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THEMATIC RELEVANCE AND PERCEPTUAL SALIENCE OF DYNAMIC GEOVISUALIZATION DISPLAYS[*]

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ABSTRACT

We propose a research agenda for empirically assessing the effectiveness of dynamic displays with the eye-movement data collection method. The proposed framework is based on the relationship between perceptual salience and thematic relevance in static (e.g., visual variables: color hue, color value and orientation) and animated displays (e.g., dynamic variables including transitions). 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 different dynamic and visual variables, and various levels of interactivity affect people's knowledge construction processes from dynamic displays as compared to static displays.

INTRODUCTION

Cartographers have achieved great effectiveness in the depiction of dynamic spatio-temporal phenomena with static, spatial representations in the form of two-dimensional maps (Bertin, 1967/83). Moreover, as early as the 1930s, cartographers also experimented with adding the time dimension to represent dynamic geographic processes with dynamic visual forms. Dynamic cartographic representations, such as cartographic movies, 2D and 3D computer animations (Moellering, 1980; Moellering, 1976), 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, Harrower, 2004). Despite 70 years of dynamic cartography, it seems that the cartographic community has only been scratching the surface of dynamic displays (Campbell and Egbert, 1990). We still have very little empirical evidence on how effective dynamic geographic data displays and highly interactive geovisualization tools are either for educational purposes (e.g., communication and making sense of what is known) or for scientific knowledge discovery (e.g., extracting new knowledge from massive data bases).

We propose a research agenda to empirically investigate how different dynamic visual variables and various levels of interactivity affect people's learning and knowledge construction processes from dynamic displays, as compared to static displays. We were inspired by the research challenge proposed by the *International Cartographic Association's Commission on Visualization and Virtual Environments* "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" (MacEachren and Kraak, 2001: 8). The proposed framework will be refined and validated through a series of experiments with dynamic displays using the eye-movement data collection method.

RELATED WORK

The proposed research framework is informed by cognitive theory on graphics that has been evolving since the early 80s (Kosslyn, 1994; Marr, 1982; Pylyshyn, 1981). Previous cognitive visualization research has focused mainly on identifying the components of humans' cognitive image processing system, but has not necessarily looked at the interplay of human internal visualization processes (e.g., learning and reasoning) with external, dynamic visual displays (Hegarty, 2002). More recently psychologist have investigated the fundamental relationship between mental and external diagrams in human reasoning (Tversky, 1981; Hegarty, 1992). Cognitive scientists and psychologist have studied how externalized visual representations (e.g., statistical graphs, organizational charts, maps, animations etc.) interact with people's internal visualization capabilities (Barkowsky et al., 2005). This study tries to provide missing pieces of the fundamental research question in cognitive science "if and how graphics can augment humans' internal

[*] This paper significantly expands upon ideas initially presented in Fabrikant (2005).

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visualization capabilities”. 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, 1993; 2002). Surveying the cognitive literature on research 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. When they are equivalent, animations show no apparent benefit; sometimes they even result in a performance deficit. The present research agenda attempts to more thoroughly investigate this claim taking advantage of the eye-movement data collection method. In their papers, Tversky and her collaborators emphasize that sound graphic principles must be employed to construct successful static graphics, but they do not suggest details on how these transfer into the dynamic domain. We contend that ad-hoc design decisions of graphic test stimuli, due to lack in graphic design training, may be an additional reason why animations might have failed in past research. Research in cartography suggests that traditional graphic design principles may only partially transfer into the dynamic realm, and therefore design for animation needs special attention (Harrower, 2003).

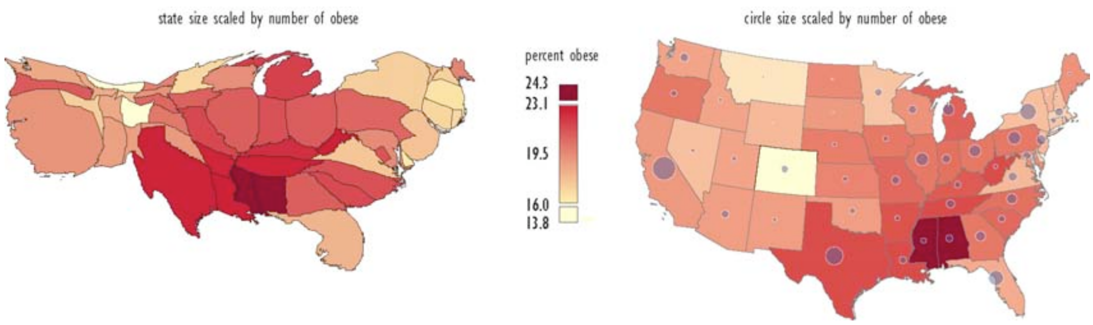
RESEARCH FRAMEWORK

Lowe’s (1999, 2003, 2004b) experiments on complex interactive weather map animations are often cited by animation skeptics as an example of where animation failed. One of Lowe’s (1999) research findings was that participants tended to extract information based on perceptual salience rather than thematic relevance. This begs the question of whether controlled changes in the animation design, i.e., making thematic relevant information perceptually salient through graphic design principles, may help overcome the suggested drawbacks of animation. Furthermore, Lowe (2004a) suggests that simply providing user control (e.g., interaction capabilities) does not always result in the desired learning improvements. He found that participants neglected the animations’ dynamic aspects, perhaps because of available user controls. Most of the time participants either stopped the animation and investigated still frames, or the animation was being viewed in a stepwise fashion, one frame at a time. This raises additional research questions such as, what kinds of interaction controls are needed for dynamic map displays, and how these controls should be designed such that they are more efficiently used. Inspired by Lowe’s findings, we propose to empirically examine three relationships relating to the overall design goal of improving the congruence of perceptual salience with thematic relevance in dynamic displays. We examine congruence of visual salience and thematic relevance...

1. *within* a map: by control of the visual hierarchy (e.g., visual variables) in a scene of an animation
2. *between* maps: by control of dynamic variables between scenes in an animation (e.g., transitions)
3. *between user* and map: by control of the human-computer interaction in dynamic displays (e.g., interactivity levels)

Visual salience and thematic relevance within a scene

The idea of generating a visual hierarchy in maps that is congruent with thematic levels of relevance is at the core of cartographic design (Dent, 1999). Supported by the three pillars of map design (map theme, map purpose, and map audience), cartographers employ a set of visual variables for 2D, static maps to systematically match levels of thematically relevant information to a perceptual hierarchy based on figure-ground relationships (Bertin, 1967/83). The relationship of perceptual salience and thematic relevance in a static, 2D scene is illustrated in Figure 1. Both maps in Figure 1 depict the same themes: raw totals and proportions of obese people per U.S. State in 2000.



(a) Cartogram (b) Choropleth map

Figure 1. U.S. obesity in 2000

Which map conveys what kind of information in a perceptually salient manner? Applying Bertin's visual variable theory, a cartographer might argue that in cartogram (a) the obesity counts per state are emphasized through variations in state size, while the proportions of the obese within a state area are depicted with color shading.
In choropleth map (b), on the other hand, the obesity counts are rendered with graduated circles, and obesity proportions are highlighted using variations in color shading.

For systematically evaluating static and dynamic scene designs (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 and Koch, 2001; Itti et al., 1998). This pre-attentive vision model (Itti et al., 1998) is used as a baseline to later compare human subject viewing behaviors collected with eye movement data. 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 and Gelade, 1980). Visual search strategies have also been studied on more realistic looking scenes such as maps (Lloyd, 1997) and aerial photographs (Lloyd et al. 2002). 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).

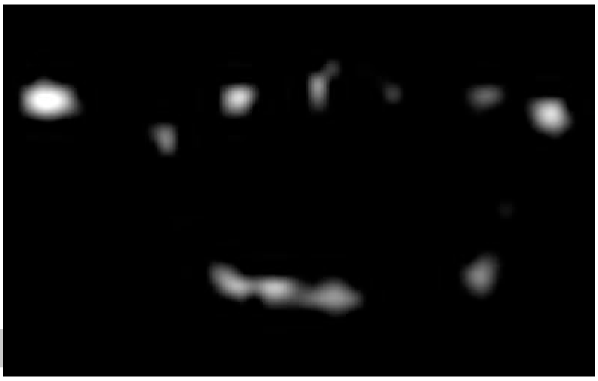
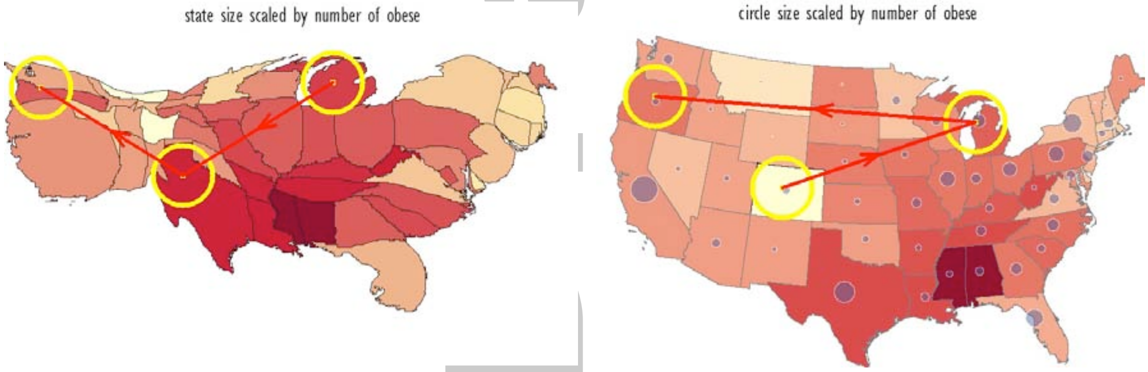


Figure 2. Saliency map of cartogram (a)

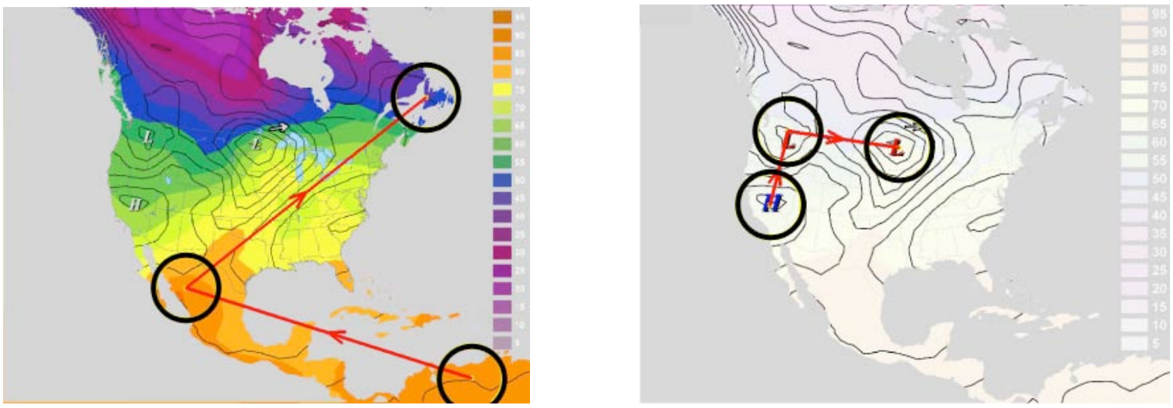
The saliency model also predicts a sequence of locations (ranked saliency peaks in the SM) that will attract a viewer's gaze in a scene. Predicted initial eye fixations (circles) and the sequence of eye scan paths (lines) in Figure 3 are derived from the gray scale saliency map shown in Figure 2 (the SM for the choropleth map is not shown). The light areas in Figure 2 identify highly salient image locations; these are represented as initial eye fixation locations in the cartogram (a) in Figure 3 (circles). The visual variables color hue, color value and orientation employed by the Itti model are the same visual variables manipulated by cartographers to generate perceptual salient figure/ground contrasts.



(a) Cartogram (b) Choropleth map

Figure 3. Top three salient locations and eye scan path sequences

Michigan, Texas and Oregon are the most salient spots above in (a), whereas Colorado, Michigan and Oregon are the most conspicuous locations in (b). Colorado, a large, but not densely populated area and with few obese people "pops out" (Treisman and Gelade, 1980) in map (b). Choropleth maps (b) emphasize the land, not the people living on the land. Obesity ratios (normalized by area) work well in (b) whereas raw counts seem to be well suited in cartogram (a).
We are exploring the saliency-thematic relevance relationship in an ongoing experiment on static 2D weather maps in collaboration with Mary Hegarty, a cognitive psychologist at UCSB. Figure 4 shows stimuli used in this experiment.



(a) mass media weather map (b) cartographically enhanced map

Figure 4. Weather map stimuli and predicted eye fixation sequences

The design of the left image (a) in Figure 4 is inspired by the typical weather maps found in mass media (e.g., USA Today, or on TV). The pressure gradients (isobars) are overlaid on the temperature isopleths (filled isotherms) over the North American continent for one particular day. The temperature distribution is the most visually salient aspect in (a), even though this information is not relevant for the experimental task. Map (b) is redesigned based on cartographic design conventions. 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—the labeled pressure cells and the isobars—has been visually promoted to the foreground (e.g., made more salient) by thickening and darkening the isolines, and by emphasizing the H/L labels with fully saturated color hues.

It should be noted that this map would not be considered a typical cartographic design solution. For example, a cartographer 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 4 (b) was the closest 'cartographically inspired display' we were able to develop to be able to compare our research results with the results of Hegarty and colleagues. Nevertheless, the Itti-saliency model predicts for the cartographic display (b) 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.

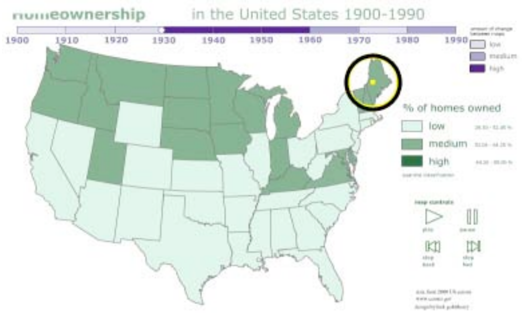
Even though our current understanding of visual attention suggests a combination of bottom-up (stimulus driven and pre-attentive) processes and top-down (task/goal dependent, thus cognitive and semantic) components, the predictions of this solely bottom-up based model are very promising. The Itti model 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's (1967/83)'s system of seven visual variables, widely used in cartography and more recently discovered in information visualization (Card et al., 1999).

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. Eye movement data collection is currently underway in our research lab and the Hegarty lab to compare test participants' viewing behavior with predicted saliency. Empirically validated results will be presented in a forthcoming paper.

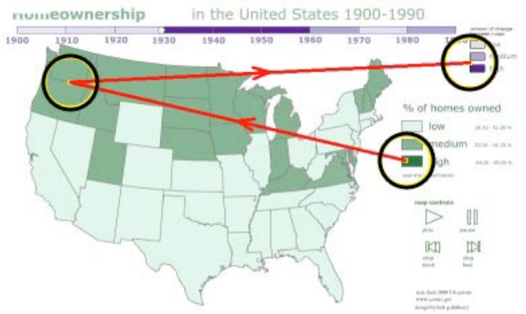
Visual salience and thematic relevance between scenes in an animation

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. In the next section we apply the Itti model to a map animation, and compare the predictions on dynamic scenes to static scenes.

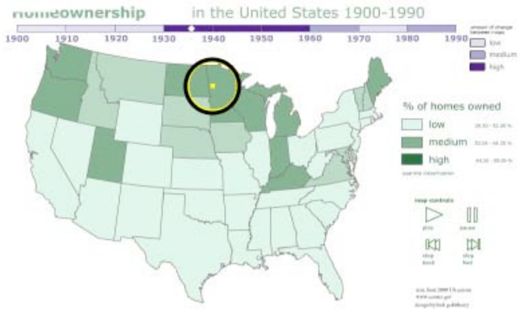
The maps in rows (a-c) in Figure 5 are three frames from a time-series animation of homeownership data in the US 1900-2000 (Goldsberry, 2004). The 1935 map (b) was linearly interpolated between the key frames 1930 and 1940 for which actual census data exists. The design goal was to achieve a smooth transition during the period of greatest decadal change (1930-1940). Gradual transitions may help to make informative change more salient by invoking the animation principle of "anticipation" (Lasseter, 1987). The rate of change between decades is depicted in the timeline above the map, using color value. The darker the purple, the greater the depicted change in the mapped variable. The animation speed is also congruent with the magnitude of change in the time series. The more change between map frames, the slower the animation (Goldsberry et al., 2004).



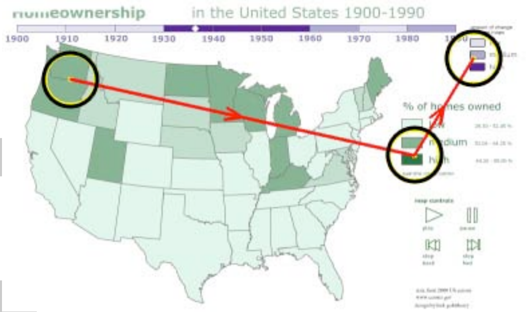
(a-1) most salient location in animation frame 1930



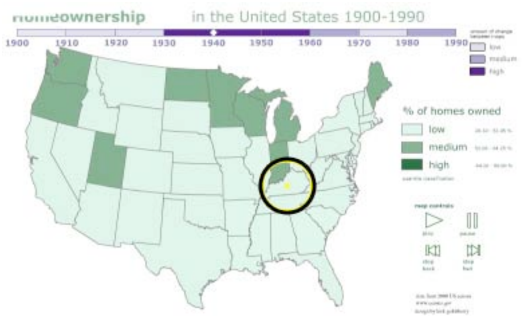
(a-2) top three salient locations in still frame 1930



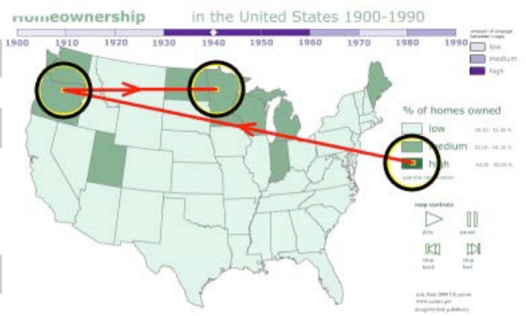
(b-1) most salient location in animation frame 1935



(b-2) top three salient locations in still frame 1935



(c-1) most salient location in animation frame 1940



(c-2) top three salient locations in still frame 1940

Figure 5. Difference in salience between identical still images and dynamic images

The static maps (a-c) in the right column of Figure 5 were subjected to the same Itti model as described above for static images. The images show the first three salient locations predicted by this model. The Itti model developed for dynamic scenes such as video footage, for example, was applied to frames in the map animation shown on the left side in Figure 5. In addition to contrasts in color hue, color value and orientation, the dynamic model also takes dynamic variables into consideration to compute the resulting saliency map (SM). Figure 6 below shows all the variables used in the dynamic Itti model. The first three panels in the top row (starting from the left) are the static visual variables (color hue, color value and orientation). These are the same variables used for the static Itti model.

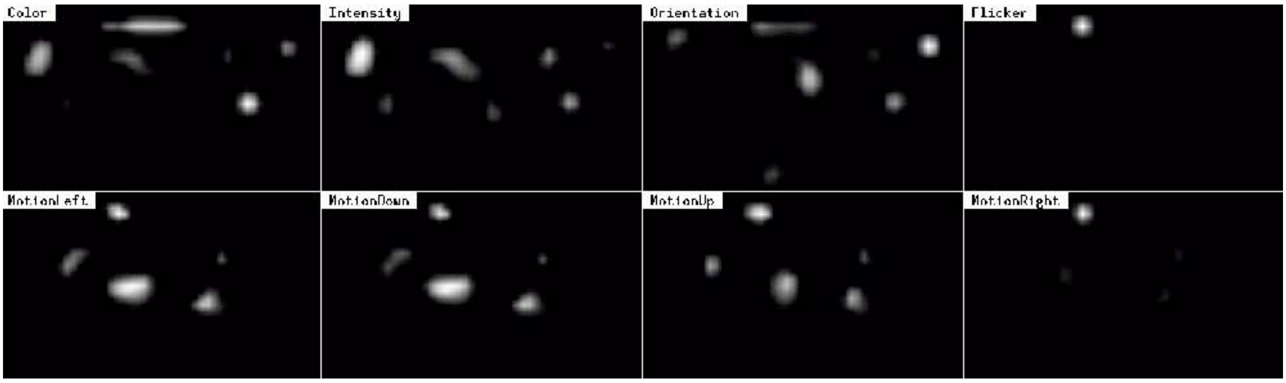


Figure 6. Saliency maps for frame 1935, including all the visual and dynamic variables considered by the Itti model

The additional dynamic variables considered are: change in location (motion up/down/right/left) as well as flicker (i.e., appearance and disappearance at a location). The area along the Minnesota–North Dakota state boundary is the most salient location in map frame 1935 (Figure 5, middle row, left panel). This could be because of greatest visual activity in this area, as five adjacent states slowly change color value and hue, due to changes in class membership in the next frame (1940). All the saliency maps of the dynamic variables in Figure 6 depict the locations of greatest activity (i.e., light areas show salient locations). It is notable that the color hue saliency map in Figure 6 (1^{st} panel left, top row) indicates the legend information (timeline, rate of change legend, and map legend) to be most salient, similar to the result for the static frame in 1935 (c-2 in Figure 5). Notice that transitions can also highlight the appearance and disappearance of features without their movement across the map, and this is picked up with the Itti model (e.g., flicker panel, top row, first on the right).

For all map frames in Figure 5, the darker areas seem to be visually more salient than lighter areas. We believe this is because the background is white in the maps. One would expect a dark feature in a field of light colored features to pop-out, whereas a light feature in a dark background would be more noticeable. Furthermore, the most salient locations for the static model and the dynamic model are different, as Figure 5 shows. This is a significant consideration for our research framework as it gives rise to the idea that, indeed, static small multiples are *not* equivalent to non-interactive animations, as Tversky and collaborators claim (Tversky, 2001).

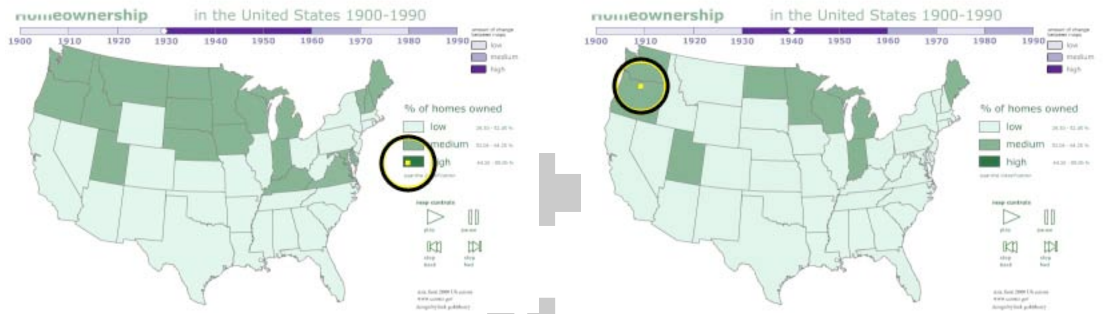
All the still frames have the legend among the most salient locations. This is not surprising, as the color value range used in the map (lightest to darkest green shades) is depicted in a compact space in the legend area, with different color patches not only very close to each other, but each separated by white background. The (static) Itti model highlights both legends (map and timeline) in the still frame for 1930 (a). In contrast, none of the animation frames on the left of Figure 5 include the legend as most salient location. The legends do not change (in location or visual property) in the course of the animation. During the animation, a small white diamond is moving across the purple time line, and at times appears in stark contrast to the dark purple patches (e.g., 1940-1960) in the background of the timeline. However, this is the only dynamic aspect of the legend, and it seems it is not salient enough to be relevant for the dynamic Itti prediction. The Itti prediction seems to give support to Peterson's (1995: p. 48) contention that "what happens between each frame is more important than what exists on each frame". The most salient locations in the animation (a-c in the left column in Figure 5) are those where significant class changes between adjacent frames occur, due to states changing from the highest class (darkest green) to the middle class (medium green). This change happens gradually in the animation, using smooth transition effects, as discussed in the next section. The use of transition effects is another reason why static, small multiples are not equivalent to animated scenes.

Visual transitions

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 (i.e., coherence) to events occurring in adjacent frames in a movie or animation. *Dissolves*, *wipes* and *fades* are all examples of visually modifying the amount of change and pacing between animation frames. Transitions are one example where the dynamic variables are manipulated to generate a specific visual effect in a dynamic display. 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).

We are considering transitions in our research, as 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. Visual transitions in dynamic scenes can be controlled by the dynamic variables listed above, 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 making it harder for the viewer to detect slight but important changes in a visually 'noisy' or cluttered background.

As already mentioned, the dynamic Itti model—which includes two dynamic variables (flicker, called display moment by MacEachren, 1995, and motion, essentially the dynamic version of Bertin's location variable)—does identify the transitions zones as salient (see Figures 5 and 6). When running the model on an animation without transitions, the outputs look different again (Figure 7).



(a-1) most salient location in animation frame 1930 (a-2) most salient location in animation frame 1940

Figure 7. Difference in salience between animated frames without transitions

The dynamic Itti model picks up even slight changes in color value or color hue in the *transition* animation. This might be the reason for a significant difference between animations with or without transitions (see Figure 5). Smooth color transitions cause slight flickers, and because both these effects are missing in the 'no-transitions' version shown in Figure 7, the dominant visual property *within* the frame takes dominance (e.g., the 'extreme' color changes in the compact legend space, as in Figure 5, a-1). Dynamic variables are not only relevant to the control of changes between scenes, but also important visual cues for facilitating human-map interaction within a digital environment. Dynamic variables for interaction are the focus of the next section.

Interactivity

We intend to evaluate how various levels of interactivity in map animations may affect viewing behavior. Tversky and colleagues (Tversky et al. 2002) suggest that interactive graphics are *superior* to animated graphics, and to static small multiples, and thus cannot be fairly compared. However, these authors do not specify what exactly makes a graphic *superior*. As we have shown in the previous section, animations themselves may not be equivalent (depending on design decisions), for instance, if they are using different dynamic variables (e.g., transitions). Consequently, the difference between two thematically identical animation sequences that are designed differently (e.g., with or without transitions) might be perceptually greater than between small-multiples and an animation of the same content.

We contend 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 may affect viewer's cognitive load (Sweller, 1988). Cognitive load theory, according to Sweller (1988), relates to the amount and duration of mental processing imposed on working memory. As Miller (1994) and Rensink (2002) have pointed out, only a limited number of elements can be attended to within a short amount of time. Non-interactive animations may therefore be especially problematic according to cognitive load theory as the viewer has no control of the visual and temporal properties of the display. Moreover, Lowe (2004a+b) has shown empirically that just adding user control does not necessarily improve learning performance when using animations in an instructional setting. In addition, Cohen (2005) suggests that individual differences (e.g., high/low spatial skills) not only affect the usage patterns of interactive tools (e.g., high spatial participants interacted more frequently with an interactive animation), but also influences the accuracy of test outcomes (high spatial participants tended to have higher accuracy). Here again, design decisions have to be carefully evaluated, and effects of interaction design on learning and knowledge construction require systematical empirical analysis.

Our research framework is also concerned with the empirical question of whether combining dynamic variables (e.g., transitions) with different levels of interactivity in dynamic displays may help reduce cognitive load, including perceptual problems (e.g., attentional blindness). Figure 8 suggests several design examples worth further empirical investigation with the eye-movement data collection method.

(a) animation/transitions* (b) sequencing & transitions* (c) hierarchical interaction§

Figure 8. Different interaction styles for animated graduated circle maps (*Mitbø et al. 2005; §Mehta, et al. 2003)

VCR-style controls shown in Figure 8 (b & c) allow playing or stepping through an animation sequentially forward or backwards. Animation (a) combines static small multiples with animation by combining transparency and transition effects. A user can either play the animation or step through the small multiples by clicking on the respective maps along the timeline. Unlike traditional sequencing, all the map frames are visible at all times throughout the animation, while the current map is visually emphasized. In animation (b) the cyclic nature of a diurnal data pattern is visualized as a clock face. The hand of the clock can be dragged to step through the animation at any speed and direction. One can also click on an hour (sphere symbol) to jump to the respective frame in the animation. Night and day hours are represented with a moon or sun symbol in a darker or lighter background, respectively. The vertical timeline in map (c) emphasizes the linear nature of population growth. The user can jump to individual time steps by clicking onto the respective year. Hierarchical interaction is provided with on/off choices for additional relevant data layers, such as water features or transportation.

SUMMARY AND OUTLOOK

We propose a research agenda, based on eye movement studies, for empirically assessing the effectiveness of dynamic map displays for learning, 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. We then compare salience predictions with actual map user behavior, taking advantage of the eye-movement data collection method. 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 (e.g., transitions) 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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