Towards an Understanding of Geovisualization with Dynamic Displays: Issues and Prospects

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Abstract

This paper explores research issues and methods for experimentally assessing the effectiveness of interactive and dynamic geographic visualization displays for knowledge discovery and knowledge construction. Based on a research framework from cognitive science, and utilizing the eye-movement data collection approach, a series of controlled animation experiments are proposed. These empirical studies adhere to experimental design standards in cognitive psychology, but are additionally grounded on a solid dynamic design framework borrowed from cartography, computer graphics and cinematography, to investigate how different dynamic visual variables, and various levels of interactivity affect people's knowledge construction processes from dynamic displays as compared to static displays.

Introduction

The need for better understanding of the cognitive processes involved in dynamic display use has become more important recently, paralleling the exponential growth of animation and dynamic graphics people are being exposed to in their everyday life (e.g., WWW, feature length computer animated movies, MTV, game controllers, and weather animation on the evening news on TV, for example). For this paper we define dynamic visualizations as all types of graphic displays that congruently display the time dimension with temporal change, including graphic user interfaces, interactive and non-interactive animations, etc. As with most rapid developments of new technologies, the theory and understanding of novel graphics technology and applications has lagged behind. Cartography, with its 5000-year history, has perfected the representation of dynamic spatio-temporal phenomena with static, spatial representations in the form of two-dimensional maps (Bertin, 1967/83). As early as the 1930s, cartographers also experimented with congruently displaying the time dimension dynamically in the form of map movies to represent dynamic geographic processes. More recently cartographers have also visualized non-dynamic processes with dynamic procedures, for example using *blinking* for depicting data quality in maps (e.g., Fisher, 1994).

Dynamic cartographic representations, such as cartographic movies (Tobler, 1970), 2D and 3D computer animations (Moellering, 1976, 1980), as well as interactive map animations and simulations have become increasingly popular since personal computers with growing graphic processing power have become cheaper, faster, and more user-friendly (Peterson, 1995). However, as Campbell and Egbert (1990) observed, in spite of 70 years of dynamic cartography, it seems that the cartographic community has only been scratching the surface of dynamic displays. As real-time three-dimensional landscape fly-throughs and interactive map animations of various spatial diffusion processes become ubiquitous with dissemination through the Internet, one important question that remains is how effective the potential increase of information density in these highly interactive visual forms really is for knowledge construction and decision-making.

We still know very little about how effective novel interactive graphical data depictions and geovisualization tools are for knowledge discovery, learning, and sense making of dynamic, multidimensional processes. To help fill this gap, my colleagues and I have proposed a research agenda using eye-movement studies to empirically assess the usefulness of dynamic depictions of spatio-temporal phenomena for exploratory spatial data analysis and knowledge discovery. This research agenda is inspired by a series of key research challenges for Geovisualization put forward by the International Cartographic Association's Commission on Visualization and Virtual Environments (ICA GeoVis). This Geovisualization research agenda was recently published in a special issue of Cartography and Geographic Information Science (MacEachren and Kraak, 2001a).

Specifically, our proposed agenda responds to ICA GeoVis' third research challenge on cognitive issues and usability in Geovisualization, namely, to develop a theoretical framework based on cognitive principles to support and assess usability methods of geovisualization that take advantage of advances in dynamic (animated and highly interactive) displays (p.8).

Background

How Does Animation Work?

A pervasive theme underlying many current geovisualization research challenges is the difficulty to effectively evaluate highly interactive visualization tools and displays, and to identify their potentially positive influence on exploratory data analysis, knowledge extraction and learning (MacEachren and Kraak, 2001b). Slocum et al., (2001) suggest that one of the key usability evaluation problems is the lack of clear task specifications (and sometimes user base) when dealing with exploratory visualization tools used for solving ill-structured problems (p. 63).

Cognitive psychologists have attempted to tackle the fundamental research question of how externalized visual representations (e.g., statistical graphs, organizational charts, maps, animations etc.) interact with people's internal visualization capabilities (Tversky, 1981; Hegarty, 1992). Experimental research has shown that static graphics can facilitate comprehension, learning, memorization, communication of complex phenomena, and inference from the depiction of dynamic processes (Hegarty, 1992; Hegarty and Just, 1993). In a series of recent publications that surveyed the cognitive literature on animated graphics, Tversky and colleagues failed to find benefits of animation for conveying complex processes (Bétrancourt et al., 2000; Bétrancourt and Tversky, 2000; Morrison et al., 2000; Morrison and Tversky, 2001). These authors argue that experimental studies reporting advantages of animation over static displays lacked equivalence between animated and static graphics in content or experimental procedures. Our research project aims to investigate this claim more thoroughly. For example, we are interested in assessing if static small multiple displays *are* indeed equivalent in information content with stop-and-go animated sequences, and if animated sequences *are not* equivalent with interactive animations, as claimed by Tversky and colleagues. We propose to assess these questions with a series of eye-movement studies.

While cognitive psychologists have done thorough research illuminating problematic aspects in animated displays, they have not fully addressed relevant issues from a geographer's perspective. Our research specifically focuses on the effectiveness of dynamic depiction principles for spatio-temporal map displays which have not been thoroughly investigated, in either cognitive psychology or geography/geovisualization. The focus of this research is not only to assess if animation works, but how and why it works or does not work. In the above listed review articles on animation, Tversky and collaborators emphasize that sound graphic principles must be employed to construct successful static graphics, but they do not elaborate which ones. The same authors further suggest that research on static graphics has shown that only carefully designed and appropriate graphics prove to be beneficial for conveying complex phenomena, but they do not offer specific design guidelines. Obviously design issues must be carefully considered as well for dynamic graphics, considering that animated graphics add an additional information dimension, e.g., that of time or change. Traditional graphic design principles may only partially apply in the dynamic realm and therefore call for special attention. The above-cited cognitive literature generally suggests that animation fails, but it does not elaborate on animation design specifics that may or may not influence experimental results (e.g., which specific dynamic design elements were used, etc.).

Thematic Relevance and Perceptual Salience

Animation skeptics cite Lowe (1999)'s experiments on complex interactive weather map animations as an example of where animation failed. Notably, one of Lowe (1999)'s research findings was that participants tended to extract information based on perceptual salience rather than thematic relevance. He additionally suggests potential reasons why animation failed, such as participant's lack of relevant domain expertise, the complexity of the depicted system, and more importantly the manner in which the system was depicted.

Studies on animation done by cognitive psychologists have focused on mechanical systems or processes with real, observable movement of objects that are constrained by physical properties (e.g., moving parts of complex mechanical systems). These kinds of studies have not been carried out on geographic visualizations of abstract, non-tangible dynamic processes represented in maps (e.g., diffusion processes, meteorological events etc.).

Cartographers choose the appropriate visual variables to make thematically relevant information perceptually salient, depending on the three pillars of cartographic design: map theme, map purpose, and audience. This begs the question whether controlled changes in the animation design, such as making the thematically relevant information perceptually salient through (carto)graphic design principles, may help overcome the suggested drawbacks of animation.

For systematically assessing the effects of cartographic design (e.g., matching visual saliency to thematical relevance), we employ a bottom-up, saliency-based visual attention model, developed by Itti and colleagues (e.g., Itti et al., 1998; Itti, 2001). This neurobiologically-inspired, pre-attentive vision model (Itti et al., 1998) is used as a baseline to compare human subject viewing behaviors collected with the eye movement data collection method. An experimental stimulus is shown below in Figure 1. The design of this display is inspired by the typical weather maps found in mass media (e.g., USA Today, or on TV). The isopleth map in Figure 1 depicts the pressure gradients (isobars) overlaid on the temperature distribution (isopleths, i.e., filled isotherms) over the North American continent at one particular day. The temperature distribution is the visually most salient aspect of this map, even though this information is not relevant for the experimental task.

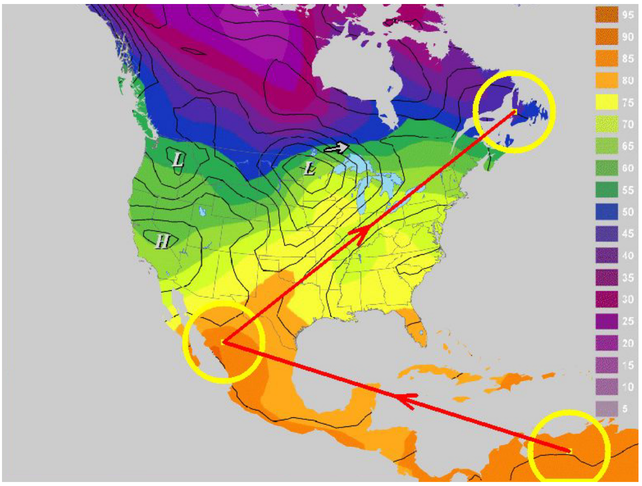

Figure 1: Weather map stimulus and predicted eye fixation sequence

Overlaid on the map display, using circles and connecting lines, is the result of the Itti et al. (1998) saliency model prediction for that stimulus. The Itti-model is a neural-net based, neurobiologically plausible vision model. The goal of the model is to identify the focus of attention of a visual system (mammal or robot) based on the 'where' (e.g., perceptually salient characteristics), but not the 'what' (e.g., semantic characteristics, requiring cognition). This model has been inspired by and successfully validated against experimental evidence for classic visual search tasks (e.g., pop-out vs. conjunctive search) proposed by Treisman and colleagues (e.g., Treisman, 1980).

In this model, three filters are applied to extract color hue, color value and orientation contrasts at several levels of image resolutions in a visual scene. Three feature maps (one for each filter) are computed based on center-surround comparisons. Feature maps are additionally computed at several image resolutions and integrated to form a single conspicuity map for each feature type. A non-linear normalization is applied to each conspicuity map to amplify peaks of contrasts relative to noise in the background. In the final stage feature maps are combined to produce a single saliency map (SM) of the visual scene (Figure 2).

The saliency model also predicts a sequence of locations (ranked saliency peaks in the SM) that will attract a viewer's gaze. Predicted initial eye fixations (circles) and the sequence of eye scan paths (lines) in Figure 1 are derived from the gray scale saliency map shown in Figure 2. The light areas in Figure 2 identify highly salient image locations; these are represented as initial eye fixation locations in Figure 1 (circles).

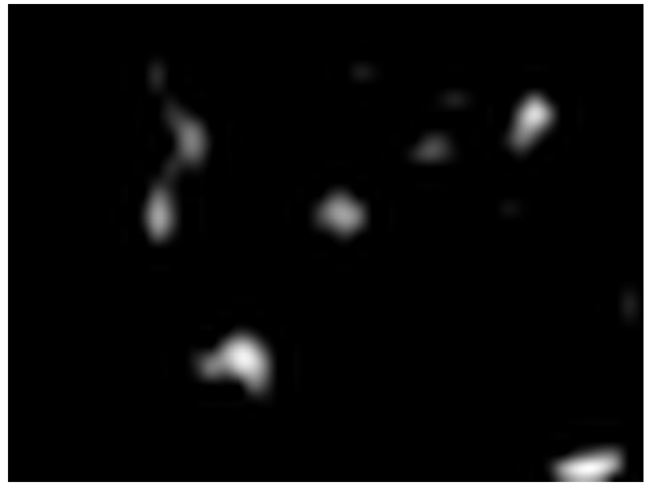

Figure 2: Saliency Map

Weather maps are typically not designed by cartographers, and thus rarely follow cartographic design conventions. Based on the Itti-saliency model, image locations that are relatively far away from the thematically relevant information for a particular experimental task (e.g., the low and high pressure cells) are the most salient spots in the map.

The map stimulus in Figure 3 below is redesigned based on cartographic design conventions, thus with the goal of rendering thematically relevant information in a perceptually salient manner. The temperature distribution, not relevant for the experimental task, has been visually demoted to the background, by de-saturating the colored isopleths. The thematically relevant information, that is, the labeled pressure cells and the isobars have been visually promoted to the foreground (e.g., made more salient) by thickening and darkening the isolines (increased contrast) and by emphasizing the H/L labels with fully saturated color hues.

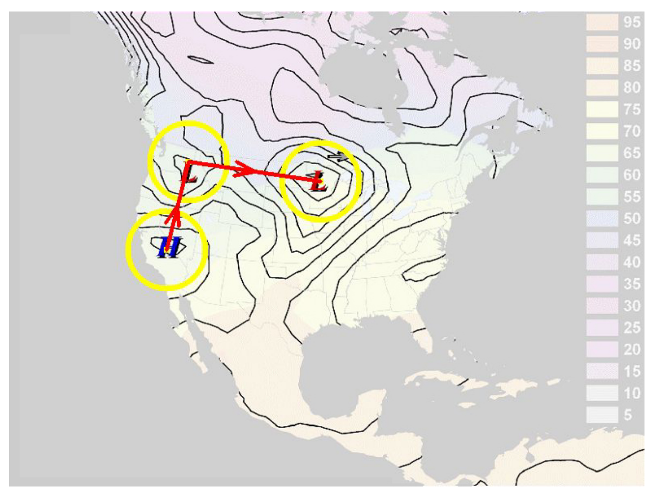

Figure 3: Cartographically enhanced map stimulus

It should be noted that this map would not be considered a typical cartographic design solution. For example, a cartographers would have chosen a diverging color progression (Brewer, 1994) to perceptually emphasize the increase/decrease of temperature magnitude with color value (i.e., lightness) and the direction of the temperature gradient (warmer/cooler) with color hue (e.g., red/blue). However, to keep a tight experimental control, the solution in Figure 3 was the closest 'cartographically inspired display' we were able to develop to be able to compare our research results with the results by Hegarty and colleagues. For the 'cartographic' display, the Itti-saliency model predicts that people should look first at the High pressure cell in blue (over California), then the Low pressure cell just North of the California High, followed by another Low to the east, located in the center of the map. These three locations carry the thematically relevant information for the experimental task, and are also most salient.

Even though our current understanding of visual attention suggests a combination of bottom-up (stimulus driven and pre-attentive) processes and top-down (task/goal dependent, thus cognitive and semantic) components, the predictions of this solely bottom-up based model are very promising. The Itti model accurately predicts the thematically relevant portions of the cartographically enhanced map stimulus, as intended by the cartographer. This result is not only gratifying for cartographers, but it gives support for the utility of Bertin (1967, 1983)'s system of seven visual variables, widely used in cartography and more recently discovered in information visualization (Card, 1999). The Itti-saliency map is the sum of several input components regarded as important for visually detecting salience, such as center-surround contrasts in color hue, color value (called intensity by Itti et al. 1998), and orientation. It is notable that these three components are also featured prominently in Bertin's (1967/1983) seven visual variables including, location, size, color value, texture, color hue, orientation and shape.

Another advantage of the Itti-model is that it can be applied to dynamic scenes (Itti, in press), including map animations. For dynamic scenes the Itti saliency map includes additional dynamic input parameters such as temporal change (flicker: on/off), and the four motion directions (up, down, right and left).

Our planned studies aim to assess the roles of thematic relevance and modeled perceptual salience, by recording human viewing behavior. A focus of interest is how novices' viewing patterns are modified when thematically relevant items are made perceptually more salient through design. In essence, we are asking if perceptually salient elements draw novice viewers' attention to thematically relevant information, whether or not users have domain knowledge. We are also interested in comparing novices' viewing patterns with those of expert users. One would expect that map viewers trained in the subject matter would guide their attention towards the thematically relevant portions of the display, regardless of what is rendered salient through design.

Methods and Experiments

To address the research questions outlined above, we propose a series of controlled (static and dynamic) map experiments that adhere to experimental design standards in cognitive psychology, but additionally are grounded on a solid dynamic design framework borrowed from cartography (Bertin, 1967; DiBiase et al., 1992), computer graphics and cinematography (Lasseter 1987).

Mary Hegarty, a psychologist at the University of California Santa Barbara, will collaborate on a study that investigates the issue of perceptual saliency vs. thematic relevance, using the eye movement data collection method. The weather map stimuli depicted in earlier Figures are presented to participants during eye movement experiments. While Hegarty is adopting a top-down approach by assessing the influence of training (e.g., level of expertise) on map viewing behavior, we are pursuing a bottom-up approach by assessing the influence of perceptual characteristics (e.g., map design) of the map display on viewing behavior. The use of an identical experimental design will allow us to directly compare experimental results for both approaches.

Aside from the visual variables employed for designing the graphic displays (e.g., control of perceptual salience and thematic relevance in a scene), we are also interested in design issues related to *change between* scenes (e.g., control for change of perceptual salience and thematic relevance between scenes), that is, the influence of dynamic variables on viewing behavior.

Interactivity Levels in Dynamic Displays

We intend to evaluate the contention that static small multiples are equivalent to (non-interactive) animations, and to explore how various levels of interactivity in interactive map animations may affect viewing behavior. Tversky and colleagues report on the lack of equivalence in static and animated graphics experiments (Tversky et al. 2002). They suggest that interactive graphics are *superior* to animated graphics, and to static small multiples, thus cannot be fairly compared. However, the authors do not specify what exactly makes a graphic *superior*. We argue that static, small multiples are also interactive, in the sense that viewers can choose to investigate the still frames in any sequence they wish, even going back and forth between frames, if necessary for the task at hand. Non-interactive animations on the other hand have a pre-determined sequence and pacing, which increases the viewer's short-term memory load. Moreover, Rensink et al. (1997) have demonstrated that observers have great difficulty noticing even large changes between two successive scenes in an animation when blank images are shown in between scenes (e.g., simulating a flicker). This *change-blindness* effect even operates when viewers know that they will occur. Rensink (2002) suggests that only about four to five items can be attended to at any moment in time in animated scenes. This means that interactivity is not just superior, but necessary to alleviate perceptual problems of non-interactive animations.

Visual Transitions Between Scenes

Our proposed experiments also focus on the effect of visual transitions between frames of an animation on viewing behavior. Visual transitions, a technique borrowed from the movie industry, deal with establishing visual ties (e.g., coherence) to events occurring in adjacent frames in a movie or animation. *Dissolves*, *wipes* or *fades* are all examples of visually modifying the amount of change and pacing between animation frames. DiBiase et al. (1992) and MacEachren (1995) suggest additional design variables specifically for the display of dynamic geographic phenomena. The six dynamic variables are: (1) display moment or display date/time (e.g., when a dynamic event becomes visible), (2) scene duration (e.g., how long a scene is displayed), (3) scene frequency (e.g., frame rate per second, or how fast graphic frames follow one another), (4) scene order (e.g., sequence in which graphics are displayed), (5) rate of change between scenes (e.g., the magnitude of change visible between two sequentially displayed scenes), and (6) synchronization (e.g., the juxtaposition of two concurrent events on the same dynamic display).

Visual transitions in dynamic scenes can be controlled by these dynamic variables, and these variables could potentially mitigate the *change blindness* effect. For example, one could de-emphasize noninformative changes for the task at hand by making transitions more gradual (Rensink, 2002), thus invoking the animation principle of *anticipation* (Lasseter 1987). Smooth transitions can be achieved by decreasing the magnitude of change between adjacent key frames in the animation. However, smoother transitions may also de-emphasize informative change, thus might make it harder for the viewer to detect slight but important changes in a visually 'noisy' or cluttered background.

Summary and Outlook

We have presented a series of research questions and have outlined a series of empirical experiments to empirically evaluate the effectiveness of interactive and dynamic geographic visualization displays for knowledge discovery and knowledge construction. We tackle this research agenda by first systematically addressing the relationship between visual saliency and thematic relevance in graphic displays, employing a neurobiologically inspired, pre-attentive vision model to quantify visual salience in static and dynamic scenes. The proposed empirical studies adhere to experimental design standards in cognitive psychology, but are additionally grounded on a solid dynamic design framework borrowed from cartography, computer graphics and cinematography, to investigate how dynamic visual variables and levels of interactivity affect people's knowledge construction processes from dynamic displays as compared to static displays. With these studies we hope to provide a better understanding of how people use static and dynamic displays to explore dynamic geographic phenomena, and how people make inferences from dynamic visualizations to construct knowledge in a geographical context.

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