Cognitively Inspired and Perceptually Salient Graphic Displays for Efficient Spatial Inference Making

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Developing a visual hierarchy in map displays that is congruent with thematic levels of relevance is a fundamental cartographic design task. Cartographers employ a set of visual variables (e.g., size, color hue, color value, orientation, etc.) for 2-D, static maps to systematically match levels of thematically relevant information to a perceptual hierarchy based on figure–ground relationships. In this article, we empirically investigate the relationship of thematic relevance and perceptual salience in static weather map displays. We are particularly interested in how novices' viewing patterns are modified when thematically relevant items are made perceptually more salient through design. In essence, we are asking whether perceptually salient elements draw novice viewers' attention to thematically relevant information, whether or not users have domain knowledge.

In a factorial experiment, we ask novice participants to evaluate the wind direction in weather maps before and after training all participants on meteorological principles. Our empirical results suggest that display design (i.e., saliency) does not influence the accuracy of response, whether participants have prior knowledge or not (i.e., training). Analysis of the eye-movement patterns, however, suggests that display design does affect viewing behavior and response time. These findings provide rare empirical evidence for generally accepted design practices within the cartographic community (e.g., the effects of visual variables). We chose weather map displays as one typical example of commonly used maps for our study, but the methods employed are generic enough to be applicable to any spatial display (static or interactive) that might be produced by GIScientists, cartographers, geographic information system (GIS) practitioners, and others. *Key Words: empirical study, eye-movement analysis, geographic visualization, spatial inference, weather maps.*

在地图的显示上建立一种视觉上的等级，使之与专题图的分级层次相一致，这是制图设计的一项基本任务。制图学家们使用了一系列的视觉变量（例如，大小，颜色的色调，颜色值，方向等），用于二维的静态地图，系统地匹配与主题相关的等级信息，基于图形和实地的关系，形成知觉上的等级。在本文中，利用显示的静态天气图，我们实证性地研究了专题地图的专题相关性和知觉显着性的关系。我们特别感兴趣的是，当与主题相关的元素通过设计使得感性更突出的时候，新手的视觉模式是如何被改变的。从本质上讲，不管用户是否拥有某领域的知识，我们关注的是感性突出的元素是否吸引了新手观众对主题相关信息的注意。在析因实验中，对所有参与者在基本气象原则的培训之前和之后，我们要求参与的新手们在天气图上评估风向。我们的实证结果表明，不管参加者是否拥有该领域的知识（即培训），展示的设计（即显着性）不影响反应的准确性。但是，对眼动模式的分析表明，显示的设计的确会影响视觉行为和响应时间。这些发现为绘图界普遍接受的设计实践提供了难得的经验证据（例如，视觉变量的影响）。我们在研究中选择了天气图显示作为常用地图的一个典型案例，但研究中所采用的方法都是通用的，足以适用于任何空间展示（静态或交互式），这些空间展示的作者可以是地理信息学家，绘图学家，地理信息系统（GIS）从业人员，等等。*关键字：经验性研究，眼动分析，地理可视化，空间推理，天气图。*

Desarrollar una jerarquía visual en los despliegues del mapa, que sea congruente con los niveles temáticos de relevancia, es una tarea fundamental de diseño cartográfico. Los cartógrafos utilizan un conjunto de variables visuales (e.g., tamaño, matiz de color, valor del color, orientación, etc.) para mapas estáticos, de 2-D, a fin de alcanzar de manera sistemática niveles de información temáticamente relevante para una jerarquía perceptual basada en la relación figura-realidad. De modo empírico, en este artículo investigamos la relación de relevancia temática y notabilidad perceptual en despliegues de mapas meteorológicos estáticos. Nos interesa, en particular, la manera como se modifican en los novatos los patrones visuales, cuando ítems temáticamente relevantes se hacen perceptualmente mucho más salientes por medio de diseño. En esencia, lo que estamos preguntando es si

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los elementos que se destacan perceptualmente captan la atención de observadores novatos hacia la información que es relevante desde el punto de vista temático, sea que los usuarios tengan o no suficiente conocimiento del tema. En un experimento factorial, le pedimos a participantes novatos evaluar la dirección del viento en mapas meteorológicos, antes y después de que a todos los participantes se les enseñaran principios meteorológicos. Nuestros resultados empíricos sugieren que el diseño del despliegue (i.e., notabilidad) no influye en la exactitud de la respuesta, así sea que los entrevistados hayan tenido conocimiento previo o no (i.e., entrenamiento). El análisis de los patrones de movimiento del ojo, sin embargo, sugiere que el diseño del despliegue en verdad afecta la conducta de la observación y el tiempo de respuesta. Estos descubrimientos nos brindan una rara evidencia empírica sobre prácticas de diseño generalmente aceptadas por la comunidad cartográfica (e.g., los efectos de las variables visuales). Escogimos para nuestro estudio los despliegues del mapa del tiempo, a título de ejemplo típico de mapas de uso común, pero los métodos son lo suficientemente genéricos para poder aplicarse a cualquier despliegue espacial (estático o interactivo) que sea producido por científicos de la información y comunicación geográficas, cartógrafos, practicantes de los sistemas de información geográfica (SIG) y otros. *Palabras clave*: *estudio empírico, análisis del movimiento del ojo, visualización geográfica, inferencia espacial, mapas meteorológicos.*

Emerging and ubiquitous spatial and nonspatial information technology (i.e., virtual globe viewers, location-based services, including information search and retrieval capabilities on the Internet, etc.) provides evidence of the “visual turn” in today’s information society. The use of complex, highly interactive displays has left the narrow domain of experts in science (i.e., scientific visualization) and has been reaching the information society at large, including broad audiences with varying backgrounds (Card, Mackinlay, and Shneiderman 1999). Many of the available visual products, such as those disseminated through the Internet (e.g., mashups), or virtual and augmented environment technologies (e.g., virtual globe viewers) are based on the intuition that people are visuo-spatially competent and have no difficulty extracting meaning embedded in graphic displays for knowledge generation and decision making (Thomas and Cook 2005). GIScience and related fields operate under the assumption that people are able to proactively explore graphics for spatial knowledge discovery, and are able to detect geographic patterns, reveal spatial relationships, and thus make intuitive sense of what is seen on a geographic information system (GIS) display. To this day, though, little is known about the effectiveness of graphic displays for exploratory data analysis, problem solving, knowledge exploration, and learning (Shah and Miyake 2005).

A few cognitive scientists and psychologists 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). More than ten years ago, however, Scaife and Rogers (1996) succinctly warned about the paucity of work on determining how graphical representations are themselves constructed and how display design decisions interact with high-level cognitive processes for inference making and knowledge construction. These authors also lamented that there has been little progress toward a sound theoretical and methodological framework that would allow a designer to evaluate existing graphical aids or improve these aids in the future. Whereas researchers with different disciplinary backgrounds (i.e., Tufte 1990; Kosslyn 1994; Card, Mackinlay, and Shneiderman 1999) have systematically looked at design issues from various perspectives, Scaife and Rogers’s (1996) call for a systematic approach is still relevant today. They proposed that a useful framework would have to include a series of independent variables, such as the users’ level of experience with graphic displays, the knowledge domain to be visualized, and the type of tasks the displays would have to support.

More recently this problem has been reidentified as one of the key research challenges for geovisualization research focusing on cognitive issues and usability put forward by the International Cartographic Association’s Commission on Geovisualization (ICA Geovis; MacEachren and Kraak 2001a). Specifically, these authors point to the need to develop a theoretical framework based on cognitive principles to support a human-centered approach to geovisualization (MacEachren and Kraak 2001b). Inspired by this call, Fabrikant and Skupin (2005) proposed a design framework for developing cognitively plausible information visualizations. Extending on *cognitive plausibility* (Edwards 2001), a term used by psychologists to assess the accuracy with which models are believed to represent human cognition, Fabrikant and Skupin (2005) further suggested the notion of cognitively adequate visualizations. Cognitively adequate depictions are understood as graphic displays that not only support humans’ internal visualization capabilities but are able to augment people’s mental visualization capabilities for complex reasoning and problem solving in abstract domains (Fabrikant and Skupin 2005).

Visualization as Internal Representation and as Augmentation of Cognition

Research in cognitive science has shown that static graphics can facilitate comprehension, learning, memorization, problem solving, and communication, including inference of dynamic processes (Hegarty 1992; Hegarty and Sims 1994). Previous cognitive visualization research has focused mainly on identifying how humans make inferences from graphics (regardless of the graphic quality of the display) but has not necessarily looked at the possible interplay of humans' visual inference-making capacities (e.g., visual learning and reasoning) with external visual displays and their specific graphic characteristics (Zhang and Norman 1994; Scaife and Rogers 1996). This is particularly true for maps or GIS displays. Hegarty (2004) suggested three possibilities regarding the interplay between internal cognition (e.g., mental representations such as images) and external visualization (e.g., graphics, maps) in an educational/learning context:

1. External visualizations might act as a cognitive prosthetic for people with limited internal visualization capabilities. If this is true, people with low cognitive spatial visualization skills might benefit from well-designed external visualizations (Hegarty 2004).
2. Use of external and internal visualizations might depend on internal visualization. That is, a base capacity to internally visualize might be needed to take advantage of external visualizations. If this is true, people without internal visualization ability might not be able to take advantage of external visualizations.
3. External visualizations might augment internal visualization for all people, regardless of a person's individual cognitive skill base (Card, Mackinlay, and Shneiderman 1999; Thomas and Cook 2005).

The question remains as to how these three possibilities transfer into the exploratory geographic data analysis, learning, and spatial knowledge construction domains. Another important question is whether more abstract (i.e., thematic) maps improve a student's learning performance, for example, when dealing with intangible environmental processes (e.g., weather phenomena) or intangible societal diffusion processes (e.g., spread of disease). On the surface, one might generally argue that based on an already established 5,000-year-old success story of map existence and map use, humans have been quite successful at making inferences from and with maps. This study, however, aims to answer the fundamental research questions of how and why cartographers can augment (external) visuo-spatial displays to provide more effective and efficient map displays for visuo-spatial inference making.

We present a conceptual and methodological framework for investigating exactly how display design decisions compare with prior knowledge and training in influencing nondomain experts' attention and inference. This framework is supported by empirical data we collected on an inference task using complex weather map displays. We are particularly interested in how novices' viewing patterns are modified when thematically relevant items are made perceptually more salient through cartographic design for one specific inference task relating to (nontangible) weather phenomena. More generally, we investigate whether perceptually salient elements draw novice viewers' attention (bottom-up processing) or whether their attention is directed by domain knowledge of meteorology (top-down processing). We chose weather maps as test stimuli because of their potential complexity for spatial inference making (i.e., multivariate data sets) but also because of their attractiveness and wide dissemination through news media including the Internet (Monmonnier 1999). The simplification of mapped weather data through mimetic icons and bright and colorful designs follows the intuition that more attractive-looking weather maps would guide novice users in extracting the relevant information from complex map displays and thus facilitate inferences from complex dynamic weather phenomena. This is just one example of how designers try to modify the graphic quality of a display to facilitate visual inference making. We did not choose weather maps simply for their popularity or to test them specifically but because they are complex enough for spatial inference making. Our complex inference-making task and visually rich stimuli are contrasted by quite a few studies on graphics comprehension in cognitive science and psychology where this kind of work has been done with rather simple tasks (i.e., read-off of values) and on simple graphs with only a dozen or so data points (i.e., line or bar graphs).

Although we chose weather map displays for our study (Figure 1) as one typical example of commonly used maps, the methods employed are generic enough to be applicable to any spatial display (static or interactive)

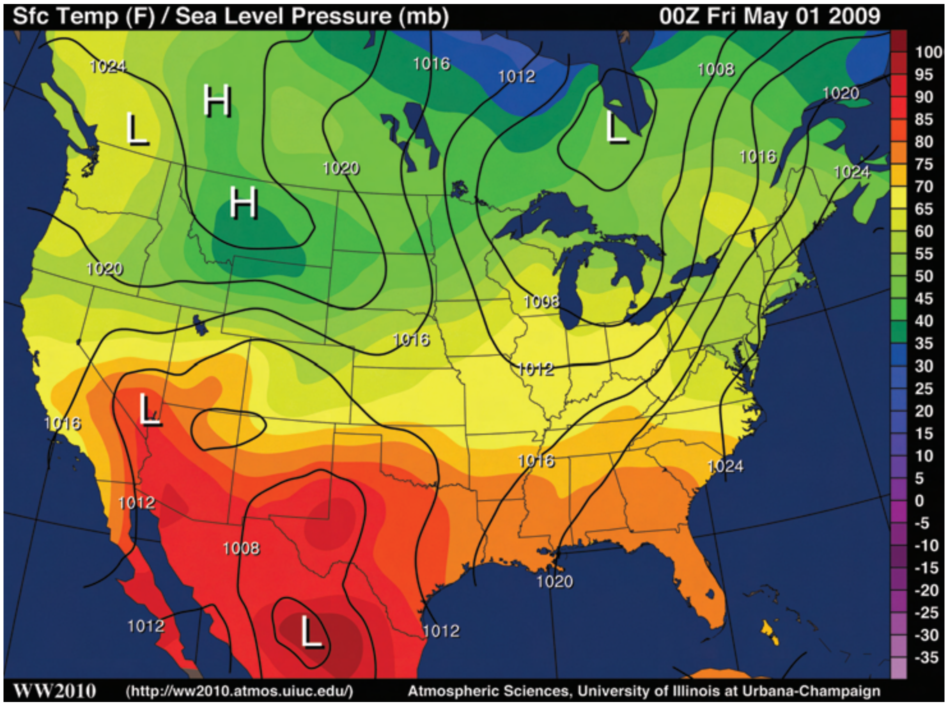


Figure 1. Typical mass media weather map display example. (© Atmospheric Sciences, University of Illinois at Urbana-Champaign. Used with permission.)

that might be produced by cartographers, graphic designers, and others.

Matching Perceptual Salience with Thematic Relevance

For a very long time cartographers have thrived in optimizing the representation of dynamic spatio-temporal phenomena with static, spatial representations in the form of two-dimensional maps (Bertin 1967, 1983). Cartographers have been applying a set of visual variables (e.g., size, color hue, color value, orientation, etc.) to mostly static 2-D maps to systematically match levels of relevant thematic information to a perceptual hierarchy based on figure–ground relationships (Bertin 1967, 1983). Today these visual variables not only represent the design foundation of all well-designed cartographic map displays (Dent 1999) but are seen more generally as the basis for any successful information visualization (Card, Mackinlay, and Shneiderman 1999).

Developing a visual hierarchy in map displays that is congruent with relevant thematic levels is a fundamental cartographic design task (Dent 1999). According to generic (and cartographic) design principles, a well-designed (cartographic) product's theme, purpose, and target audience should be known before it is created for maximizing effective and efficient communication, regardless of the target audience's expertise. According to MacEachren (1995), however, cartographic design theory has been subjected to only limited empirical verification. How can cartographers be sure that their designs are indeed cognitively inspired and perceptually salient? A design framework based on empirical evidence would certainly help cartographers and graphic designers to systematically evaluate their map products.

Domain-specific design conventions that might not be cognitively adequate or perceptually salient but have accumulated over time or in rapidly changing technological settings might also be issues to consider for certain (expert) audiences. Arguably, changing well-established design conventions might be often more problematic for expert users than for others. For example, for a long time meteorologists have been specifically trained on and use a well-defined set of symbols for their weather forecasts. Similarly, air traffic controllers are trained on and rely on a specific vocabulary of graphic codes displayed on their radar screens when guiding pilots.

Unfortunately, weather maps are rarely designed by cartographers and thus rarely follow long-standing and well-established cartographic design principles or specific design conventions. The relationship between

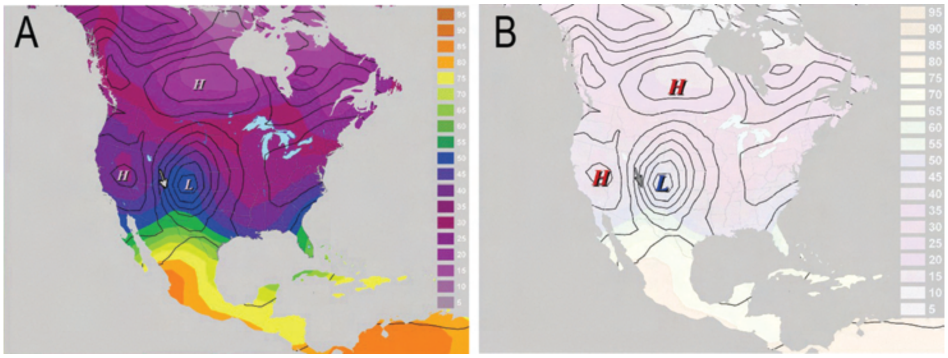


Figure 2. Two different map design solutions containing the same weather information. (A) Commonly used mass media map. (B) Cartographically modified map.

perceptual salience and thematic relevance in a static, 2-D weather map is illustrated in Figure 2.

The two map designs in Figure 2 are informationally equivalent; that is, they show the same thematic weather-relevant information (temperature and pressure). *Informational equivalence,* a term coined by Simon and Larkin (1987), expresses the idea that all information encoded in one representation is also inferable from the other, and vice versa. We posit that design decisions (i.e., relationship between thematic relevance and perceptual salience) affect *computational equivalence,* another useful concept proposed by Simon and Larkin (1987) for assessing the effectiveness of graphic representation for inference making. Two representations are said to be computationally equivalent when any inference that is easily and quickly drawn from the encoded information in one display can be easily and quickly drawn from the other (informationally equivalent) display and vice versa. They suggest, for instance, that the advantages of graphics over text in general are computational, not because they contain more information but because the presentation of the information can support extremely useful and efficient (computational) inference-making processes. We contend that by systematically making thematically relevant information perceptually salient for a particular inference task, display designers can facilitate useful and efficient (computational) inference-making processes.

Can we predict which parts of the displays would attract a nonexpert viewer's gaze based solely on design? Applying Bertin's (1967, 1983) visual variable theory, a cartographer might argue that the temperature in the mass media-inspired weather map (a) has more thematic emphasis, as the visually dominant color shading is perceptually more salient than the pressure gradient depicted with black isolines. In the cartographically modified map, (b) the pressure system dominates visually, and a viewer's gaze might be attracted to it by additionally contrasting the relevant pressure cells with highly saturated red (Highs) or blue colors (Lows) against the desaturated temperature color scheme. Assuming a task that depends on the information about pressure in the map (e.g., inferring wind direction, which depends on pressure), a cartographer could argue that Figure 2B is the more appropriate display. The thematically relevant information (e.g., pressure gradient) is purposefully made perceptually more salient through design by applying the visual variable color hue and size to the pressure system labels and by reducing color saturation of the temperature color scale.

To systematically investigate this design principle we adopt an interdisciplinary approach using experimental methods from psychology and cognitive science, but also grounding our work in a solid design framework borrowed from cartography. In addition to the commonly employed performance measures in controlled empirical experiments such as task response time (i.e., inference speed) and response accuracy (i.e., quality of inference), we measure eye fixations, which allow us to directly observe whether and how people's viewing patterns change when thematically relevant items are made perceptually more salient through design. A compelling advantage of eye-movement recordings, when compared to traditional experimental data (response time and accuracy), is that they provide relatively unobtrusive, real-time measures of visual attention and cognitive information processing (Henderson and Hollingworth 1998).

Eye-movement behavior reveals where people look on a visual display. By correlating the response pattern of the where (attention focus) and the what (information content at that location), one can more specifically evaluate design issues in a graphic display used for problem solving (Grant and Spivey 2003; Thomas and Lleras 2007).

Eye-Movement Analysis as a Window to Internal Visuo-Spatial Inference Making

Since the first half of the twentieth century, psychologists and other researchers have recorded human eye movements to learn about how people read texts and view various static graphic displays such as advertisements, works of art, charts and diagrams, and so on (Wade and Tatler 2005; Duchowski 2007). The basic principle of eye-movement studies is based on the fact that humans move their eyes over the visual field about three to four times per second. These eye movements are called *saccades*. Saccades are interrupted by phases where our eyes are relatively static, focusing on an object of interest. These static phases are called *fixations*.

Visual acuity is best at the center of one's retina, the fovea (Irwin 2004). People move their eyes so that the fovea (the center of highest acuity) is directed toward the location in the visual world to which they wish to attend or to visually process at the highest possible level of detail (Rayner 1992). Just and Carpenter (1976, 441) proposed the "eye-mind assumption," which states that "The eye fixates the referent of the symbol currently being processed if the referent is in view." Although there are some caveats to this assumption (Irwin 2004), it is still generally agreed that the location of a person's gaze is an indication of to what the person is currently attending. As people's gazes are an overt behavioral manifestation of attention allocation during visual inference making, cognitive scientists utilize eye-movement records to infer knowledge about the cognitive processes involved in various visual cognition tasks (Grant and Spivey 2003; Henderson and Ferreira 2004). Furthermore, cognitive operations involving visuo-spatial processing take place during eye fixations only (Irwin 2004), which makes eye-movement studies especially attractive for investigating spatial cognition issues in geography, GIScience, and related fields.

In recent research, Grant and Spivey (2003) argued that spatio-temporal eye-movement behavior literally embodies visuo-spatial inference making on graphic displays. In line with embodied cognition postulates (Wilson 2002), experiments by Thomas and Lleras (2007) offer strong support for the hypothesis that eye movements can act as an embodied mechanism to guide inference making and problem solving. Empirically validating and extending Grant and Spivey's (2003) ideas on the spatial reasoning–eye movement linkage, Thomas and Lleras (2007) were able to demonstrate that when actively guiding people's eye movements on a graphic display, by a secondary task, they could substantially affect people's chances of problem-solving success.

Figure 3 depicts how a participant's eyes moved over a map showing weather information during an inference

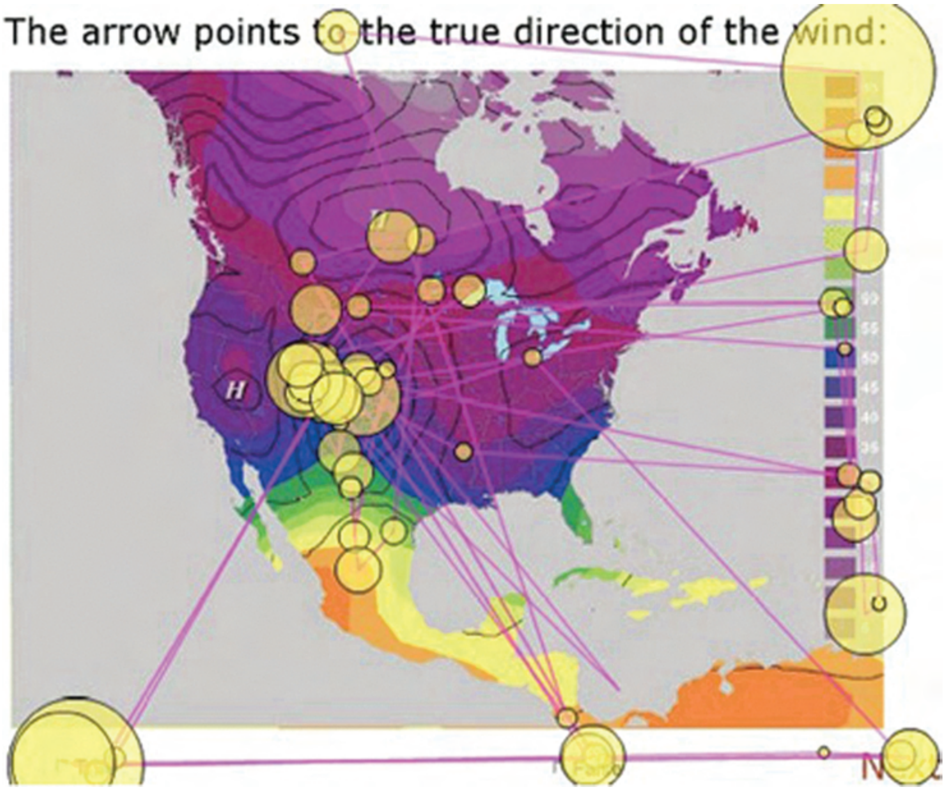


Figure 3. A gaze plot containing eye fixations and saccades overlaid onto a weather map stimulus.[1]

task. Eye fixations are shown with graduated circles (larger circles represent longer eye fixations). Eye movements between eye fixations (e.g., saccades) illustrate the viewing sequence and are depicted with connecting lines.

This example illustrates a typical finding that eye fixations are not randomly distributed over a scene. Since early eye movement studies on visual displays (Buswell 1935; Yarbus 1967), it has been known that people concentrate their fixations on interesting and informative scene regions (Henderson and Ferreira 2004). Only recently, however, have vision and cognitive researchers attempted to formalize and quantify interestingness or informativeness by looking at scene factors that might influence people's viewing behaviors. In one direction of this research, investigators have begun to build perception-based, neurobiologically inspired saliency models to predict human eye movements (Itti, Koch, and Niebur 1998; Itti and Koch 2001; Oliva and Torralba 2001; Rosenholtz et al. 2005; Torralba et al. 2006). Most of this work has been based on natural scenes containing real-world objects (sketches, line drawings, or photographs). The Itti, Koch, and Niebur (1998) model has been quite successful for simple displays used in attention experiments, but it has not shown encouraging results in predicting where people look in meaningful scenes (Henderson 2003; Torralba et al. 2006). Although this approach has not been fully tested on or validated against more abstract representations such as maps, diagrams, or other kinds of more abstract graphic displays, promise of the saliency map-based model for cartographic work has been demonstrated on static and dynamic thematic map displays (Fabrikant and Goldsberry 2005) and for remotely sensed images (Swienty, Kurz, and Reichenbacher 2007).

Cartographers utilized the eye-movement recording technique as early as the 1970s to investigate how people look at static maps (Steinke 1987). Cartographers were particularly interested in improving the design of their map products based on eye-movement research, thereby creating better and more user-friendly products (Montello 2002). After an increased interest in eye-movement studies on maps during the 1970s and early 1980s, the collection of eye-movement data in academic cartography has almost disappeared. Montello (2002) suggested that one of the factors might have been that eye-movement analysis tended to be very expensive and difficult to perform. Other critical voices argued that this kind of data collection technique did not tell mapmakers anything more than what they already knew and thus did not warrant the extra effort and expense (Montello 2002). A final reason for the limited success of eye-movement studies in cartography might have been that researchers tended to focus their studies on where people looked, rather than getting at questions of how and why or relating eye fixation behavior to specific tasks (Brodersen, Andersen, and Weber 2002). We suggest that to interpret eye fixations on maps, and understand at a process level why a certain cartographic display works better than another, cartographers need to frame their studies within cognitive theory, as we do here.

Saliency Assessment

To systematically investigate the cartographically inspired design assumptions made earlier, we first compared the maps on the basis of bottom-up models of visual salience (Itti, Koch, and Niebur 1998; Rosenholtz et al. 2005). The Itti, Koch, and Niebur (1998) salience model is a neurobiologically based bottom-up attention model that 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). Eye-movement predictions based on saliency maps (SMs) are driven entirely by preattentive processes and do not reflect cognitive (top-down) factors such as knowledge of the task, type of visual display, or domain knowledge (Henderson 2007). For our purposes, one function these models can serve is to validate that our display design solutions indeed vary in perceptual salience. They also offer predictions of the locations of eye fixations based on visual salience alone, but of course it is important to realize that with a meaningful task such as ours, there will also be top-down influences (Henderson 2007).

We applied the computer-based saliency models to systematically evaluate the salience of different types of information in the created map stimuli before running the experiment with participants. The Itti, Koch, and Niebur (1998) saliency model predicts eye movements based on the visual variables color hue, color value (intensity), and orientation. 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 nonlinear normalization

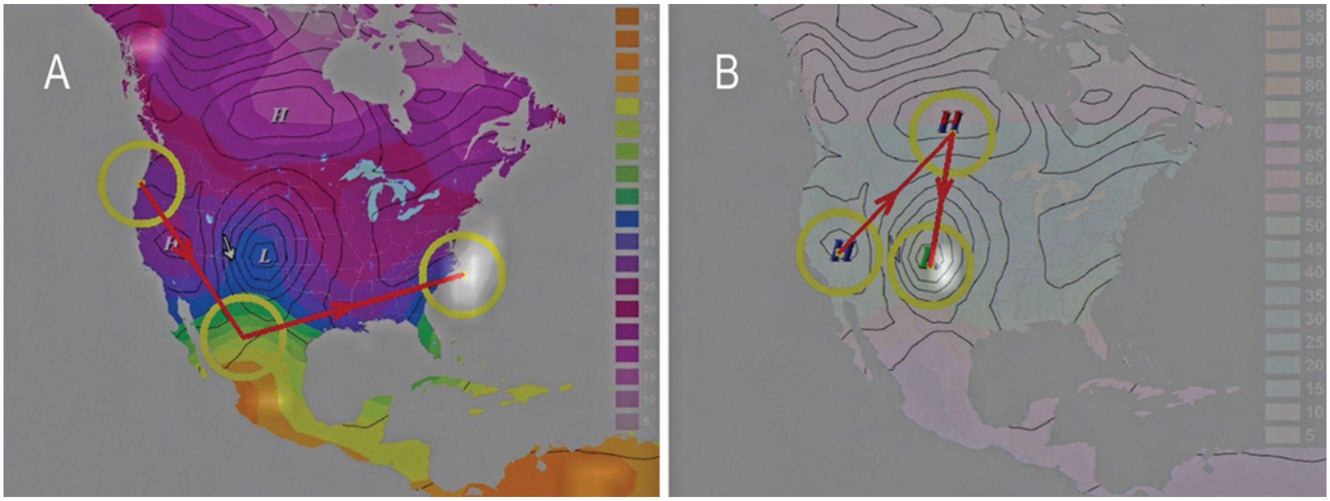


Figure 4. First three eye fixations predicted by a saliency-based attention model. (A) Mass media map. (B) Cartographically modified map.

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 SM of the visual scene. In Figure 4 we show an example of two SMs (with varying gray tones) overlaid onto two respective map stimuli. The more salient a map element (in Figure 4), the lighter its shade in the SM (i.e.,"spotlight" metaphor). In the mass media map (Figure 4A) the lightest zones are distributed in four disjoint areas over the map but not where the thematically relevant items (pressure systems) are located. In contrast, for the cartographic map (Figure 4B), the center of highest saliency (i.e., strongest visual contrast) seems to be only the zone where the three pressure cells and the arrow are located.

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 4 are derived from the grayscale SM. 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.

According to the model, the thematically relevant information (pressure) in the cartographically modified map (Figure 4B) is perceptually salient and thus is predicted to be fixated. Figure 4B is actually a special case, as the center low pressure system is so salient that the others do not show up in the SM. When looking at the predicted eye-movement sequence (based on the SM), however, all pressure systems are identified as salient and are predicted to be fixated. In contrast, none of the thematic relevant items are predicted to be salient in the mass media type map shown in Figure 4A.

The model results depicted in Figure 4 are gratifying for cartographers, as they suggest validity for the visual variables proposed by Bertin (1967, 1983) more than forty years ago. In other words, the intention of the cartographer to visually emphasize the thematically relevant pressure cells for the wind direction task using the visual variable color hue has been successfully validated according to the Itti SM model (i.e., by desaturating temperature hues and increasing color contrasts of the pressure cell labels).

We examined this prediction with another perception-based saliency model proposed by Rosenholtz, Li, and Nakano (2007). Their proposed feature congestion measure of visual clutter rests on the assumption that the more cluttered a display is, the more difficult it would be to add a new item that would reliably draw attention or, in other words, be salient. The clutter measure is based on a statistical saliency model, related to the local variability of color hue, luminance (color value), and orientation contrasts between items in a display, similar to those employed by cartographers (Bertin 1967, 1983) and in other SM models from vision scientists (e.g., Itti, Koch, and Niebur 1998). Specifically, the statistical saliency model is based on the idea of a feature space where the mean of a visual distractor distribution (i.e., color hue, color value, orientation, velocity, etc.) is compared with the value of a search target. The larger the difference between distractors and target, the more salient the target in a visual scene. The advantage of the Rosenholtz model is that it has been successfully validated with search tasks with

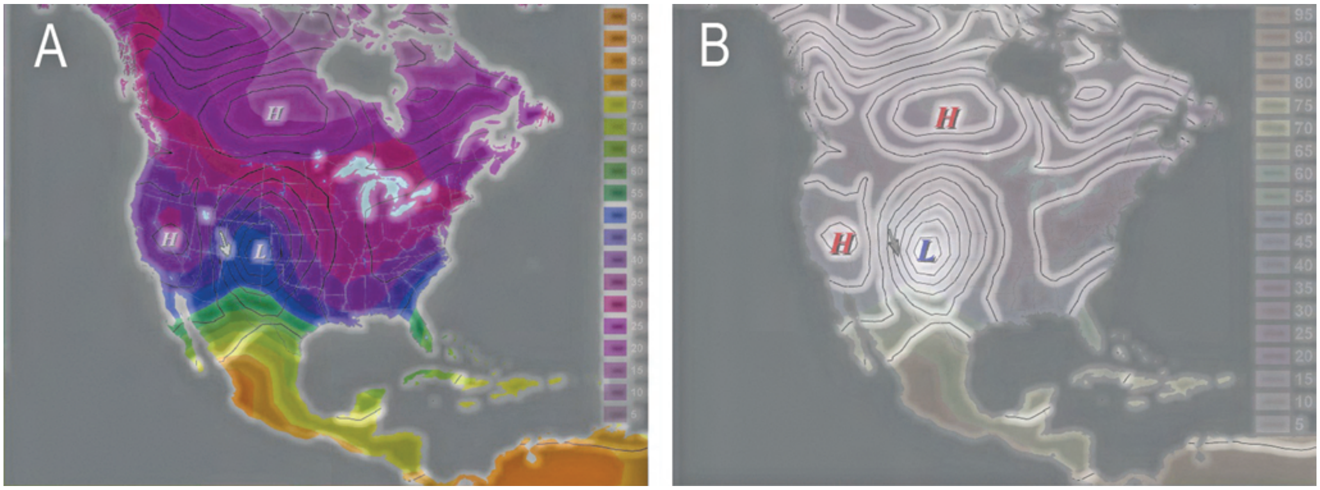


Figure 5. Clutter maps for (A) mass media map and (B) cartographic map.

meaningful displays, using a variety of graphic stimuli (Rosenholtz and Jin 2005), including even reference maps (Rosenholtz, Li, and Nakano 2007).

According to the clutter model that includes the saliency model, the mass media map is less cluttered with an average clutter value of 3.6 compared to 4.7 for the cartographically modified map. In other words, adding a salient graphic element to the cartographically enhanced map would be more difficult than for the mass media map. Salient, in this case, means that those high-contrast features—represented in lighter shades in Figure 5—are statistical outliers to the local distribution of features in the display. One can also see why this might be the case as shown in Figure 5. In Figure 5B the thematically relevant items such as the pressure cell labels, and even more so the isobars, fill the entire display space such that there would be little room to add another salient item. In Rosenholtz, Li, and Nakano's (2007) words, too many existing feature contrasts (i.e., in color hue, color value, and orientation) are already clamoring for attention. This is in contrast to Figure 5A, where more space for attention-grabbing items is still available; for instance, in the (darker) center and upper West parts of the American continent. In Figure 5B, the thematically relevant isobars vanish into the background due to lacking contrasts in color value and color hue. Although the thematically relevant pressure cells are salient, the irrelevant temperature legend also seems to unnecessarily attract a person's gaze.

The results in Figure 5 are again very encouraging for cartographers, to see that the thematically relevant features in Figure 2B were successfully made perceptually salient according to a second (statistical) SM model shown to be predictive of human's eye movements during visual search tasks on various images (Rosenholtz et al. 2005).

Supported by the already mentioned saliency models, cartographers potentially do have a sound theoretically motivated baseline at hand to develop map displays or visual analytic tool interfaces based on cognitive and perceptual principles. In a next step, we compare results from the computer-simulated models with behavioral data collected through an eye-movement experiment with human participants using the same map stimuli.

Experiment

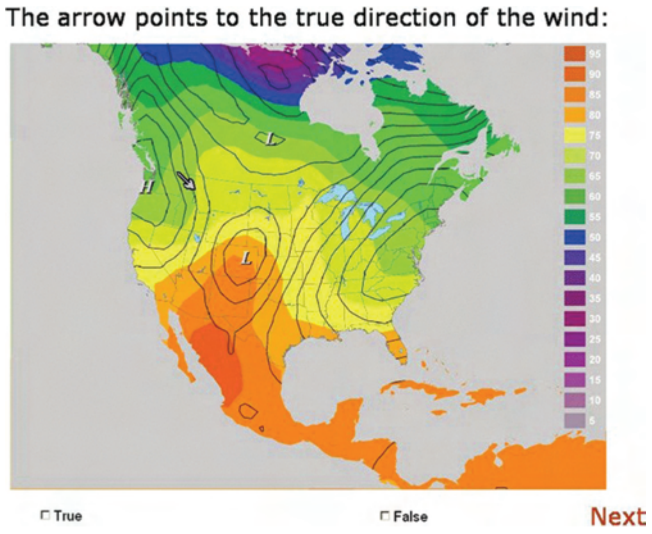
In an experiment, we asked novice participants to evaluate the veracity of the wind direction that is indicated by an arrow on weather map types such as those shown in Figure 2. Eye-movement and response data were collected for participants as they performed this wind inference task before and after training on meteorological principles. Half of the participants worked with the mass media maps and the other half worked with the cartographically designed maps. Thus, the experiment had a two (type of map) by two (before and after training) mixed factorial design. Based on the preceding discussion, we hypothesize the following eye-movement patterns:

1. Prior to training on the task-relevant weather principles, and thus less aware of which information is thematically relevant, novice viewers' attention (as

revealed by eye movements) will be attracted by salient items in the display (i.e., stimulus-driven, bottom-up factors). For instance, novice viewers' eye fixations in the mass media map condition will be attracted to the salient but task-irrelevant temperature legend, especially when temperature is more salient in the display. These predictions are suggested by the preattentive saliency models and by prior empirical research (e.g., Lowe 1999).

2. After training and demonstrating their knowledge of the task-relevant weather principles, viewers' attention will be directed to the thematically relevant items, regardless of their saliency (i.e., knowledge-driven, top-down). For instance, viewers' gaze in the mass media map condition will be attracted to the task-relevant items (i.e., closest pressure systems to the arrow) even if they are not salient.

We also predicted that the maps would not be computationally equivalent (cf. Simon and Larkin 1987), such that the cartographically enhanced map would be more efficient for inference making than the mass media map. According to the employed saliency models, the cartographic map matches thematic relevance with perceptual salience much more effectively than the mass media map. Thus, it should support more efficient (e.g., faster or more accurate) inference making.


The arrow points to the true direction of the wind:

☐ True ☐ False Next

Figure 6. Sample map stimulus, including test question and response boxes.

Method

Participants

Thirty students (thirteen male and seventeen female) from an undergraduate introductory human geography class, with a mean age of 20.1 years, took part in the experiment. They received a small amount of course credit in return for their participation. The test sample was judged to be a good sample of the desired novice user population, as the vast majority of the participants (72 percent) had not taken more than one geography class (including the first one they were just taking). On average, participants reported that they had used maps only occasionally and had never had training in meteorology, cartography, GIS, computer graphics, or graphic design.

Materials

Participants viewed computer displays that were created using Environmental Systems Research Institute's (ESRI; 2003) ArcMap. The displays consisted of full-color weather maps including surface temperature and pressure, inspired by weather maps similar to that shown in Figure 1. We chose actual weather data from the National Oceanic and Atmospheric Administration (NOAA)'s hourly NCEP/NCAR reanalysis Data Composites^2 on random days. For each display, participants needed to evaluate the possible wind direction that was indicated by a gray arrow. To determine whether the wind direction indicated was indeed the true wind direction, it was necessary for participants to use the display to obtain information about the pressure gradient, which was represented by black isolines, and the two or three neighboring pressure cells labeled H (High) or L (Low; see Figure 6). Wind direction can be inferred from surface pressure (thematically relevant information), but the temperature information is irrelevant for the task.

Participants' eye movements were recorded using an iView X RED II by SensoMotoric Instruments (SMI). The experiment was administered on a Windows 2000 Pentium IV personal computer using Microsoft PowerPoint to display the map stimuli and training materials on a 21-inch color monitor, at 1024 × 768 pixel spatial image resolution. The GazeTracker software by Eye Response Technologies (2003) was employed to run the SMI eye tracker. A standard mouse and keyboard were used to answer questions. Gaze recordings were recalibrated after data collection. This means that we were able to improve the accuracy of raw fixation locations after recording, to overcome initial calibration inaccuracies and accumulating drift error. Fixations were then extracted using eyeMAT, a Matlab toolbox codeveloped by one of the authors.[3]

Answers were recorded automatically and stored digitally, including the time required to respond to the questions. Response time was measured as the elapsed time in milliseconds between the trial display appearing on the screen and the participant proceeding to the next trial.

Procedure

Participants were randomly assigned to two map design conditions: mass media map or cartographic map, which varied in the visual salience of the task-relevant information. Participants were told they would be presented with two series of thirty U.S. weather maps, and that each map would include an arrow pointing in a possible direction that the wind might be blowing at that location. Participants were asked to determine whether the wind directions indicated by the arrows were true (correct wind direction) or false (wrong wind direction). They were also told that the maps included temperature information indicated by color and that the black lines represented pressure (isobars). They were told that their response would be timed but to take as much time as they needed to answer the questions as accurately as possible.

Participants then performed six practice trials to become comfortable with the test instrument and with having their eye movements tracked. For each weather map display, participants were asked to click on a True or False button in response to the statement "The arrow points to the true direction of the wind" (arrow verification task). Following the practice trials, they responded to the main test trials organized into two separate blocks, each including thirty different maps and true–false tasks. The presentation order of the map displays was varied systematically such that the pressure cell configuration changed in location and distance from the arrow. The orientation of the arrow (wind direction) was also varied systematically. Whereas in one third of the trials the arrow pointed in the correct direction of the winds, in the other two thirds of the trials the arrow showed an incorrect wind direction. Trials within each block were presented in one of three different randomized orders. The three display orders were systematically rotated through the participant pool to avoid potential order confounds.

After the first block of thirty trials, participants were trained on the principles of surface air movement (i.e., pressure gradient force, Coriolis force, cyclones, etc.). During this training phase participants read information and viewed diagrams that explained how to predict wind direction based on pressure gradient and knowledge of Coriolis force. After participants viewed the on-screen training materials on pressure gradients and Coriolis principles extracted from meteorology textbooks, the researcher led them through a set of exercises designed to check their understanding of the materials before the second block of trials began. For example, participants were given three practice problems on the wind verification task that were similar but not identical to the experimental task. Participants had to verbally explain their answers to the experimenter and received feedback on the quality of their answers. They were not allowed to continue with the experiment until the experimenter was satisfied with the correctness of their answers.

The participants were given the second set of thirty trials only after the experimenter felt that they had learned and understood the task-relevant weather principles. Participants' eye movements were not recorded during the training session. After completing the second block (including eye-movement recording) participants were debriefed, thanked, and marked down for credit.

Results

Whereas participants' accuracy on the inference task (i.e., wind direction assessment) was at chance prior to training for both map types, their accuracy improved significantly after training for both map types. Mean accuracy for both map type and training are shown in Figure 7. Accuracy scores were subjected to a two-way (mixed) analysis of variance (ANOVA) having two levels of training (within subject: pre, post) and two levels of map types (between subject: mass media, cartographic map).

The within-subject main effect of training yielded a significant effect, $F(1, 28) = 64.72$, $p < 0.001$, such that the percentage of correct responses was greater after training ($M = 0.74$, $SD = 0.13$) than before training ($M = 0.51$, $SD = 0.13$). The between-subject main effect of map type yielded an F ratio of $F(1, 28) = 0.315$, indicating that map design did not significantly affect the mean accuracy scores.

The pattern of participants' response times in seconds on the wind inference task is depicted in Figure 8. For the repeated-measures ANOVA on response time, there was a significant effect of training, $F(1,$

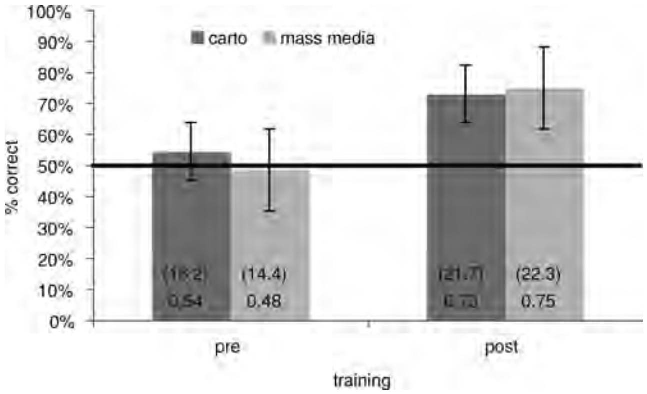


Figure 7. Mean accuracy on the wind direction task as a function of training and map type. The numbers in brackets show absolute number of correct responses (max. = 30). Error bars show standard errors.

28) = 14.38, $p < 0.001$, indicating that participants took significantly longer to respond after training (M = 265.03 ms, SD = 143.11) than before (M = 197.08 ms, SD = 87.32). The between-subject main effect of map type was also significant for this variable, $F(1, 28) = 7.81$, $p < 0.001$. Although participants in general took significantly longer to respond after training, they responded significantly faster with the cartographically enhanced map compared with the mass media map, as predicted. We did not find any correlation between response time and response accuracy.

The first step in the eye-movement analysis was the identification of areas of interest (AOIs) based on their relevance or irrelevance to the task. Pressure systems were selected as AOIs as they show high task relevance. The pressure systems decrease in thematic relevance with increasing distance from the gray (wind direction) arrow (Figure 9).

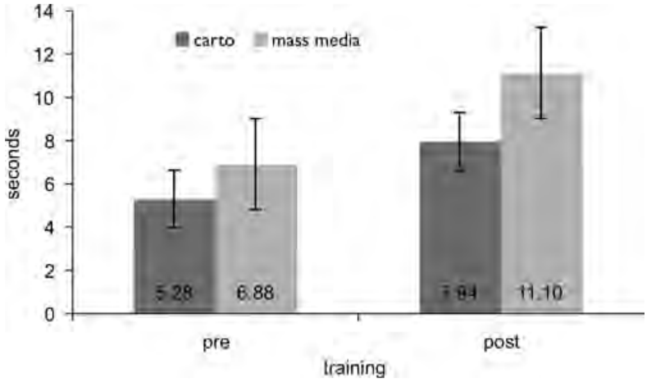


Figure 8. Mean response times on the wind direction task as function of training and map type. Error bars show standard errors.

The temperature information shown in the legend is also selected as an AOI. It is not considered task relevant. Although it is perceptually demoted in the cartographically enhanced map, the temperature legend is perceptually more salient (i.e., a distractor) in the mass media map (see also the darker gray shades in the Rosenholtz saliency model representing the legend in Figure 5A compared to Figure 5B).

We set the task-relevant AOIs to different sizes, depending on the display item.[4] We tested the stability of our results by varying the AOIs' sizes (i.e., pressure cells, etc.). As we specifically modified the pressure labels to increase saliency we chose AOI sizes that covered the labels well but did not extend too far. Based on available theory (Henderson and Ferreira 2004; Irwin 2004), suggesting fixation times between 50 and 300 ms for various viewing tasks, we determined a 100-ms threshold for a fixation for our study. Again, we tested the stability for our results by varying the sampling threshold.

Overall, participants spent more time looking at the closest pressure system (e.g., task-relevant information) after training (M = 43.86 ms, SD = 33.56 ms) than before training (M = 21.41 ms, SD = 14.15 ms). This increase is significant, $F(1, 28) = 14.67$, $p < 0.001$, indicating that participants spend more time fixating on thematically relevant task items after learning the weather principles. This pattern is also evident in relative terms. Before training, participants spent 10.8 percent of their fixation time on the closest pressure system (see P1-pre in Figure 10), compared with 16.4 percent after training (P1-post in Figure 10).

It is noteworthy that proportions of fixation times for the pressure system AOIs overall decrease with increasing distance from the arrow, in analogy to the first law of geography (Tobler 1970) that closer things are more related than distant things, even for inference making (i.e., a distance-decay process). Figure 10 depicts the proportions of fixation times for the examined pressure systems (P1–P3). P1 is the pressure system closest in distance to the arrow, followed by P2, and P3 is the farthest.

The proportion of fixation time increase as an effect of training is significant for pressure systems 1 and 2. This is true for both the mass media map type and the cartographic map (indicated with an asterisk in Figure 10). The fixation time proportion for pressure system 3 is very low (less than 3 percent) and this does not change significantly after training. We found no interaction effect of map type.

The main effect of training on the proportion of fixation time on the legend is also significant, $F(1, 28) =$

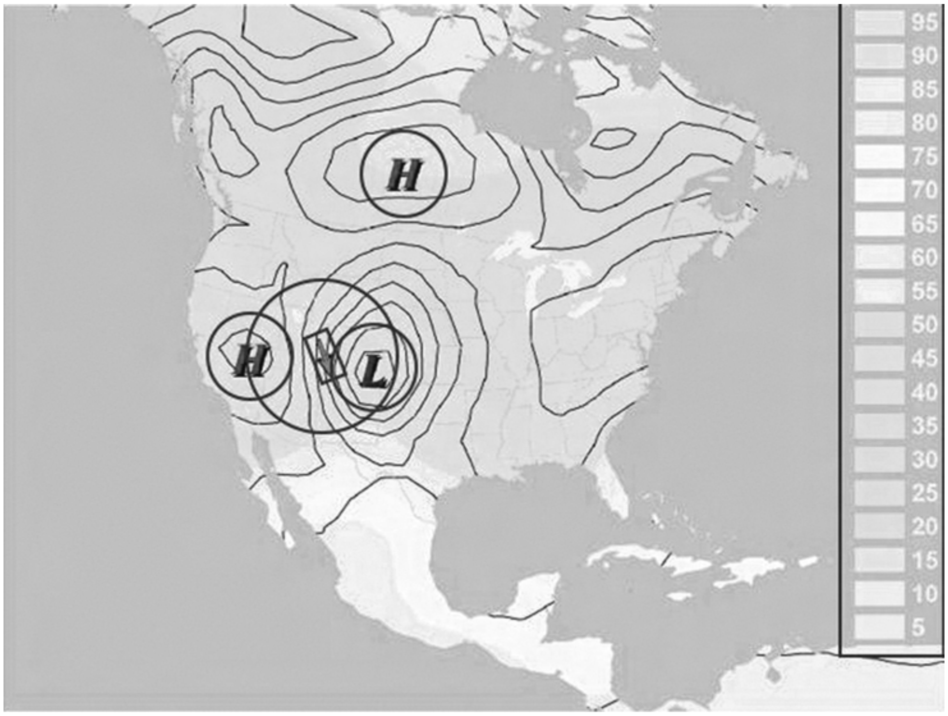


Figure 9. Selected areas of interest to analyze participants' gaze patterns during task completion.

8.28, $p < 0.009$. Task-irrelevant information such as the temperature legend is fixated significantly less after training—that is, not at all ($M = 0.002$, $SD = 0.005$)—than before training ($M = 0.02$, $SD = 0.03$; Figure 11). The same pattern is revealed when inspecting fixation time totals. Participants spend significantly less time fixating the temperature legend after training ($M = 0.85$ ms, $SD = 1.76$ ms) than before training ($M = 4.01$ ms, $SD = 8.79$ ms).

The interaction of training and map type is also significant, $F(1, 28) = 9.01$, $p < 0.007$, however, indicating that the fixation duration change on the legend between pre- and posttraining is significantly different for the mass media map compared to the cartographically enhanced map. In general, in the cartographic map condition the proportion of fixation time on the legend is significantly lower than for the mass media map. This proportion of fixation time is essentially zero on this map both before (0.0007; total time: 0.29 ms) and after training (0.0013; total time: 0.49 ms). The minimal increase after training is not significant. The proportion of fixation time on the legend in the mass

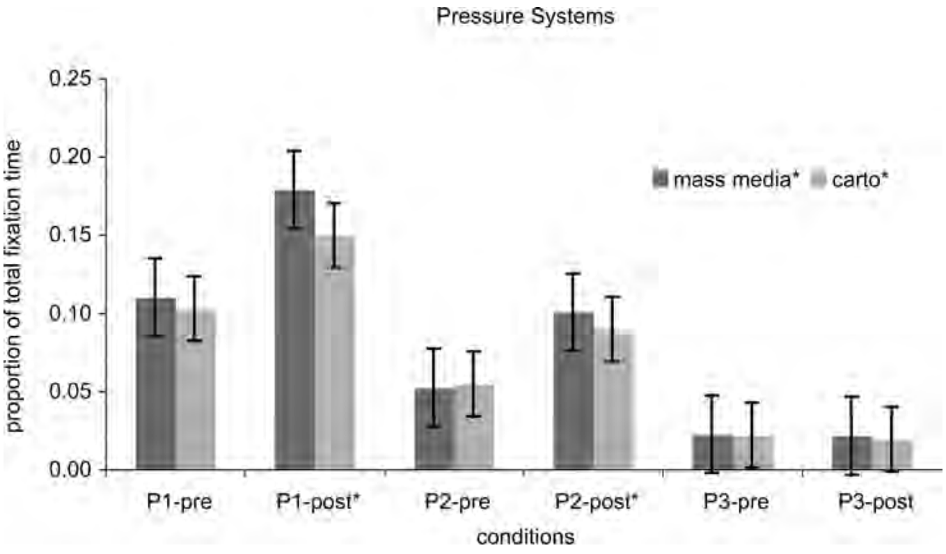


Figure 10. Proportions of fixation times for examined pressure systems (P1–P3).

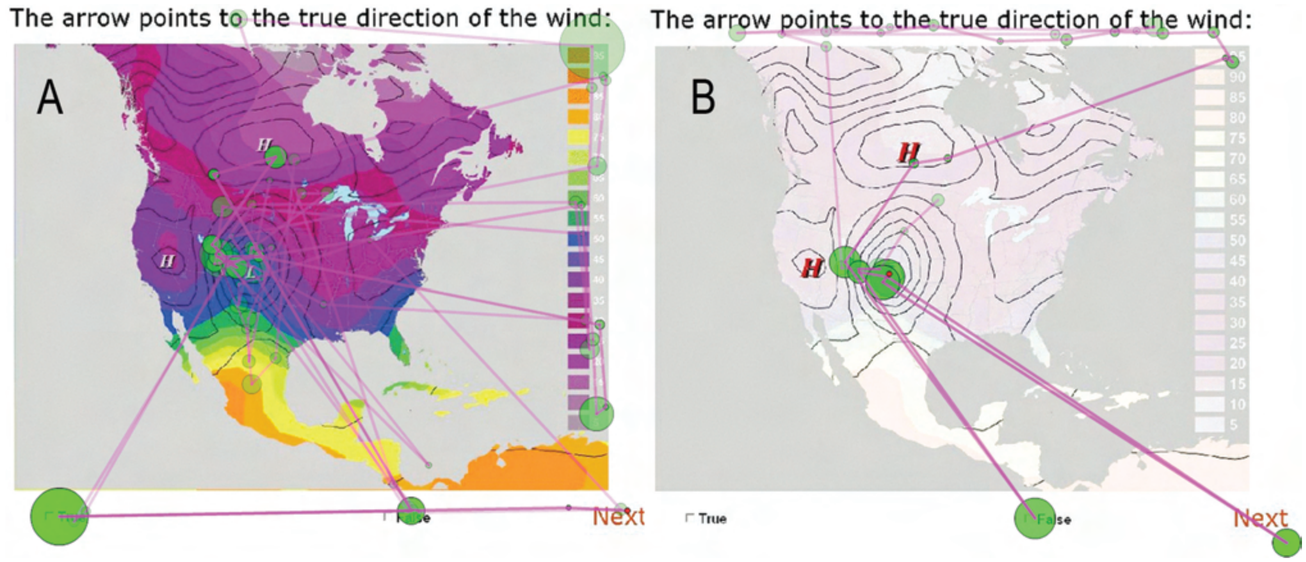


Figure 11. Prototypical eye-movement behavior during the pretraining phase for (A) mass media map and (B) cartographic map.

media map drops significantly from 0.03 (total time: 7.73 ms) before training to essentially zero (0.003; total time: 1.21 ms) after training ($p < 0.001$).

Discussion

To summarize the empirical results, accuracy of response (inference quality) increases significantly after participants learn the task-relevant weather principles. Participants' response accuracy does not depend on the type of graphic display they viewed. Overall, response time increases significantly after training. In terms of the eye fixation patterns, we find that participants spend more time fixating on thematically relevant task items (i.e., closer pressure systems) and less on task-irrelevant items (i.e., legend) after learning the weather principles.

The knowledge gain from the training session significantly and positively affected people's quality of inference. Whereas participants' accuracy was essentially at chance before training, it rose to 75 percent after training. The inference quality improvement is paralleled by a significant increase in response time between pre- and posttraining sessions. The observation that participants took almost twice as long to respond after learning the weather principles might seem counterintuitive at first, but it can be explained. Before training, and when they did not know the task-relevant meteorological principles, people probably guessed, so that they answered quickly but with low accuracy. After they learned the principles, participants needed more time to process the newly acquired information and to apply it correctly to the changing configurations shown in the various displays. Knowledge gain has not only significantly changed what people answer but also where people look in the display. Before training, perceptually salient items, such as the temperature legend, seem to have attracted novice viewers' attention more than less salient items, as predicted by the cartographic principles and validated with the preattentive saliency models. This was evident when the visual variable color hue indicating temperature was more salient in the display. In contrast, after training, and armed with new task-relevant knowledge, viewers focused entirely on the thematically relevant items (i.e., pressure cell closest to arrow) on the graphic display, regardless of their visual properties. It is noteworthy that this significant performance improvement was accomplished in only about ten to fifteen minutes of training.

Our results generally support the information-reduction hypothesis proposed by Haider and Frensch (1996), which states that the transition from novice to expert in a task involves learning to separate task-relevant from task-redundant information. This reduces potential information overload by limiting cognitive processing to relevant aspects of the task at hand. In eye-movement studies Haider and Frensch (1999) found that task-redundant information is ignored at the perceptual and not just at the conceptual level. Our results are consistent with this conclusion and suggest that good map design might even accelerate information processing for participants learning to become more expert, as further elaborated later.

Our results are also consistent with research by Lowe (1999) on animated weather map displays, in showing that participants tend to extract information based on perceptual salience rather than thematic relevance.

When comparing the Itti, Koch, and Niebur (1998) SM model predictions (Figure 4) with a typical sample of actual collected eye-movement data (as shown in Figure 11) one can see that whereas the collected gaze plot for the cartographic map matches the Itti prediction well, a viewer's gaze plot for the mass media map does not match the model prediction at all. The Rosenholtz, Li, and Nakano (2007) model shown in Figure 5 provides a better fit of empirical data for both map types. The Rosenholtz model has been validated with meaningful displays. This is in contrast with the Itti, Koch, and Niebur (1998) model, which has not always been a good predictor of eye fixations in meaningful tasks (Henderson 2003), so the Rosenholtz model might have more potential for use by cartographers in designing displays.

The significant difference in the inference efficiency (response speed) between the mass media map and the cartographic map is where the power of perceptually salient design lies in this study. In Simon and Larkin's (1987) words, our results show that the mass media map and the cartographic map differ significantly in computational equivalence. After training, inferences drawn from the cartographic map seem to have been made more easily and quickly than from the informationally equivalent mass media map. We contend that this is because thematic and task-relevant information is presented in a perceptually more salient manner. This efficiency gain from better display design must draw on an existent knowledge base. In other words, people need a relevant knowledge base for taking best advantage of the perceptually inspired display, conforming to Hegarty's (2004) relation number 2 that comprehension of external displays depends on internal cognition.

Conclusions and Outlook

We have presented a theoretical and methodological framework, grounded in cognitive theory and cartographic design principles, for constructing and systematically evaluating cognitively and perceptually inspired depictions for making spatial inferences with complex map displays. This framework combines the application of saliency models developed in research on human vision with the assessment of inference processes by combining traditional performance measures (accuracy and speed) with eye-movement recordings.

In the first phase, our framework employs stimulus-driven (bottom-up) saliency models for assessing the design quality of a graphic display and predicting eye-fixation patterns based on bottom-up stimulus factors alone. In a second step, the effect of top-down (cognition) factors on inference making is assessed through a controlled experiment, by comparing performance of individuals with more and less domain knowledge. Our empirical results suggest that good display design affects viewing behavior, especially for naïve participants who do not yet have the relevant domain knowledge. Moreover, matching thematically relevant information with perceptual salience significantly improves the efficiency with which people make inferences from graphic displays. With the collected empirical evidence we hope to have provided a better understanding of how good map design can help people extract relevant information from complex thematic maps and make inferences from these displays in the domain of meteorology.

Although visual attention involves a combination of bottom-up (stimulus-driven) processes and top-down (knowledge-driven) components, the predictions of solely bottom-up-based models seem to be promising for cartographers, as they provide a systematic approach to validate their map designs based on well-established but rarely empirically validated design principles (Bertin 1967, 1983). Cartographers can utilize saliency-based models to get a first insight into their design decisions and systematically assess effects of visual variables for the mapping task at hand. This study shows that both the SM approach and the measurement of eye fixations can be employed to systematically assess the utility of Bertin's (1967, 1983) system of seven visual variables widely used in cartography and more recently discovered in information visualization (Card, Mackinlay, and Shneiderman 1999). The visual variable system was developed specifically to help cartographers to better control the visual salience of symbols on maps. Until today, however, it lacked in systematical validation procedures, which we hope to have provided with this contribution.

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Notes

1. Gaze plots shown in this article (i.e., Figures 3 and 11) were visualized with a developed visual analytics tool called EyeView described in Grossmann (2007).
2. Available online at http://www.cdc.noaa.gov/cgi-bin/data/composites/printpage.pl/hour/ (last accessed 24 January 2009).
3. This Matlab toolbox was developed by João Hespanha of the Department of Electrical and Computer Engineering and Stacy Rebich Hespanha of the Department of Geography at the University of California, Santa Barbara.
4. For example, for the pressure systems we selected circles with a 92-pixel diameter.

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