

Visualization of Relationships Between Spatial Patterns in Time by Cartographic Animation

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ABSTRACT: This paper deals with dynamic visualization methods. The focus is on synchronization, one of the aspects that can dynamically control visualization. Synchronization refers to the possibility of running several animations simultaneously and manipulating their starting points in display time to discover relationships. The literature provides examples where animations are juxtaposed to discover (usually) causal relations. Can synchronization be relevant for other relationships? How complex is its application in practice? And are there alternatives for the perceptually difficult juxtaposing of animations? We investigated design options for the visual exploration and analysis of three relationships between spatial patterns in time: convergence, similarity, and stability. For each relationship we used two data sets to produce experimental designs, in which we tried to incorporate knowledge on vision and cognition. It seems useful to distinguish between synchronization in world and in display time. If it is not necessary to view the data sets separately and to manipulate them independently in display time, one animation is sufficient. In other cases, two animations and, sometimes, alternative options for juxtaposing seem useful. However, empirical testing is still required to determine whether the proposed tools are effective. The experimental designs discussed in this paper are published on the Web.

KEYWORDS: Visual exploration and analysis, pattern-related map use tasks, cartographic animation, synchronization, visualization tools

Introduction

Because our world is dynamic, many users of geographic information are interested in spatial dynamics, or changes that occur over time in the locational and attribute components of geographic data. The interest may stem from a wish to understand processes and relationships, to interfere in (undesired) developments, to optimize human activities, or to extrapolate current developments into the future. Investigation of the spatial and temporal patterns of one data set or variable is often not enough in those cases. In both mono- and multidisciplinary applications, a comparison of multiple data sets and variables is

often needed to identify and compare patterns, find relationships, or discover trends.

For the identification of patterns and relationships in the spatio-temporal domain, a temporal GIS would be a suitable environment. In the GIS community, spatio-temporal data handling is attracting more attention than ever before. Important research has been done (e.g., Langran 1992), and prototypes have been developed (e.g., Peuquet and Wentz 1994). However, little has been implemented in the real world. Spatio-temporal data collection and storage is a major obstacle, and the debate is still about formal representation in temporal data models (see e.g., Castagneri 1998; Stead 1998), and flexible user interfaces to query and manipulate spatio-temporal data are yet to be developed (Castagneri 1998). With respect to interfaces, the *Tempest* prototype is a good example (Peuquet and Wentz 1994). It is hoped that, in the near future, at least the conceptual, design and implementation aspects of temporal GIS will be solved. Temporal data collection may still remain a problem for those dynamic phenomena that cannot be easily detected from space, such as the dynamics of many socio-economic phenomena.

The search for patterns, relationships, and trends in a (temporal) GIS environment is commonly accomplished by computational methods supported

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by the graphic display of intermediate and final analysis results. It seems that methods which rely more on visual interpretation in an environment where the user has possibilities to interact with the data and/or the display can be considered as complementary to the computational ones. Both approaches have strengths and weaknesses. Ideas about the use of animation as a spatial analysis tool are described by, for example, Openshaw et al. (1994). The full power of a combined use, however, can only be realized if (temporal) GIS and scientific visualization environments become better integrated. Until recently, developments in these environments were rather independent, but there are efforts for more integration (see Rhyne (1997) for levels of integration and current achievements).

This paper focuses on visual methods of exploring and analyzing spatio-temporal data. In a (temporal) GIS context, the attribute, the geometric and temporal characteristics of phenomena, have to be included in the visualization. Among the methods that can be used to represent temporal characteristics of spatial data, animated mapping seems particularly suitable. It allows representation of data characteristics by a quick sequence of static maps, or a map that changes dynamically. The viewer will obtain an impression of continuity if the difference between successive frames is not too large, and the correct display speed is chosen. In animations, a direct link can be made between changes of characteristics in world time and their representation in display time (Kraak and MacEachren 1994). World time is the time at which changes took place in the real world, and display time refers to the moment at which a viewer sees the animated representation. Animated mapping thus allows a person to see the data in a spatial as well as a temporal context. In most cases the spatial context is provided by geographic space, and the temporal context is chronological order. However, representing geographic data in attribute space, e.g., in cartograms or bivariate scatterplots (Dorling 1992; Monmonier 1990), or using time for attribute order (e.g., DiBiase et al. 1992) can also be useful for the discovery of patterns and relationships. In the animations described in this paper, however, the spatial context is a geographic space, and the frames are chronologically ordered.

From a design perspective, dynamics in an animation can be created by changes in the graphic variables that are commonly used to represent the characteristics of data in the individual frames (position, form, hue, value, size, etc.). In addition, dynamic visualization variables can be used to control, or manipulate, the animation at various levels in

display time (Kraak and Klomp 1996). Six dynamic variables¹ have been distinguished so far: order, duration and rate of change (DiBiase et al., 1992); and display date (or moment of display), frequency, and synchronization (MacEachren 1994). Researchers have investigated the use of several of these variables for particular purposes, but there is still need for a broader investigation into the characteristics, application possibilities, and limitations of the variables.

In the framework of such a research, we investigated aspects related to synchronization. This variable refers to the possibility of running several (temporal) animations simultaneously, and then manipulating their starting points in display time until the patterns match and relationships can be discovered. The method is, as far as we know, hardly applied in practice, but in the literature it is proposed to use spatially separate (e.g., juxtaposed) animations, and the relationships that are commonly used as examples are causal (MacEachren 1995; Kraak and Ormeling 1996), although MacEachren also mentions synchronization to check whether post-processing is required to achieve correspondence between the spatial and temporal coordinates of field samples recorded by different teams. We were wondering how complex it is to apply synchronization in practice, and whether the method can be used for more relationships. Another challenge was to find out whether there are design alternatives for the (perceptually difficult) juxtaposing of two animations. Finally, we thought that it might be useful to distinguish between synchronization of data sets in world time and in display time for animations. Finding (at least partial) answers to these questions is the goal of this paper.

In order to achieve that goal, we selected three relationships between spatial patterns in time: convergence, similarity and stability, and investigated the possibilities to visualize them. In all three relationships, (de-)synchronization between data sets plays a role, either in world or in display time. We could have selected other relationships as well, but we assumed that these three illustrate the various aspects related to synchronization, while making it possible for us to achieve our goal. The design of appropriate animations, and of tools to manipulate (or produce) them, is complex. One has to deal with series of representations and their sequential and simultaneous display, and tools to interact with the data and/or the display must be provided. Therefore, we tried to incorporate knowledge about vision and cognition in our experimental designs.

¹ Because the term "variable" implies change, or dynamics, the authors prefer to refer to the visualization process in which the variables are used and call them dynamic visualization variables.

The following section offers a perspective on visualization. It is emphasized that in the visualization of geographic data, graphic and cognitive representations of phenomena in the real world play a role. This paper concentrates on the graphic representation. For the design of appropriate animations and tools, knowledge of the way in which cognitive representations interact with graphic representations can be helpful. A model which tries to explain how this interaction works for the identification of spatial patterns can be a good starting point, but more knowledge is needed to produce workable tools. Next, aspects related to visualization tools are described. Then the relationships that we investigated are introduced. This is followed by a discussion of the experimental design of the sample animations and tools that we propose for the three relationships. Finally, we consider the application of synchronization in animated representations and provide some guidelines.

Visualization of Geographic Data: A Matter of Representation

The term "visualization" has at least two meanings when applied to geographic data. One refers to making geographic data visible, or creating (carto)graphic representations in the use context. Visual exploration is characterized by highly interactive, private use of representations of mainly unknown data (MacEachren 1994). Together with confirmation, exploration is an important aspect of scientific visualization. In scientific visualization, visual thinking (or hypothesis generation and testing) are key elements (DiBiase et al. 1992). Visualization can therefore also be considered as the process of making something visible in terms of cognitive representations (MacEachren 1995).

What kind of tasks can a user perform with (carto)graphic representations in an exploratory context? Finding patterns and analyzing their characteristics, comparing patterns to discover anomalies and relationships, and seeking trends in pattern development are important tasks performed by users of geographic data of various backgrounds. MacEachren (1995) distinguished pattern-related tasks at increasing levels of complexity:²

- Pattern identification (in locational and/or attribute space);
- Pattern comparison (in locational and/or attribute space). Involves identification of several patterns, and the relationships between them;

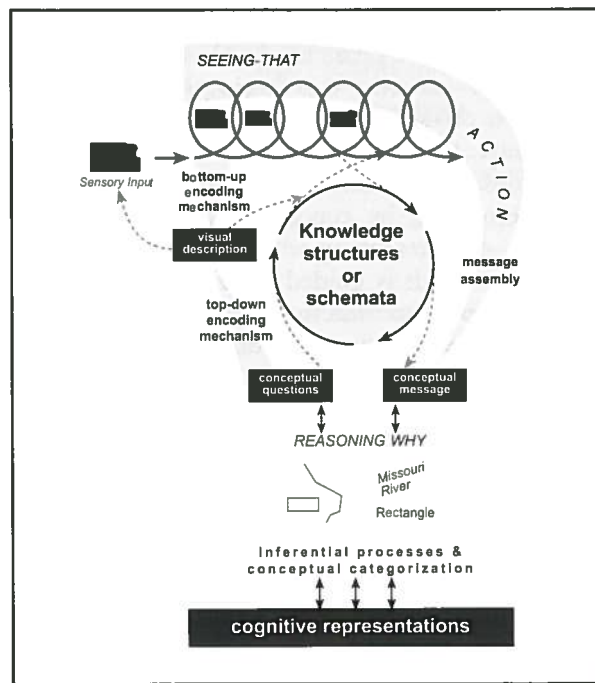


Figure 1. A map-based pattern identification model after MacEachren (1995). (Adapted with permission of the Guilford Press). [The concepts used in the original figure were modified as follows: "propositional, image, event schemata" was re-named "knowledge structures or schemata" and "propositional, image and procedural representations" became "cognitive representations."]

- Space-time analysis. Involves the former tasks, but in a temporal domain.

Because pattern comparison (in locational and/or attribute space) needs multivariate data, it is more complex than identifying patterns. We think that this is also valid for comparisons in the spatio-temporal domain. Therefore, we suggest to extend MacEachren's three-level classification to four levels, where the third and fourth level refer, respectively, to pattern identification and pattern comparison in the spatio-temporal domain.

In order to explain how cognitive representations of patterns interact with patterns on maps, a pattern (or feature) identification model was introduced by MacEachren and Ganter (1990) and later extended by MacEachren (1995). A slightly simplified version of the more recent model is used here to explain the complex information processing cycle (Figure 1). The model refers mainly to the exploration and confirmation phases of scientific research. Based on sensory input, vision and cognition together attempt to match patterns to internal knowledge structures (schemata), which are available to

² MacEachren uses the term "feature" instead of "pattern," because he feels that patterns are usually considered to have a global extent, while features may either be local or global. We prefer the term "pattern" to be used in the context of (constellations of) both local and global (individual) features.

mentally organize the input. The matching process consists of a phase in which vision tries to recognize patterns: the “seeing that” or exploration phase. This gives a quick, largely unconscious (bottom-up) reaction (a visual description). The usually correct reaction is then interrogated by conceptual (top-down) processes—the “reasoning why” or confirmation phase—which is guided by prior knowledge and experience. Interrogation may result in the acceptance or adaptation of the meaning derived from the seeing that phase. Besides assisting in the recognition of patterns, vision and cognition can also act together to categorize sensory input and infer patterns that become noticed. This may lead to the development of new schemata. Although described here in a sequential way, the information processing is at least partly parallel and cyclic: if no pattern match can be made, more fixations or iterations are required (MacEachren 1995).

Pattern identification is essential for the tasks at all four levels of complexity distinguished above. For pattern comparison, identification of two or more patterns is required before they can be compared to find correspondences, deviations, and relationships. Although not explicitly stated by MacEachren, it seems that the mechanisms at work in pattern identification also play a role in pattern comparison. “Seeing that” and “reasoning why,” in this case, refer to such identifications as “identical,” “different” or “related. For tasks in the spatio-temporal domain, the identifications “when,” “how long,” and “how often,” can be added (Figure 2). However, this assumption needs further investigation. Research is also required on cognitive issues to find out, for example, how people perceive dynamic phenomena in graphic representations,³ and to learn more about the way in which people conceptualize in interactive environments.

It might be that the pattern identification models need to be extended, particularly for the more complex tasks in the spatio-temporal domain. It can already be concluded, however, that in scientific visualization, thinking is prompted by cyclic, iterative processes, at least to identify patterns. Providing multiple, even unusual, perspectives to data, and providing possibilities to interact with data and their graphic representation are both important in this context. But for the actual design of dynamic representations, more detailed knowledge is required about vision and cognition on the one hand, and about graphic design principles on the other.

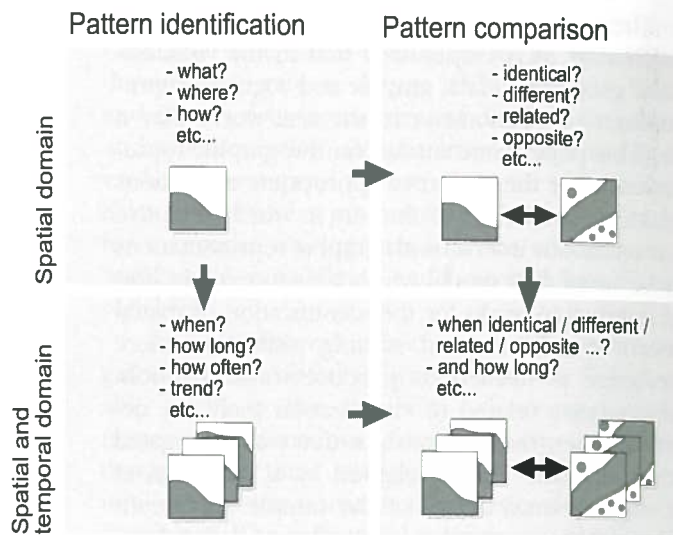


Figure 2. Pattern identification and comparison with map-based representations.

Visualization Tools

Visualization tools are required for the exploration of geographic data. We define visualization tools as options that allow a user to interact with (geographic) data in order to build and/or manipulate representations of the data in a computer environment. The options include basic functions (e.g., zoom, pan, scale); algorithms which allow user-defined parameters (e.g., a line simplification algorithm); or tools in which (carto)graphic knowledge is incorporated (e.g., data classification functions, or functions that produce default symbols based on the characteristics of the data) (Kraak 1998). According to the above definition, the graphic representation itself can also be considered as a visualization tool, but interaction remains an important key word: it is essential for visual exploration.

In order to accomplish the various pattern-related visualization tasks distinguished in the previous section, the visualization tools required in an exploratory context can be classified as follows:

- **Tools to identify locational and attribute patterns**, e.g., options to switch between representations or viewpoints; or manipulating the scale, resolution or contrast to change emphasis from local to global pattern processing or vice versa may reveal otherwise hidden patterns;
- **Tools to compare locational and attribute patterns and to identify relationships**

³ An example, see the research initiatives by the Panel on Cognitive Models of Geographic Space of the National Center for Geographic Information and Analysis (NCGIA) [<http://www.ncgia.ucsb.edu/varenius/initiatives/ncgia.html>].

Relationship	Application in display time	Application in world time
Convergence	Explore / analyse patterns	Create / optimize synchronization
Similarity	Explore pattern correlation, synchronize representations	Predict patterns
Stability	Explore patterns, desynchronize representations(?)	Decide on measures, predict(?)

Table 1. Spatio-temporal relationships and data synchronization.

between them, e.g., tools offering juxtaposing or overlay of patterns, linked views, or geographic brushing (Monmonier, 1990), allow users to make comparisons;

- **Tools to identify and compare patterns in the spatio-temporal domain** (e.g., animated representations to view and compare dynamic phenomena; options to stop and rehearse the display of processes that are continuous in the real world; and temporal legends offering, besides a key to the map, interaction possibilities with the display (Kraak et al. 1997)) can all contribute to revealing spatio-temporal patterns and relationships.

Many more tools have or can be developed. Tools are particularly needed for modern visual exploration, however, uncertainties exist about what those tools should be. One thing does seem to be clear, though, namely that knowledge about the interaction between conceptual and graphic representations should be considered for tool development.

Pattern Comparison in the Spatio-Temporal Domain and Synchronization

In geography, most definitions of the term "pattern" refer to spatial patterns, not to temporal ones (see, e.g., *The Concise Oxford Dictionary of Geography* or *The Dictionary of Human Geography*). Consequently, we define "pattern" in a map-based representation as (a constellation of) "perceptual units (symbols, pixels) in space and/or in time that form(s) a figure or an entity." The identification of patterns in a map-based representation depends on a number of factors, including the purpose of observation, application, the phenomenon being investigated, the ability and expertise of the observer, and the scale and time frame considered, to name just a few.

Comparing map-based spatio-temporal patterns yields information about relationships. Pattern comparison in the spatio-temporal domain is a task at the highest of the levels of complexity distinguished earlier. We were interested in the animated representation of a particular type of spatio-temporal

relationships, namely those in which (de-) synchronization between data sets plays a role, either in world or in display time.

Three relationships were selected: convergence, similarity, and stability of patterns, all of which are in the spatio-temporal domain (Table 1). These relationships were selected because they could help provide answers to our questions about synchronization in cartographic animation. How complex is the application of synchronization in practice? Can synchronization be applied for other than causal relationships? Can animations also be used for data synchronization in world time? And finally, are there design alternatives for the juxtaposition of two animations?

There are other relationships than the ones selected for which synchronization in animated representations is a potential option. Our goal, however, was not to define a complete typology of such spatio-temporal relationships.

To demonstrate convergence of spatial patterns in time, we selected a case where synchronization in world time is used to coordinate streams of goods, services or people at nodes in a network. At a railway station, for example, passengers need to have reasonable connections from trains to buses and visa versa, so both public transportation systems not only need to be synchronized but also feasible in world time. Data about Friday train and bus connections in Enschede, The Netherlands, in 1997, are used as an example. The purpose of the representation is to allow domain specialists such as public transportation planners to explore/analyze the temporal correspondence in connections. It seems easier to investigate the complex transportation patterns in a graphic representation than to compare all the individual bus/train schedules.

To compare similarity of spatial patterns in time, we looked for data sets with a possible existence of a causal relationship. If, indeed, a causal relationship exists, a time lag can be expected between the occurrence of the variables in world time. Synchronization in display time can be used to determine to what extent patterns are similar, and what the time lag in world time is. Although this is a "classic" example of using synchronization as a dynamic visualization

Spatio-Temporal Relationship	Sample data	Animated representation method	
Convergence	Train and bus connections	Common frames	Composite image
Similarity	Rainfall and vegetation	Separate frames	Spatially separated animations
			Transparently overlapping animations
Stability	Geomorphological objects and fuzziness		Spatially separated animations
			Transparently overlapping animations
			Alternating frames in one animation

Table 2. Investigated spatio-temporal relationships, the data sets used, and experimentally designed animated representations.

variable, it was included here to obtain insights into the complexity of synchronization use, and to investigate design alternatives for juxtaposing animations. Data for rainfall and vegetation coverage in Kenya were used in this example. The rainfall patterns were formed by pixels with a monthly maximum precipitation of >60 mm between February and July 1996. The vegetation patterns were formed by pixels with a monthly maximum vegetation index⁴ of >0.4 over the same period. If a causal relationship can be discovered between the patterns that are visible with certain threshold values, and if the time lag can be estimated, then it might be possible to predict vegetation patterns on the basis of rainfall data (e.g., if there is rainfall in location (x,y) at time 1, then there will be vegetation at time 2). The advantage of visual over computational methods (e.g., lag calculation) for the exploration of such a relationship is that actual patterns can be observed in a spatio-temporal context, so it is possible to see where, when, and to what extent patterns match. Imperfect matches (due to local anomalies, for instance) can thus be judged directly.

If a user wants to find out how stable certain spatio-temporal patterns are (e.g., in areas where stability is endangered because of susceptibility to erosion or flooding), he or she may analyze the data, while also taking into account the quality of the data (e.g., whether the boundaries are fuzzy). Judgments about the stability of spatio-temporal patterns can play a role in decisions about protective measures. Metadata are directly related to data, so both can be considered as synchronous in world time. An option to desynchronize and manipulate them separately in display time is perhaps useful for the discovery of trends in the spatio-temporal patterns of the data and the metadata. It might, for example, be useful to explore whether a cycle in the data is also apparent in the metadata, and playing the animations at

different speeds may be required to reveal a trend in each. We selected geomorphological data about a coastal zone on Ameland, one of the barrier islands along the northern coast of The Netherlands as an example. Elevation data were collected once a year between 1989 and 1993 and modeled to geomorphological objects (Cheng et al. 1997). The fuzziness of the boundaries between them was also calculated. The purpose of the animation was visual comparison of patterns to discover trends in the stability of the geomorphologic objects, taking into account their fuzziness. An interesting question is whether, or to what extent, it is possible to "predict" the state of geomorphological objects at a particular time, based on trends in the data and in the metadata (e.g., if during time 1-n the boundary between objects A and B shows an eastward shift and the fuzziness of the boundary is $>\alpha$, then at time $n+1$ the boundary will be shifted further eastward).

Animated Representations and Visualization Tools: Examples

Four types of animated representations were used to experimentally design six animations (Table 2). Exploration is at one end of what can be considered as a map use continuum. Presentation is located at the other end. Along the continuum, but closer to exploration—at least with respect to the required interaction and the type of user—is visual analysis (MacEachren and Kraak 1997). It is assumed that most of the principles of visual exploration will be valid for visual analysis because of the proximity of analysis to exploration and the fuzzy line (in our opinion) between these two goals of map use goals. Both visual exploration and analysis can support decision making.

We do not pretend that the animated representations and visualization tools proposed here are the

⁴ The index used was the Normalized Difference Vegetation Index (NDVI), also referred to as the "greenness" index. The index is derived from the red and near-infrared channels of NOAA satellite data where chlorophyll and mesophyll absorption and reflection are strongly represented. The theoretical range is $-1 \leq \text{NDVI} \leq 1$, but the realistic values (excluding those for water, soil, noise) range from about -0.1 (not very green) to about 0.6 (very green) (Kidwell 1991).

only ones possible, or the best for any given problem, user context, and data. Valuable animated methods for exploring relationships have been proposed, e.g., sequencing by Slocum et al. (1990), and geographic brushing and atlas touring by Monmonier (1990; 1992). The example representations and tools may result in workable possibilities that can be added to the multiple perspectives to data which seem important in scientific visualization.

Design Considerations

To explore and analyze relationships in the selected cases, one needs to identify and compare patterns in animated representations. This is a complex task, particularly because the patterns are changing in display time. The processing load of the viewer, who largely has to rely on memory deduction, is high, even though there are often options to pause and rewind. As was mentioned earlier, map-based pattern identification (which is essential for all pattern-related tasks), and perhaps also pattern comparison rely on pre-attentive, very quick, and partly parallel processing and further interrogation of the reaction. If patterns (and perhaps relationships) are graphically represented in such a way that they can be quickly recognized or noticed in the first phase, the processing load may not be overburdened. Consequently, we took perception and cognition aspects that are important in this phase into account. MacEachren's publication *How maps work* (1995) is an important source of information in this regard.

To identify map-based patterns in the spatial domain where the basic questions "where," "what," and "how" (Figure 2) are asked, figure-ground separation is particularly important. Most likely this separation is influenced by cognition, but it also relies on some pre-attentive processes, of which the most important ones are briefly mentioned here. Contrast and the possibility to group information obtained from sensory input are among them. Contrast can, for example, be perceived from the way in which graphic variables are used. Grouping principles have been defined in 1923 by the Gestalt psychologist Wertheimer. Examples of principles that are relevant for grouping in the spatial domain are proximity (of locations), similarity (of attributes), closure (of shapes) and simplicity. Figure-ground perception is influenced by stimuli that attract the attention of the viewer (e.g., selective graphic variables and certain shapes), and by whether global or local processing is applied. Global processing seems more important

for pattern identification than local, detailed processing (MacEachren 1995).

In the spatio-temporal domain, where the basic questions "when," "how long," "how often," "what is the trend" are added, and particularly when dealing with animated representations, perceptual organization is further influenced by the Gestalt grouping principles "objective set" and "common fate." Objective set refers to the tendency that once seen as a group, perceptual units remain a group, even if the position of the units changes over time. Common fate refers to the fact that objects or entities that are moving together tend to be seen as a group. Visual attention and perceptual organization in animated representations are greatly influenced by symbols that change in display time⁵ (MacEachren, 1995). Our sensitivity to motion is apparent from the fact that we have cells in our brains that respond only to motion, with some cells responding to motion in a specific direction only. Because the form of objects, color, motion, and probably other aspects are processed separately but in parallel and then combined, a single, generally consistent perception results from sensory input (Gregory 1998).

When patterns have to be compared in the spatio-temporal domain, i.e., when the basic questions "same," "different," and "related," are added, top-down processes may be more important than the pre-attentive, bottom-up ones, but this assumption needs further investigation. Relevant for all tasks performed on non-static displays is that there is evidence that people are "blind" during saccades—the brief moments during which the eyes re-focus on something else. Changes that happen in a representation during saccades remain unnoticed (Gregory 1998). Levin and Simons (1997) found that even big changes in objects that are at the focus of attention may not be detected, because we apparently do not automatically use all the information available to track objects over time. These limitations seem even more relevant for tasks in which changing patterns have to be compared in animations. A designer of animated representations should aim to avoid saccades induced by irrelevant (particularly changing) elements in the display, and to provide essential interaction possibilities which allow the user to stop, rehearse, and perform other functions.

Several display options are available for pattern comparison. According to Muehrcke and Muehrcke (1992), pattern comparison seems easiest when the patterns are superimposed. Because this is not always possible, they also mention a side-by-side arrangement and alternating projection of patterns on a

⁵ MacEachren (1995) mentions that Kubovy, in a publication of 1981, refers to time and space as "indispensable variables." These variables are more discriminable and selective than others, they have stronger configurational properties and are dominant in perceptual organization.

screen. Although Muehrcke and Muehrcke refer to pattern comparison in static maps, basically the same methods can be applied in animations, i.e., pattern representation in one map/frame using a composite (e.g., superimposed) image, or in separate maps/frames, which can be displayed together in a number of ways—juxtaposed, transparently overlapping, and in alternating frames. It is perceptually difficult to compare two patterns that are only briefly displayed (such as in an animation) at different locations. Even with simple “same-different” discrimination tasks executed on isolated patterns, it is easier to identify same patterns if both are presented at identical locations (Dill and Fahle 1998). It seems worthwhile, therefore, to look at possible alternatives for the juxtaposed representation of animations in which synchronization of data sets plays a role.

Animated Representations: The Train and Bus Connections Example

To enable domain specialists explore and analyze the spatial and temporal convergence of bus and train connection patterns, the data sets should be displayed in the same frames of an animation. This was applied in Figure 3 where the location of the lines in the network and their origins/destinations are represented in a schematic way. The frequency at which trains and buses arrive and depart is represented by the temporarily highlighted lines of the network. Highlighting, or “blinking,” is an example of varying symbolism in display time which dominates perception and attracts attention. Highlighting should be used with care, because this kind of repeated retinal activity overloads the visual system and may annoy the viewer (Gregory 1998). Blinking provides contrast with the static appearance of other elements of the map. Although the Gestalt grouping principle of common fate refers to symbols that move together, it seems more generally valid for symbols that change, or “blink,” together.

To explore and analyze this relationship, interactions such as those common on video recorders (stop, pause, slow, and fast forward and backward) are required. Interactions with the geometric, attribute, and temporal components of data are needed. This was implemented in our example by providing

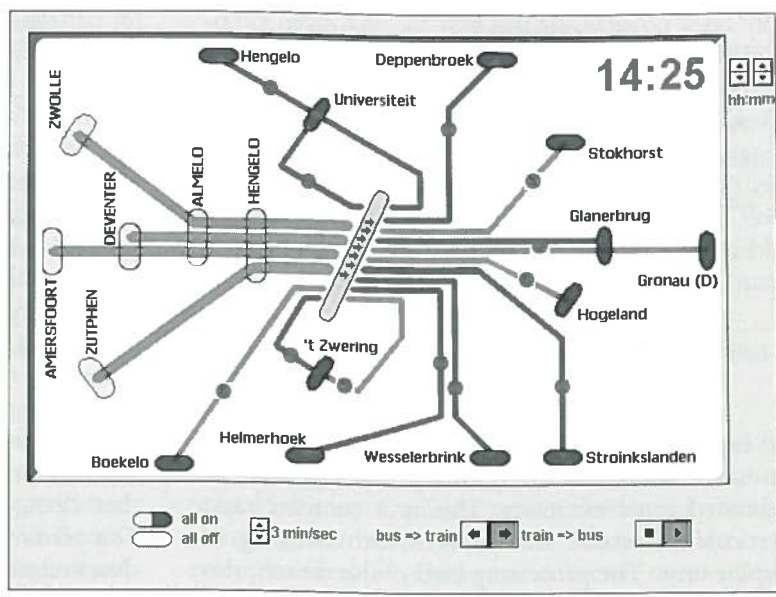


Figure 3. The train and bus connections example.

the option to focus on specific connections, choose bus-train or train-bus connections, and select specific departure/arrival times. The overall patterns can be analyzed at temporal scales. The latest scale is a second in display time, which equals a minute in world time, but smaller scales can be selected as well. The table containing the data can be accessed to make changes in the bus-train schedules, thus allowing “what if” type of questions.⁶ Finally, a button gives access to an explanation of the tools is provided. An interaction that might be useful, but which was not implemented, is the possibility to aggregate world time. That would allow a user to see all trains and buses that arrive/depart within, say, 10 minutes displayed simultaneously at a constant display speed.

The animation is primarily meant as a visual decision-support tool for domain specialists. It can be used to optimize timetables for (part of) the transportation system, but it can also be used in all kinds of other situations in which the temporal correspondence of streams of people, goods, services, perhaps even data, at nodes in a network plays a role.

Animated Representations: The Rainfall and Vegetation Data Examples

Causal relationships between rainfall and vegetation patterns can be explored in time by manipulating the world time of the individual data sets within the display time and synchronizing patterns. We used animations in which the data were represented in separate frames, forming different images for each

⁶ For pragmatic reasons, the table is not accessible in the Web version of the example.

variable. Depending on how these images are displayed, different categories of animations can be distinguished. The two categories suggested for possible causal relationships are:

- **Spatially separated animations:** two animations, one for each data set, are juxtaposed and run simultaneously (Figure 4);
- **Transparently overlapping animations:** the frames of one data set are displayed transparently on top of the frames of the other data set; the animations are physically separate, and individual controls are provided for each animation (Figure 4).

The patterns of different juxtaposed static maps can be mentally integrated (MacEachren et al. 1998). However there does not seem to be any conclusive evidence about human ability to pay attention to pairs of dynamic maps. Research suggests that comparison is difficult in space and time, whatever symbolization is used (MacEachren 1995). We used spatially separated animations because synchronization literature suggests the method, and because such animations make it possible to explore a relationship in both the spatial and temporal contexts.

Our brains are sensitive to motion. MacEachren (1995) contends that some cells in our brain seem to respond only to changes in spatial distance between moving edges, or pattern contours. This may facilitate pattern comparison, but it is questionable whether the same assumption holds for patterns in spatially separated maps or images. Perhaps this sensitivity can be used to advantage in transparently overlapping animations. If animations could be shifted in time independently, it would be easier to identify whether, where and when those overlapping patterns match.

Global processing is more important than local processing for exploring causal relationships, but dispersed pixels and multiple classes are likely to cause problems. Figure-ground separation is likely to be hindered by lack of simplicity and attribute similarity (two of the Gestalt grouping principles) and by lack of contrast. In an attempt to reduce the viewer's processing load and to improve figure-ground separation, we decided to use thresholds and visualize binary data. The objective set and common fate grouping principles were assumed to have more impact in this way. The evidence that we are blind during saccades (Gregory 1998), and that even changes on objects that are in the focus of our attention may remain unnoticed in motion pictures (Levin and Simons 1997), argues for keeping the images simple. If users can stop and rehearse the animations, and if the display area is kept relatively small,

it may be possible to avoid some of the problems mentioned above.

In both categories of animation proposed for rainfall and vegetation data, independent interaction is required with the time component. In the transparently overlapping example, this has been implemented by providing separate control tools for both animation layers.⁷ We would like to propose the method as a potentially powerful one for the visual exploration of causality between spatial patterns in time. The usual video recorder type of interaction needs to be provided, but it is not easy to start two animations synchronously after a pattern correspondence has been discovered. The example allows the user to manually drag the time sliders, determine a common starting point, and click on the PLAY ALL button to run the animations synchronously. Resetting is possible as well.

Another interaction that might be useful, but was not implemented, is changing the time scale (by stretching/compressing the data in display time) for at least one of the animations, because changes in the patterns of the two variables may occur at different speeds in world time. Slicing, an independent and dynamic change of the thresholds of the binary data (see Van der Wel et al. 1994), is also important for exploration purposes: patterns may look quite different if thresholds are changed, and the values used in our example are quite arbitrary. The manipulation of contrast (or filtering) may further facilitate global processing of patterns derived from satellite data. The use of manipulatable temporal legends instead of separate sliders and text to indicate the time periods would be a further improvement (Kraak et al. 1997).

Animations should prompt thinking about spatio-temporal relationships. Spatial patterns may not match completely in time, even when a causal relationship between the variables exists. Visualization helps a user to identify whether, where and when there is a match, and to judge what the relevance of anomalies is. If flexible tools are provided, differences in the speed of pattern development can also be detected.

Animated Representations: Geomorphologic Objects and Fuzzy Data Examples

One way to make a judgment about the stability of geomorphological objects in time is by exploring the trends in the data and in the fuzziness. Data and metadata have been represented in many

⁷ Unfortunately, this does not work in the Web version of the animated representation because of a bug in the Web browser plug-in software. It only works in a stand-alone version that can be downloaded from the Web.

ways (see, e.g., Van der Wel et al. 1994; MacEachren 1995). There are methods that represent both aspects in one map (e.g., using a composite graphic variable or symbol overlay) and methods that use separate maps (e.g., juxtaposed). Most representations are two-dimensional, but draping a data layer over a 2.5D certainty surface is also possible. The representation can be passive or allow interaction, such as focusing on part of the (meta-) data; it can be static or animated, e.g., with

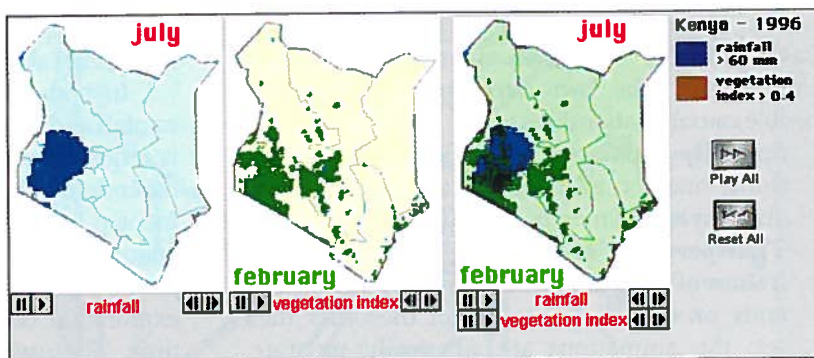


Figure 4. Rainfall and vegetation data examples. Left: two frames of the spatially separated animations. Right: transparently overlapping frames.

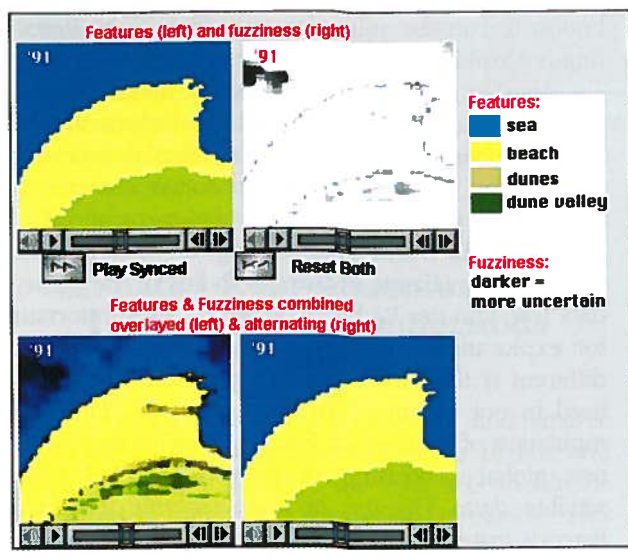


Figure 5. Geomorphological objects and fuzziness data example. Top: two frames of spatially separated animations. Bottom: frames that are displayed side-by-side in the illustration are alternated in the animated representation.

dynamic visualization variables. Last but not the least, one can use visual displays alone or in combination with sound (Fisher 1994).

The examples deal with (de)synchronization in animations. The possibility to observe developments in the patterns of data and metadata separately *and* in combination with each other is important for the identification of trends. Therefore, data and metadata were represented in separate frames in our experimental designs. The frames were displayed in three ways.

- Spatially separated animations;
- Transparently overlapping animations; and
- Alternating frames.

In spatially separated and in transparently overlapping animations, one set of frames shows the different states of the geomorphological objects in

different years. Displaying them in an animated sequence simulates the dynamics resulting from erosion and accumulation at the interface between the marine and the terrestrial environments. The other set of frames shows the fuzziness of the boundaries between the objects (Figure 5). We opted to include the spatially separated animated method because of the opportunity this provides to observe developments in isolation and to interact independently with the representations, e.g., to desynchronize them. However, because perception problems may arise when the two representations are mentally integrated (even with a limited number of classes), the transparently overlapping animated representation is also suggested. The use of transparency to represent data and metadata was proposed by MacEachren (1995) but, as far as we know, there is no mention in literature about the use of independent interaction in animated representations.

Alternating graphic displays (also mentioned by Muehrcke and Muehrcke 1992) were used by Monmonier (1992) by rapidly alternating on screen two choropleth maps, each depicting a different variable. In this method, the occurrence of annoying flickering signals dissimilarity between the variables. MacEachren (1995) suggested that this technique might be particularly suitable for representing data and metadata, with excessive flickering indicating relatively unstable areas. The method has been implemented in a prototype geographic visualization system developed by Howard and MacEachren (1996). Evans (1997) conducted a user investigation in which she compared the method with other representations. In a display loop, she alternated a land-use map with a map in which land-use classes were represented in a hue with 100 percent saturation for pixels that reached a 95 percent reliability threshold, and a lower saturation for other pixels. In order to create continuity of the classified pixels in the second map, Evans alternated representations of

the data and data plus metadata. Her subjects found the method helpful.

The alternating frames method was not used in the rainfall and vegetation example because of the assumed time lag in the data. However, the method does seem suitable for variables that are synchronous in world time, perhaps particularly to identify instability. We designed an animated representation in which for each time slice, geomorphological objects are alternated with objects plus fuzziness (Figure 5). This representation is comparable to Evans' method, but it is applied to temporal data, and no threshold values are used for the metadata. Furthermore, we used transparent symbol overlay for the combined frames.

Considerable motion is visible in the animated representations. The location of the objects is changing, objects appear/disappear, and the fuzziness is changing. Those changes in display time attract attention and dominate perception. It has to be further investigated whether vision is able to quickly decide what to focus on in such a display. Figure-ground separation with geomorphological objects and fuzziness examples is likely to be more difficult than with the rainfall/vegetation data, but the task is also different—trends have to be identified. As mentioned earlier, the Gestalt principles "objective set" and "common fate" are important when identifying trends. These principles are expected to have a relatively strong impact in the examples of Ameland, particularly in the juxtaposed animations. Evans (1997) found that the separate display of reliability information was not effective due to lack of continuity in the classified pixels in her example. It made geographic reference difficult. In our example, grid cells were represented by a value scale ranging from white (for low fuzziness) to black (for high fuzziness) and displayed in an animated way. This approach gave a strong impression of motion from which trends can perhaps be derived.

The interaction implemented for the rainfall and vegetation data was also implemented in the in the geomorphological objects and fuzziness examples. Although recognized as useful options, adjustments to the speed of the animations and the rate of flickering (Evans 1997) can only marginally be controlled by manually changing the slides in our examples. In the current samples it is only to a certain extent possible to control it by manually dragging the slider. A number of improvements, useful to reveal trends, can be suggested, including manipulation of contrast and filtering (Howard and MacEachren 1996), or adding temporal legends (Kraak et al. 1997), and focusing on a particular object or class or fuzziness threshold (Van der Wel et al. 1994).

The animations are meant to make judgments about the stability of dynamic phenomena. The effectiveness of the methods, and the role of the Gestalt principles "objective set" and "common fate" have to be further investigated.

Conclusions

Synchronization was described as a tool that allows identification of pattern correspondences in time series. If the "peaks and troughs" of the data match, the series are in phase, if not, they are out of phase (MacEachren, 1995). Patterns that are in phase but not synchronous in world time, can be synchronized in display time. However, the match of the patterns may not be always perfect in a space, nor in time. It may, for example, take longer for patterns of a dependent variable (e.g., cases of a disease) to develop than it takes for the independent variable (e.g., pollution emission). Independent interaction with the data in display time is then required to stretch or compress the data along the time line. Pattern correspondence thus needs to be discovered during exploration and analysis of the graphic representation, and various interactions are usually required to run the animations synchronous in display time. From a user's perspective, the task may be quite complex. Synchronization can, therefore, be considered as a way to visually explore and analyze data sets (aided by appropriate interaction tools), rather than as a dynamic visualization variable. The application of a visualization variable seems a more elementary activity to manipulate the representation of data.

Synchronization in display time can be used for visual exploration and analysis of causal relationships, as was done in the example of rainfall and vegetation data. Synchronizing spatio-temporal data sets in world time plays a role in such animations as provided in the train and bus connections example. For particular applications it might be useful to desynchronize data that are essentially synchronous in world time, as was done for the geomorphological objects and fuzziness example. Further examples in which synchronization plays a role can no doubt be imagined.

It still has to be investigated whether users are able to discover relationships between two or more juxtaposed animations, which may be accompanied by separate legends. We speculate that juxtaposing is particularly difficult for the exploration and analysis of similarity to find causal relations between spatial data in time. The transparently overlapping animations may provide a better alternative. Juxtaposition might be more appropriate for the highly global processing task that is involved in the exploration of

data and metadata, provided the aim is to identify trends separately and in combination. Combined representation (e.g., transparent overlap), however, allows users to better judge which objects have to be considered with caution (at least in static maps) (see MacEachren et al. 1998). Independent interaction with the temporal component does not seem to be very useful here, so composite frames can perhaps be used. The alternating method, although useful for the representation of data and metadata, may not be suitable for the task considered here. Composite frames can also be applied if it is not necessary to view the data sets separately and to manipulate the temporal component independently. Thus, the problem context may influence the choice of a representation method.

Although we tried to take cognitive issues into account in the design and implementation of the examples, many issues related to the perception and conceptualization of dynamic representations still need investigation. Even principles that are known may have unknown effects (e.g., the relative strength of the Gestalt principles is not known). The question remains, therefore, what tools are appropriate. Single optimal tools can hardly be expected to exist (MacEachren and Ganter 1990), but tools that work may add to the multiple views that are important for exploration.

Our experimentally designed tools may not all be equally relevant, and the data that were selected for the examples may not provide the best illustrations. We have, however, formed some expectations about what may and may not work, and ideas for improvement. In a first attempt to obtain reactions, the examples were uploaded onto the World Wide Web (<http://www.itc.nl/~carto/webcartoforum>). Visitors are invited to use the tools, and fill out a questionnaire intended to provide feedback about the suitability of the representations for the task, preferences in terms of design and interaction, and suggestions for improvements and alternative applications. This information may lead to improvements of those tools that receive favorable reactions. A more structured approach to the design and implementation will be needed (Lindholm and Sarjakoski 1994; Howard and MacEachren 1996), followed by a formal assessment of the tools.

For the tasks described here, visual exploration and analysis seem to allow a relatively quick assessment of a relationship (and anomalies in it) in a spatial and temporal context. For some relationships, once they have been discovered, the strength can be further examined and/or quantified by application of computational methods. It seems therefore, that visual exploration of the relationships described

here can be considered as at least complementary to computational approaches.

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