systems Vancouver, Canada ACM
Plaisant, C., B. Shneiderman, et al. (1998). "An information Architecture to Support the Visualization of Personal Histories." Information Processing and Management **34**(5): 581-797.
Plumlee, M. and C. Ware (2003). Integrating Multiple 3D Views Through Frame-of-Reference Interaction. Proceedings International Conference on Coordinated and Multiple View in Exploratory Visualization
Ponsoda, V., D. Scott, et al. (1995). "A probability vector and transition matrix analysis of eye movements during visual search." Acta Psychologica **88**: 167-185.
Powsner, S. M. and E.R. Tufte (1994). "Graphical Summary of Patient Status." Lance **344**: 386-389.

Raper, J. (2000). Multidimensional Geographic Information Science. London, Taylor and Francis.
Raper, J. (2005). Time As Well: An Introduction. Re-presenting GIS. D. U. Peter Fisher. London, Wiley. **13:** 200.
Rayner, K., Ed. (1992). Eye Movements and Visual Cognition: Scene Perception and Reading. New York, N.Y., Springer Verlag.
Reichenbach, H. and M. Reichenbach (1999). The Direction of Time. California, University of California
Reinders, F., F. Post, et al. (2001). "Visualization of time-dependent data with feature tracking and event detection." the Visual Computer **17**(1): 55-71.
Rekimoto, J. (1999). TimeScape: A Time Machine for the Desktop Environment. ACM CHI'99 Extended Abstracts.
Rekimoto, J. (1999). TimeScape: A Time-Machine for the Desktop Environment. Conference on Human Factors in Computing Systems, Pittsburgh, Pennsylvania ACM.
Roberts, J.C. (2005). Exploratory Visualization with Multiple Linked Views. Exploring Geovisualization. J. Dykes, M. A.M. and M.J.Kraak. London, Elsevier. **8:** 159-180.
Roberts, J.C. (2008). Coordinated Multiple Views for Exploratory GeoVisualization. Geographic Visualization: Concepts, Tools and Applications. M. Dodge, M. Mcderby and M. Turner. Chichester, John Wiley & Sons Inc. **3:** 25-48.
Robinson, C.A. (2006). Highlighting techniques to support geovisualization. Proceedings of the ICA Workshop on Geovisualization and Visual Analytics, Portland.
Robinson, G.H. (1979). "Dynamics of the eye and head during movement between displays: A qualitative and quantitative guide for designers." Human Factors **21**(3): 343-352.
Scaife, M. and Y. Rogers (1996). "External Cognition: How do graphical representation works?" International Journal of Human-Computer Studies **45**: 185-213.
Schlesier, L., J. Hughes (2006). The LuMPB Key: A Multiple View Interface to Explore High Dimensional Mountain Pine Beetle Simulation Data. International Conference on Coordinated & Multiple Views in Exploratory Visualization London, England, IEEE Computer Society.
Scientific American: Special Edition: A Matter of Time **287**(3): 34-41.
Scinto, L. and B.D. Barnette (1986). "An algorithm for determining clusters, pairs and singletons in eye-movement scan-path records." Behavior Research Methods, Instruments, & Computers **18**(1): 41-44.
Shahar, Y. and C. Combi (1998). "Timing is Everything: Time-Oriented Clinical Information Systems." Western Journal of Medicine **168**: 105-113.
Shneiderman, B. (1996). The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. Proceedings of the 1996 IEEE Symposium on Visual Languages, Boulder, CO, USA, IEEE Computer Society Press, Piscataway
Sifer, M. (2003). A Filter Co-ordination for Exploring Multi-Classification Sitemaps. International Conference on Coordinated & Multiple Views in Exploratory Visualization, London, England, IEEE Computer Society.

Silva, S. F. and T. Catarci (2000). Visualization of Linear Time-oriented data: a survey. Web Information Systems Engineering, 2000.
Slocum, T.A., C. Blok, et al. (2001). "Cognitive and Usability Issues in Geovisualization " Cartography and Geographic Information Science **28**(1): 61-75.
Slocum, T.A., J. Robert S. Sluter, et al. (2004). "A Qualitative Evaluation of MapTime, A Program For Exploring Spatiotemporal Point Data " Cartographica: The International Journal for Geographic Information and Geovisualization **39**(3): 43-68.
Someren, M.V., Y. Barnard, et al. (1994). The think aloud method: A practical guide to modelling cognitive processes.
Steincke, T.R. (1987). "Eye Movement Studies In Cartography and Related Fields" Cartographica: The International Journal for Geographic Information and Geovisualization **24**(2): 40-73.
Stenning, K. and J. Oberlander (1995). "A Cognitive theory of graphic and Linguistic reasoning: Logic and Implementation." Cognitive Science **19**: 97-140.
Stewart, D., P. Shamdasani, et al. (2007). Focus groups: Theory and practice.
Suchan, T.A. (2002). Usability studies of geovisualization software in the workplace. Proceedings of the 2002 annual national conference on Digital government research Los Angeles, California Digital Government Society of North America.
Suchan, T. and C. Brewer (2000). "Qualitative methods for research on mapmaking and map use." The Professional Geographer **52**(1): 145-154.
Tessler, F. N. (1993). "Desktop Calendars." Macworld **10**(7): 104-109.
Tominski, C., J. Abello, et al. (2003). Interactive Poster: Axes-Based Visualizations for Time Series Data. Poster Compendium of IEEE Symposium on Information Visualization, IEEE.
Tominski, C., P. Schulze-Wollgast, et al. (2005). 3D information visualization for time dependent data on maps. Information Visualization, 2005. Proceedings. Ninth International Conference on.
Treinish, L. (2003). Web-based dissemination and visualization of mesoscale weather models for business operations. 19th Conference on IIPS.
Tufte, E.R. (1983). The Visual display of quantitative information. Cheshire, CT: Graphic Press.
Turnbow, D., K. Kasianovitz, et al. (2005). "Usability testing for web redesign: a UCLA case study." OCLC Systems & Services **21**(3): 226-234.
Tversky, B., Ed. (1995). Cogntive origins of graphic conventions. Understanding images. New York, Springer.
Vallesi, A., M.A. Binns, et al. (2008). "An effect of spatial-temporal association of response codes: Understanding the cognitive representations of time." Cognition **107**: 501-527.
van Elzakker, C.P.J.M. (2004). The use of maps in the exploration of geographic data. Geo-information processing. Utrecht, University of Utrecht. **Ph.D**.
Van Sommers, P. (1984). Drawing and cognition: Descriptive and experimental studies of graphic production process. Cambridge, Cambridge University Press.

Van Sommers, P. (1984). Drawing and cognition: Descriptive and experimental studies of graphic production process. Cambridge, Cambridge University Press.
Vasiliev, I.R. (1997). "Mapping time." The international Journal for Cartographic Information and Geovisualization **34**(2): 1-49.
Vlag, D.E. v. d. (2006). Modeling and visualizing dynamic landscape objects and their qualities. Geoinformation Process. Enschede, Wageningen University, ITC. **Ph.D**.
Wade, N. and B. Tatler (2005). The Moving Tablet of the Eye: The Origins of Modern Eye Movement Research. Oxford, UK, Oxford University Press.
Wearden, J. H. and L. A. Jones (2007). "Is the growth of subjective time in humans a linear or non-linear function of real time?" Quarterly Journal of Experimental Psychology **60**: 1289-1302.
Weber, M., M. Alexa, et al. (2001). "Visualizing time-series on spirals." Information Visualization: 7-13.
Webster (2003). Webster's New Universal Unabridged. New York, Barnes & Noble Publishing, Inc.
Wijk, J. v. (2002). Image based flow visualization. SIGGRAPH, San Antonio, USA.
Wijk, J. v. and E.R. v. Selow (1999). Cluster and Calendar based Visualization of Time Series Data. IEEE Symposium on Information Visualization (INFOVIS'99), San Francisco.
Wraver, C. (2006). Metavisual Exploration and Analysis of DEVise Coordination in Improvise. International Conference on Coordinated & Multiple Views in Exploratory Visualization, London, England, IEEE Computer Society.
Wyatt, J.C. (1994). "Clinical data systems. I: Data and medical records." The Lancet **344**: 1543-1547.
Xavier, A.C., B.F.T. Rudorff, et al. (2006). "Multi-temporal analysis of MODIS data to classify sugarcane crop." International Journal of Remote Sensing **27**(4): 755-768.
Xiong, R. and J. Donath (1999). PeopleGarden: Creating Data Portraits for Users. 12th Annual ACM Symposium on User Interface Software and Technology (UIST '99), NC; USA.
Yattaw, N.J. (1999). "Conceptualizing space and time: A classification of geographic movement." Cartography and Geographic Information Science **26**(2): 85-98.
Zarks, J. and B. Tversky (1999). "Bars and Lines: A study of graphic communication." Memory & Cognition **27**: 1073-1709.
Zhao, J.,P. Forer, et al. (2008). "Activities, ringmaps and geovisualization of large human movement fields." Information Visualization **7**(3): 198-209.

# Appendix I Typical questions for each block of temporal task space (TTS)

**Object**

**Elementary:**
- If+Object+Elemenaty: does the object A exist?
- When+Object+Elemenaty: when does the object A exist?
- How long+ Object+Elemenaty: how long does the object exist?
- How fast+ Object+Elemenaty: Null
- How often+ Object+Elemenaty: how often does the object exist?
- In what order+ Object+Elemenaty: Null But: in what order does the object exist in location A and location B?
- Synchronization+ Object+Elemenaty: Null But: Does the object (bird flu) exist in location A and location B synchronously?
- Trends+ Object+Elemenaty: Null

**Intermediate:**
- If+Object+Intermediate: Do the object A and object B exist?
- When+Object+Intermediate: when do the object A and object B exist?
- How long+ Object+Intermediate: how long do the object A and object B exist?
- How fast+ Object+Intermediate: Null
- How often+ Object+Intermediate: how often do the object A and object B exist?
- In what order+ Object+Intermediate: in what order do object A and object B exist?
- Synchronization+ Object+Intermediate: do the object A and object B exist synchronously?
- Trends+ Object+Intermediate: Null

**Overview**
- If+Object+Overview: do the objects exist?
- When+Object+Overview: when do the objects exist?
- How long+ Object+Overview: how long do the objects exist?
- How fast+ Object+Overview: how fast do the number of objects change?
- How often+ Object+Overview: how often do the objects exist?
- In what order+ Object+Overview: what is the order do objects exist?
- Synchronization+ Object+Overview: do the objects exist synchronously?
- Trends+ Object+Overview: what are the trends of objects? (more)

**Location**

**Elementary:**
- If+Location+Elemenaty: does the terrain in location A change?

- When+Location+Elemenaty: when did the terrain in location A change?
- How long+ Location+Elemenaty: how long has the terrain changed in the location A?
- How fast+ Location+Elemenaty: how fast does the terrain in location A change?
- How often+ Location+Elemenaty: how often does the terrain in location A change?
- In what order+ Location+Elemenaty: in what order does the altitude change? (up first and then down)
- Synchronization+ Location+Elemenaty: does the gradient and altitude in location A change synchronously?
- Trends+ Location+Elemenaty: what is the trend of the terrain change in location A?

**Intermediate:**

- If+Location+Intermediate: does the terrain change in location A and location B exist?
- When+Location+Intermediate: when the terrain in location A and location B change?
- How long+ Location+Intermediate: how long have the terrain change in the location A and location B?
- How fast+ Location+Intermediate: how often does the terrain change in location A and location B?
- How often+ Location+Intermediate: how often does the location A and location B terrain change?
- In what order+ Location+Intermediate: what is the order for terrain change in location A and location B?
- Synchronization+ Location+Intermediate: does the location A and location B terrain change synchronously?
- Trends+ Location+Intermediate: what is the trend of terrain change in location A and location B?

**Overview**

- If+Location+Overview: does the terrain change in whole area?
- When+Location+Overview: when does the terrain change in whole area?
- How long+ Location+Overview: how long does the terrain change in whole area?
- How fast+ Location+Overview: how fast does the terrain change in whole area?
- How often+ Location+Overview: how often does the terrain change in whole area?
- In what order+ Location+Overview: what is the order for the terrain change in whole area?
- Synchronization+ Location+Overview: does the terrain change in whole area synchronously?
- Trends+ Location+Overview: what are the trends of the terrain change in whole area?

**Attribute**

**Elementary:**

- If+Attribute+Elemenaty: does the temperature 0oC change?
- When+Attribute+Elemenaty: when does temperature 0oC changes?
- How long+ Attribute+Elemenaty: how long does the temperature stay at 0oC ?
- How fast+ Attribute+Elemenaty: how fast did the temperature 0oC change?
- How often+ Attribute+Elemenaty: how often the temperature 0oC appear?
- In what order+ Attribute+Elemenaty: Null But: in what order the temperature 0oC is reached in location A and B?
- Synchronization+ Attribute+Elemenaty: Null But: is the temperature 0oC is reached on location A and location B synchronously?
- Trends+ Attribute+Elemenaty: Null But: what is the trend for this area to reach the temperature 0oC?

**Intermediate:**

- If+Attribute+Intermediate: is the object's temperature ranging from 0oC to 30 oC?
- When+Attribute+Intermediate: when does the object's temperature change from 0oC to 30 oC?
- How long+ Attribute+Intermediate: how long does the object's temperature change from 0oC to 30 oC?
- How fast+ Attribute+Intermediate: how fast does the object's temperature change from 0oC to 30 oC?
- How often+ Attribute+Intermediate: how often does the attribute A and attribute B terrain change?
- In what order+ Attribute+Intermediate:in what order the object's temperature reach to 0oC and 30 oC?
- Synchronization+ Attribute+Intermediate: does the temperature change from 0oC to 30 oC synchronously?
- Trends+ Attribute+Intermediate: what is the general trend of temperature changing from 0oC to 30 oC?

**Overview**

- If+Attribute+Overview: does the temperature change?
- When+Attribute+Overview: when did the temperature change?
- How long+ Attribute+Overview: how long did the temperature change?
- How fast+ Attribute+Overview: how fast did the temperature change?
- How often+ Attribute+Overview: how often did the temperature change?
- In what order+ Attribute+Overview: what is the order for the temperature changing?
- Synchronization+ Attribute+Overview: did the temperature change synchronously?
- Trends+ Attribute+Overview: what are the trends of changing temperature?

# Appendix II Questionnaire: Time and your research project

Current data collection techniques bring a wide variety of data in many different spatial and temporal resolutions. The challenge faced is how to process, manage, and use these continuous streams of data to support problem solving and decision making. The application of graphic representations in a dynamic and interactive geo-visualization environment is part of the solution. However, most researches of geo-visualization environment are focused on the spatial (e.g. maps) or attribute (e.g. graphs, tables) aspect. The temporal aspect is mostly neglected. This is where my research comes in: developing temporal presentation and exploration environment.

Because I have to evaluate my theories in practice, I am looking for assistance. The objective of this questionnaire is to find out if 'time' is part of your research-problem and to see what kind of temporal question you have:

1. Is there a time parameter in your research?
   Yes □ No (go to end) □

2. Were you aware of the temporal characteristics of your data before you started to work with them? (temporal characteristics，for example, the temperature changes with day and year)

   Yes □ No □

3. Could you indicate the temporal character of your data (multiple option possible)

| | 1 | | | 2 | | 3 | | 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| characteristics | Linear | Cycle | Both | Discrete | Continue | Single scale | Multiple scale | Relative | Absolute | both |
| Example: | 2003, 2004, 2005…. | Season Week Month | | Time point | | Every day | Day, Month, Year…. | Three Hours After now | 3pm-5pm, | |
| Yes with "X" | | | | | | | | | | |
| Do not understand the term | | | | | | | | | | |

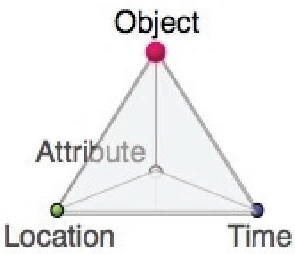
What is your feeling when you try to answer above questions about temporal data?

Easy □ Just Ok □ Confused and difficult □

4. What kind of time related question do you have on your data?

Background:
The spatio-temporal characteristics of an object are described by three components, which are also used to structure the spatio-temporal questions (see figure):

- Location (related to the 'Where?' question),
- Attribute (related to the 'What?' question)
- Time (related to the 'When?' question):




Related to time, three kinds of change could be distinguished:
Object: existential changes (appearing and disappearing)
Location: changes in spatial properties (location, shape, size, orientation, altitude, height, gradient, and volume)
Attribute: changes in thematic properties including qualitative changes and changes in ordinal or numeric characteristics (increases and decreases)

4.1 Can you give examples of your temporal research questions based on:
**Object:**
Q1:

Q2:

Q3:

**Location:**
Q1:

Q2:

Q3:

**Attribute:**
Q1:

Q2:

Q3:

4.2 Furthermore, Time questions are defined by the elementary temporal query types: such as when, in what order, how often and etc. Based on above information, where would you questions fit in following table?

| | Object | Location | Attribute |
|---|---|---|---|
| If | | | |
| When | | | |
| How often | | | |
| How faster | | | |
| In what order | | | |
| How long | | | |
| Synchronization | | | |
| trend | | | |

What is your feeling when you try to answer above questions about temporal user tasks?

Easy □ Just Ok □ Confused and difficult □

5. Do you visualize your temporal data?

   Yes □ No (go to end)

6. What time characteristics do your visualize?

| | In linear | In cycle | both | In single scale (day only) | In multiple scale (day, week and month…) |
|---|---|---|---|---|---|
| **Show temporal pattern** | | | | | |
| **Others** | | | | | |

7. What tools do you want to use in your visualization?

| | In linear | In cycle | both | In single scale | In multiple scale |
|---|---|---|---|---|---|
| **Select time (interval)** | | | | | |
| **Identify moment** | | | | | |
| **Locate in time** | | | | | |
| **Others** | | | | | |

What is your feeling when you try to answer above questions about temporal visualization?

Easy □ Just Ok □ Confused and difficult □

8. If you cannot structure your temporal tasks based on above questions, or you feel confused, please tell us what your research problem about time issues is.

## End: Thank you!

**Supplementary:**
Based on the feedback so far, many people feel confused in question 4.
Following is an example:

- object (whether): existential changes

When was the town built?
How many times of rain today?
When were you born?
**Town, you and rain are object.**

- location (where): changes in spatial properties

When did you leave here?
In what order the two cars arrive in the end-point?
**Here and end-point are location.**

- attribute (what): changes in thematic properties

When your body temperature is 39?
When the amount of rainfall is 45mm in Beijing?
**Temperature and amount of rainfall is attribute.**

# Appendix III VBA Code in Excel

## Part 1 (figure 7-9a)

```
Dim MyControl As Object
Dim Mystartime
Dim myendtime
Dim ControlsIndex As Integer

Private Sub CommandButton1_Click()
  Dim MyTime
MyTime = Time
myendtime = MyTime

Dim timecost
timecost = myendtime - Mystartime

Sheet1.Cells(2, 2) = Int(timecost * 60 * 60 * 24)

   If OptionButton1.Value = True Then
      a = 1

   ElseIf OptionButton2.Value = True Then
      a = 5
   ElseIf OptionButton3.Value = True Then
      a = 0

   End If
   Sheet1.Cells(2, 1) = a

   Mystartime = myendtime
    UserForm1.Hide
  UserForm2.Show


End Sub

Private Sub UserForm1_Initialize()

  ' ControlsIndex = 0

  ' OptionButton1.Caption = "Yes"
  ' OptionButton2.Caption = "No"
   'OptionButton3.Caption = "Can not answer"
   'OptionButton1.Value = True
    'OptionButton2.Value = True
    ' OptionButton3.Value = True
```

```
End Sub
Private Sub UserForm_Activate()
Dim MyTime
MyTime = Time
Mystartime = MyTime

End Sub
Private Sub UserForm_Click()
End Sub
```

**Part 2 (figure 7-9b)**

```
Dim Mystartime
Dim myendtime

Private Sub CommandButton1_Click()

Dim MyTime
MyTime = Time
myendtime = MyTime
Dim a
Dim b

Dim timecost
timecost = myendtime - Mystartime
Sheet1.Cells(2, 3) = Int(timecost * 60 * 60 * 24)

   If OptionButton1.Value = True Then

      a = 5

    Else

      a = 0

   End If

Sheet1.Cells(2, 1) = a

   If OptionButton3.Value = True Then
      b = 5

    ElseIf OptionButton4.Value = True Then
      b = 4

   ElseIf OptionButton5.Value = True Then
      b = 3
   ElseIf OptionButton6.Value = True Then
      b = 2
```

```
    ElseIf OptionButton7.Value = True Then
        b = 1

    End If
    Sheet1.Cells(2, 2) = b

    Mystartime = myendtime
      UserForm1.Hide
   UserForm15.Show

    End Sub

Private Sub UserForm_Activate()
 Dim MyTime
MyTime = Time
Mystartime = MyTime

End Sub
```

# Summary

Traditionally the GIScience community is well able to deal with the locational and attribute component of spatial data. However, the methods and techniques to deal with the data's temporal component are less developed. This research aims on studying multivariable spatio-temporal data from temporal perspective using visual analytical methods. To achieve this aim, a temporal visualization concept is discussed based on different views on time. Visualization theories accepted in GIScience and information visualization are extended with a specific temporal component. This is done by analyzing a commonly accepted visual problem solving approach. This approach has specific attention for the nature of the data, the user task and the visualization environment. Hereby the limitations of existing temporal visualization method and the need to structure time space are discussed. Time space is a concept which represents time and answers the temporal questions. This term is based on the data components and user task framework: location (where), attribute (what) and time (when). From a visualization perspective this translates in: location space (maps), attribute space (diagrams) and time space. To structure time space the suggested graphic representation should allow the user to represent the temporal data, to display different views on time (e.g. linear or cyclic), and last but not least should allow for interaction. According to this temporal conceptual framework, the time wave is introduced as the main element of time space. It allows access to and exploration of the large amounts of spatio-temporal data. The time wave, not only combines linear and cyclic time, but also combines temporal data representations and interaction, and allows a limited representation of attribute and location data. It can be used as a temporal reference, a temporal data representation system and a temporal interaction tool. It can answer the important time-related questions, and in combination with graphic representations in location and attribute space most complex questions related to temporal geodata can be answered, and as such it supports the task the user has at hand in discovering spatio-temporal patterns and relations. The time wave is a good example of how an alternative view on the data might reveal patterns not always obvious from traditional graphic representations. A case study about meteorological data is used to demonstrate this alternative approach.

An extensive usability evaluation has been executed to review the time wave. Based on the nature of the temporal visual user needs the time wave is compared with the time line and the time wheel. In additional usability tests that looked at the effectiveness, the efficiency and user satisfaction of the operation of the time wave as such, and the time wave in the location, attribute, and time space was studied while user were solving complex space-time problems. Advanced methods such as eye-tracking have been used in the evaluation process. The success of the time wave proved to be partly dependent on the nature of the temporal questions.

## Samenvatting

De geoinformatie wetenschappen zijn traditioneel goed in staat om de locatie en attribuut component van ruimtelijke gegevens te verwerken. Echter, methoden en technieken welke kunnen omgaan met de temporele component van de gegevens zijn slechts matig voorhanden. Dit onderzoek richt zich op de studie van multivariabele ruimte-tijd gegevens van uit een temporeel perspectief gebruik makend van visuele analytics methoden. Hiertoe wordt een temporeel visualisatie concept besproken op basis van de verschillende gezichtspunten op tijd. Bestaande visualisatie theorieën uit de geoinformatie wetenschappen en de informatie visualisatie worden uitgebreid met een temporele component. Dit wordt bereik door de analyse van de algemeen geaccepteerde benadering van het visueel oplossen van problemen. De benadering besteed speciale aandacht aan de aard van de gegevens, de gebruikerstak en de visualisatieomgeving. De beperkingen van de huidige temporele visualisatie methoden en de noodzaak de tijds-omgeving te structureren worden eveneens besproken. De tijds-omgeving is een concept dat tijd grafische representeert en temporele vragen kan beantwoorden. The term is gebaseerd op de componenten van de ruimtelijke gegevens en gebruikerstaken: locatie (waar), attributen (wat) en tijd (wanneer). Vanuit een visualisatie perspectief vertaalt zich dit in een locatie-omgeving (kaarten), een attributen-omgeving (diagrammen) en de tijds-omgeving. De grafische representatie die de tijds-omgeving moet structureren dient de verschillende perspectieven op tijd (lineair, cyclisch) kunnen vertegenwoordigen en boven al interactie toestaan. Op basis van deze voorwaarden wordt de time-wave geïntroduceerd als het belangrijkste element van de tijds-omgeving. Het maakt de toegang tot en exploratie van grote hoeveelheden tijd-ruimte gegevens mogelijk. De time-wave combineert niet alleen de lineaire en cyclische tijd, maar ook de diverse temporele representaties and interacties. Op kleine schaal is ook de representatie van locatie and attribuut gegevens mogelijk. De time-wave kan gebruikt worden als een temporele referentie, als temporele data representatie, en als temporeel interactie middel. Het beantwoord temporele vragen, en in combinatie met e grafische representaties in de locatie-omgeving en de attribuut-omgeving kunnen complexe tijd-ruimte vragen beantwoord worden. Als zodanig ondersteunt het de gebruiker bij het ontdekken van tijd-ruimte patronen en relaties. De time-wave is een voorbeeld van hoe een alternatieve kijk op de gegevens patronen en relaties kan onthullen die bij de traditionele benadering ongezien blijven. Een case study met meteorologische gegevens is gebruikt om deze alternatieve methoden te illustreren. Een uitgebreid gebruikersonderzoek heeft plaatsgevonden om de waarde van de time-wave te toetsen. Op basis van de aard van de behoefte aan visuele temporele representaties is de werking van de time wave vergeleken met lineaire en cyclische oplossingen. Vervolgens is de werking van de time wave als zodanig onderzocht en tenslotte is de time wave in de setting van de locatie- attribuut- en tijd-omgeving beoordeeld bij het oplossen van complexe tijd-ruimte problemen. Hierbij werd de time wave beoordeeld op effectiviteit, efficiency en gebruiker tevredenheid. Bij de gebruikerstesten, waarbij geavanceerde methoden en technieken als de eye-

tracking zijn gebruikt, bepaalde de aard van de vragen het succes van de time-wave.

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