Attention on Maps

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Wilson's (1998) notion of consilience among disciplines should be a goal for cartographers. Consilience requires important facts and fact-based theories to apply across disciplines. This paper reviews research on visual attention as an example of a topic shared by information science disciplines. Attention is considered as a competition between neural processes that allow information to be selected and emphasized for perceptual processing. Visual attention has been modeled as a spotlight, zoom lens, gradient, and multiple spotlights. It is argued that visual attention can impact multiple map reading processes and that cartographers can use knowledge about the effects of attention on map reading to design more effective maps. Attention can be directed to locations, objects, and features in the visual field and impacts performance on a variety of map reading tasks. Important general questions relating visual attention and map reading are stated and the literature providing answers discussed. The "dark side" of attention is also discussed and linked to the concepts of *inhibition of return*, *visual marking*, *inattentional blindness*, *change blindness*, and the *attentional blink*. Specific map-reading processes affected by visual attention are considered that include figure-ground segregation, visual search, and object selection and grouping. Research trends related to cartographic design and map reading are considered for these processes. Future cartographic studies are considered in four categories—vision before attention, vision with attention, vision after attention, and vision without attention. Understanding the role of visual attention in map reading should be a goal of cartographers interested in producing effective maps.

Key words: visual attention, map reading, figure-ground, visual search, perceptual grouping

INTRODUCTION

> *A united system of knowledge is the surest means of identifying the still unexplored domains of reality. It provides a clear map of what is known, and it frames the most productive questions for future inquiry* (Wilson, 1998, 326).

Consilience is the word Edward O. Wilson used to describe the unity of knowledge. His basic argument was that science should seek a unified knowledge "by the linking of facts and fact-based theory across disciplines to create a common groundwork of explanation" (Wilson, 1998, 8). If Geographic Information Science (GIScience) is to contribute knowledge to a united system of knowledge, we must understand our place within the larger system and know what common ground we share with sister information science disciplines. For example, information processing by humans can occur at various scales in space and time. Geographers tend to focus on certain scales and be less interested, or completely ignore other scales. Our distances are more likely to be measured in miles than in mil-

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limeters or light years. Our times are more likely to be measured in years than in milliseconds or eons. We also have a focused interest in methods for acquiring knowledge. Geographers are not the exclusive users of maps and the techniques of cartography, but "we" should feel responsible for their scientific advancement. Achieving the goal of consilience will require cartographers to rethink old ideas and explore new ideas. Visual attention is an important established concept in map design and map reading that is also a fundamental and extensively researched topic in other disciplines. A review of research on visual attention across disciplines can provide cartographers a current perspective on this important topic and make a small initial step toward consilience.

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The trilateral relationships illustrated in figure 1 shows the flow of information in a communication process between the maker (cartographer) and map on the left side of the triangle. Maps are designed and produced by professional cartographers using conventional wisdom.[1] Medyckyj-Scott and Board (1991, 91) suggested this conventional wisdom has primarily been based on the practice of a craft in the sense that cartography "solves its problems of map design by carrying out design and evaluation, the latter generally informally." Evaluations of productions can be done using any number of criteria.[2] The criterion appropriate for the current discussion is based on whether or not a map reader will be able to process the information on the map efficiently. The information flow between the map and map reader on the right side of figure 1 represents this process. If efficiency is achieved, the map reader should be able to acquire informa-

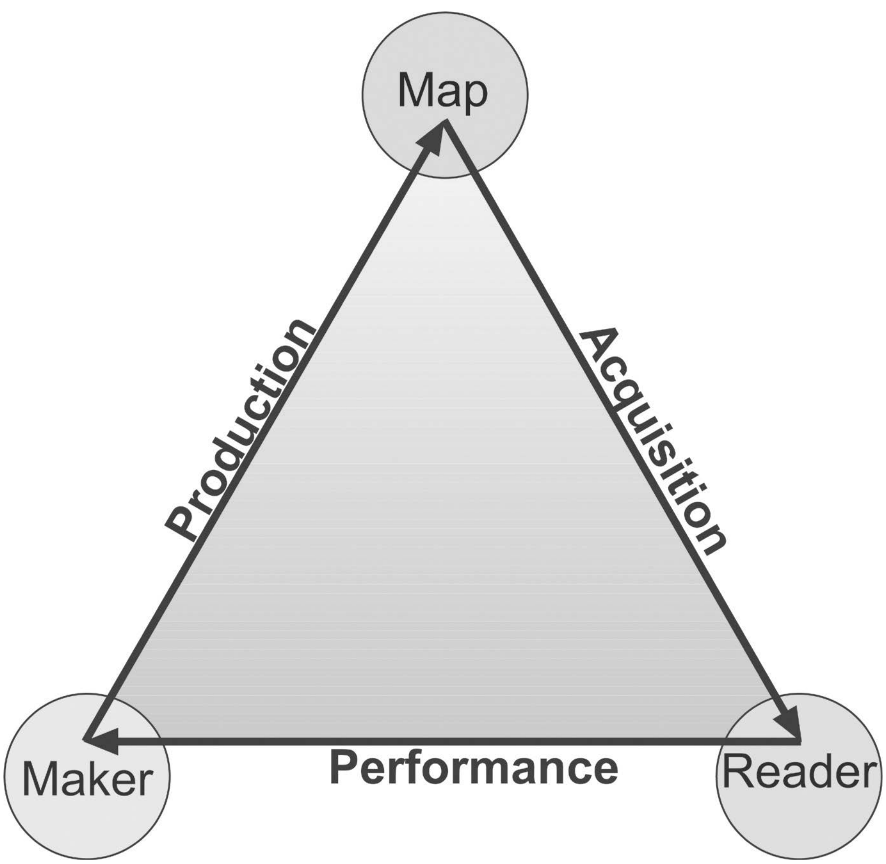

Figure 1. Trilateral relationships involving makers of maps, maps, and readers of maps.

tion from the map quickly, accurately, and confidently (Lloyd and Bunch, 2003).

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Most of the time, the production and acquisition processes are done independently. In these cases, the makers of maps will not know if their productions have resulted in efficient or inefficient acquisitions. Trial maps, however, can be produced as part of a planned experimental research design that would allow hypothesis testing. For example, two animation productions might be compared. Map readers might do a vigilance task that required them to respond by clicking a mouse every time a target map symbol appeared during an animation. If animation ***x*** has target map symbols with unique colors and shapes that provides a contrast with non-target map symbols and animation ***y*** has target symbols that share colors and shapes with non-target symbols, it might be hypothesized that the performance (reaction time, accuracy, and confidence) of map readers would be better with animation ***x***. This is because objects with unique characteristics are more likely to attract the map reader's attention. The performance results are represented as the flow of information between the map reader and map maker in figure 1. The map-maker can use significant patterns in the performance information to refine the subsequent and final productions of the animation. A new round of experiments might determine which unique colors or shapes allow the map reader to acquire information most efficiently.

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There is a shared interest by cartographic researchers and researchers in cognitive neuroscience and psychology in how humans process spatial information. If consilience is to be achieved for the information sciences, then compelling facts and theories developed in one discipline should also apply in sister disciplines.[3] I believe that cartographers could contribute to a greater degree of consilience if experiments leading to map readers acquiring mapped information with optimal efficiency were based on accepted facts and theories from these sister information sciences. Consilience, however, is not an easily achieved goal. A compromise must always be made between controlling the independent variables of a cognitive experiment, and the more complex realistic map. Cartographers who wish to do experimental research encounter a paradoxical situation, a "Catch-22", so to speak. Conducting meaningful experiments requires the researcher to control the spatial information displayed on the map, while real maps frequently have a large number of characteristics affecting efficient processing that cannot be controlled easily. The Catch-22 is that strong experimental controls and realistic maps are extremely difficult to be used at the same time in research designs. The choice would appear to be between studying controlled simplified situations that do not represent actual maps, or conducting experiments with real maps without being able to control or even identify many important variables that affect the acquisition of information from maps. Since most psychology studies that have used maps have tended to favor strong controls and sacrifice realism, it may be up to cartographers to draw the line of compromise. If the line is drawn nearer to the use of realistic maps, the loss of experimental control may result in meaningless experimental results. If the line is drawn nearer to complete control and oversimplified visual displays, the experimental results may say nothing about performance with realistic maps. Consilience progress from a cognitive cartographic perspective depends on doing experiments with as much control as possible with maps that are as realistic as possible.

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Visual attention is intuitively an important process related to map reading, but reviews of research in cognitive cartography suggest that researchers have not routinely considered attention directly in their studies (Lloyd, 2000; Montello, 2002). Although cartographers have discussed how graphic variables might interact with map readers' attention processes, relatively few hypotheses have actually been tested (Bertin, 1983; Shortridge, 1982; MacEachren 1995; Nelson, 2000a). The primary purpose of this paper is to review current literature related to visual attention and discuss how visual attention is connected to map reading processes. Attention can be directed to locations, objects, or specific types of features in the visual field that can potentially provide important information (Fernandez-Duque and Johnson, 2002; Itti and Koch, 2001). Attention might be directed by information already in memory (top-down processes) or by information being encoded from the map (bottom-up processes) (Miyashita and Hayashi, 2000; Sarter *et al.,* 2001). In most cases some combination of these two sources of direction are used to select information during a map reading task.

COMMON GROUND

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Figure 2 illustrates some processes that might be involved in identifying a target map symbol on a map (Lloyd 1997). A person is given the task of determining if map symbol **X** is on the novel map they are about to view, and making a response of either present or absent. When the map appears, the person first must segregate the figure of the map from the background. The global patterns might be accessible for processing first followed by local objects and their features. If the target is known to have certain features that might be useful for identification, objects with these features might be grouped for further consideration and objects without these features might be grouped and suppressed. If the target has a unique

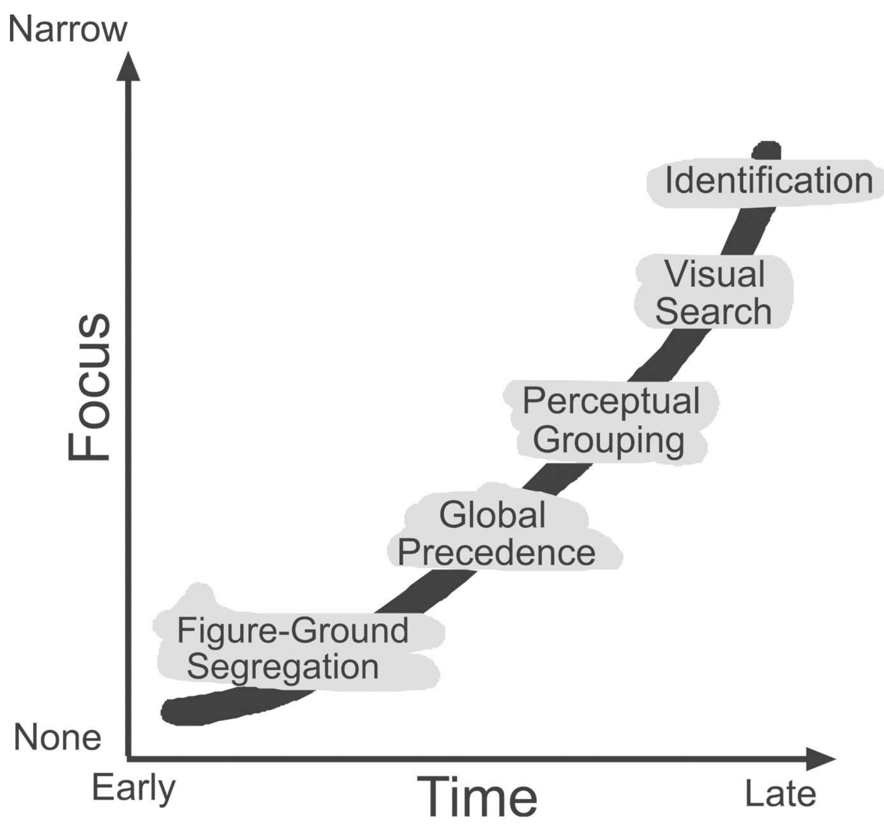

Figure 2. Processes the might be used to identify a target map symbol on a novel map.

feature, it might be identified quickly because it can easily be separated from all other objects. If the target shares one or more features with distractor objects, those grouped for further consideration can be selected for focused attention, one at a time, until the target is identified as present or absent. Information on the map and in a person's memory can contribute to visual attention as it might impact the various cognitive processes that occur between the onset of the map and the final decision.

SPATIAL ASPECTS OF VISUAL ATTENTION

A number of relevant questions emerge when considering attention's role in map reading. First, *what Is visual attention?* Attention can be related to any sensory input, but, for map reading, vision is paramount (Posner, 1994; Treue, 2003; Djordjevic *et al*., 2004; Tatham, 2004). Visual attention is a limited resource controlled by a number of distributed brain activities stimulated by visual input. "The term *attention* has been used for many different psychological, behavioral, and physiological acts and states, such as focused awareness and certain activated conditions of the nervous system. In this context, it may be expedient to define attention as a set of those neural functions by which sensory information is selected and emphasized for perception" (Kohonen, 2002, 9813). The human brain is a biological neural network with approximately a hundred billion neurons and a million billion connections between neurons (Damasio, 1999). Systems of neurons become activated as needed as we process visual information (Martindale, 1991). Although some cognitive processes operate outside our conscious awareness, at any moment in time we have a conscious awareness of information related to neurons activated above a threshold value (Posner 1994). Attention relates to a subset of our most highly activated neurons and the stimuli that inspired the high activation.

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What directs attention during map reading? Visual attention is directed in two basic ways. Sometimes attention can be directed consciously by the map reader using information already stored as prior knowledge in memory. This would be considered a top-down process because the critical information directing attention is coming from the map reader's memory. Vecera (2000) suggested it might be useful to think of top-down processes as driven by the goals of a person. For example, if a person is interested in finding names of capital cities among other cities on a map, she could direct attention only to star-shaped symbols on the map. Other times visual attention is directed by information found on the map. For example, a person viewing a map of a space to identify sight-seeing opportunities might attend novel locations specifically because they were unfamiliar. Vecera (2000) indicated bottom-up attention processes are driven by the stimulus. These are considered bottom-up processes because the critical information is the novel information being perceived at that moment in time by the map reader. Map reading frequently involves both types of processes that interact to achieve a specific goal. Unless the map being considered is a cognitive map that is completely stored in memory, some bottom-up processes are part of any map reading experience. Most top-down visual search processes are assisted by bottom-up information (Hodsoll and Humphreys, 2001) and most bottom-up visual search processes are assisted by top-down information (Turatto and Galfano, 2000). Even when a person is looking at a map of a novel space, he may be aided by memories of previous map-reading experiences, or previously learned knowledge of cartographic conventions.

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Visual attention impacts the efficiency of some very basic map reading processes. A map is easier to process if it has been designed so the figure and background are clearly defined (Dent, 1972; MacEachren, 1995). Cartographers have considered bottom-up principles when designing maps, but recent studies have suggested top-down processes may also affect figure-ground assignments (Vecera, 2000; Peterson, 2003).

Attention processes can affect what spatial information is considered and when it is considered. Sometimes a highly salient feature that pops out of the map captures our attention automatically. Objects having a unique shape, size, color, orientation, or texture on a static map can cause a pop-out effect (Johnson *et al*., 2001; Lloyd, 1997). Objects that suddenly appear or have a unique motion can cause a pop-out effect on animated maps (Peterson *et al*., 2002; Weidner *et al*., 2002).

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When does attention affect the processing of spatial information? Early theories of visual search argued for an initial stage of visual processing that would complete substantial parallel processing of the entire map and do pre-attentive processing of map features (Treisman and Gelade, 1980; Cave and Wolfe, 1990). Features here are defined as characteristics of objects, for example, a map symbol might be large, round, and red. In a later stage, focused attention would be used to inspect locations that were most likely to have a target object. This conforms to the *late selection* view of attention (Kanwisher and Wojciulik, 2000). A contrary view argues for *early selection*. This view argues that relatively little perceptual processing is carried out pre-attentively. It is thought that systems driven by top-down information can affect processing relatively early. For example, neuroimaging techniques have identified regions of the brain that operate on preferred stimuli such as faces (Eimer, 2000), places (Epstein *et al*., 1999) and houses (Aguirre *et al*., 1998a). These are examples of object-based attention (Sholl, 2001).

Downing *et al*. (2001) had subjects perform a number of tasks using pictures of faces and houses while monitoring these specialized regions of the brain using neuroimaging techniques. The authors were able to demonstrate that these specialized brain regions have an early contribution to both location-based and object-based attention. The most convincing evidence for *early selection* comes from neuroimaging studies that have indicated specialize areas of the brain activate in preparation for an expected, but yet unseen stimulus, when they are cued by top-down information (Hopfinger, 2000 & 2001; Shulman *et al*., 2002).

On what mapping units do attention processes operate? Early studies of attention used a spotlight model (Figure 3a) to describe attention (Posner *et al*. 1980). Any objects inside the spotlight were selected for attention and any outside the spotlight were suppressed. A variation on this model was the zoom lens model (Figure 3b) that allowed spatial resolution to be adjusted (Eriksen and St. James, 1986). The zoom lens model also implies there is a trade off between the intensity of the focus and the efficiency, i.e., processing time and accuracy, of the visual processing. One can focus attention on a small area with higher resolving power or on a large area with lower resolving power. Gradient metaphors (Figure 3c) have also been suggested where processing efficiency is high near the target location and gradually declines away from that point (Anderson and Kramer, 1993; Handy *et al*. 1996). Some studies have suggested the spotlight does not always apply because we sometimes do not attend to all the objects at the same location (Most *et al*., 2001; Simons and Chabris, 1999). Multiple spotlights that that can split attention have also been suggested as another model (Figure 3d) for visual attention (Hahn and Kramer, 1998; Awh and Pashler, 2000). Other studies have shown it is possible to attend to groups of objects spread across space based on their common features (Driver and Baylis, 1989; Kastner and Ungerleider, 2002). Recent research has also argued that discrete whole objects rather than locations or features sometimes capture attention (Driver *et al*., 2001; Sholl, 2001).

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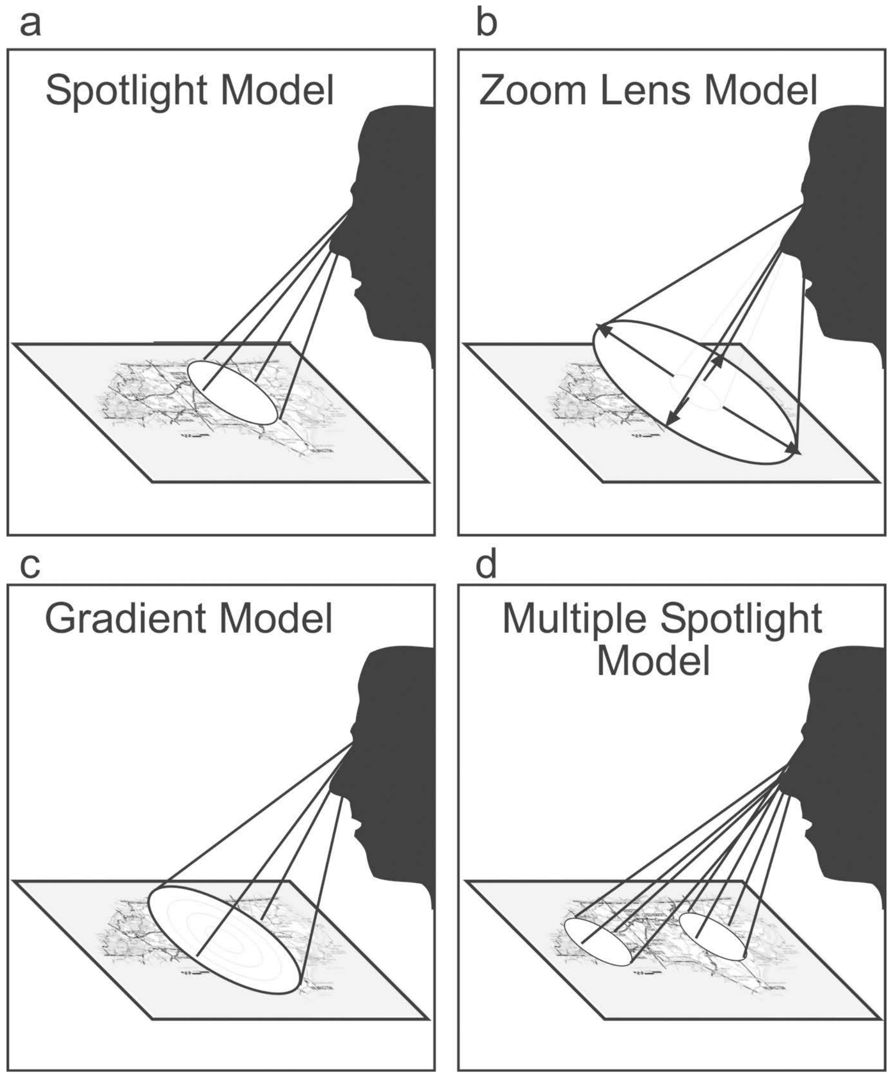

Figure 3. The spotlight (a), zoom lens (b), gradient (c), and multiple spotlight (d) models that have been suggested to represent possible allocations of visual attention.

"This biased competition *approach argues that many different brain systems compete to capture attention and the winners emerge to direct attention."*

Studies that have considered the neural mechanisms of attention suggest, "attention is an emergent property of many neural mechanisms working to resolve competition for visual processing and control of behavior" (Desimone and Duncan, 1995, 194). This *biased competition* approach argues that many different brain systems compete to capture attention and the winners emerge to direct attention. A review of neruroimaging studies has supported the notion that "competition may be biased in advance of stimulus presentation, by preparatory states that 'prime' representation of the target stimulus" (Driver and Frackowiak, 2001, 1259). Another review of neuroimaging studies concluded, "attention can under different conditions select locations, features, objects or a combination thereof" (Kanwisher and Wojciulik, 2000, 98). For a map-reading task, the competition among neural processes related to both top-down and bottom-up information should be biased by information related to the current task. Attention is directed to items that have characteristics processed by the winning systems and away from the items processed by the losing systems. The *biased competition* model has been applied to both selective attention for locations, objects, and features (Desimone and Duncan, 1995) and to the segregation of figure and background (Vecera and O'Reilly, 1998; Vecera 2000).

On what spatial locations can attention operate? Eriksen and St. James (1986) argued selected regions could be scaled like a zoom lens. The region selected for attention might be made relatively large to encompass a single large target or made relatively small to surround a very small target. Intriligator and Cavanagh (2001) investigated the spatial resolution of visual attention. Their experiments measured the smallest distance between objects that still allowed individual objects to be attended. Results suggested that the selection of attention has a coarser grain than visual resolution. At a fixed scale, you can see individual small objects, but cannot attend to them as individuals when they are located too near each other. This same study also reported the limits of selection increase away from a central fixation point, and that selection limits are less below the fixation point than above the point. This suggests one's ability to select attention is not uniformly distributed away from a central point of focus.

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Recent studies have suggested it is possible to divide attention and direct it as multiple spotlights under some circumstances. Hahan and Kramer (1998) conducted experiments with linear arrangements of stimuli that suggested multiple foci could be maintained as long as new distractors did not appear between the attended locations. They further considered if this was possible because the two spotlights were in different hemifields and, therefore, controlled by different hemispheres of the brain. Another experiment demonstrated subjects could maintain two spotlights within one hemifield. Awh and Pashler (2000) considered the possibility of multiple spotlights within a 5 X 5 array that was represented as a two-dimensional space. Each trial briefly displayed an array filled with 23 letters and 2 numbers. Numbers appeared at two pre-cued positions in the array on either side of a fixation point for valid cues. Numbers appeared at positions between the two pre-cued positions and on the other side of the fixation point for invalid cues. Subjects simply identified what numbers were displayed. The authors concluded, "it is possible for observers to achieve multiple foci of attention in the visual field" that had "a bimodal distribution of processing quality, in which accuracy was highest at two noncontiguous locations and markedly lower directly in between those locations" (Awh and Pashler, 2000, 845).

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McMains and Somers (2004) conducted functional magnetic resonance imagery studies that monitored brain activity while subjects performed tasks involving spatially separated stimuli. They found neural activation patterns that suggested subjects could maintain attention spotlights both across hemispheres and within hemispheres. They argued, "this provides direct evidence that spatial attention can select, in parallel, multiple low-level perceptual representations" (McMains and Somers, 2004, 677).

It has also been suggested that individual differences in allocation patterns are related to the amount of available working memory (Kane *et al*., 2001). Bleckley *et al*. (2003) presented results suggesting that individuals with a low working memory capacity allocated attention as a spotlight while individuals with a high working memory capacity showed a more flexible allocation of attention.

THE DARK SIDE OF ATTENTION

Chun and Marois (2002) argued that visual attention has a bright side and a dark side. The bright side is that attention improves access to important information that can be used to complete a task or solve a problem. The dark side is that the selection of a part of the total information available in a visual field such as a map may result in other potentially important information being missed. A number of research categories are briefly reviewed here that considers the dark side of visual information processing.

Inhibition of Return: As the focus of attention is shifted on a map the effect of that attention may still influence how one processes information. A large number of studies have reported on the inhibition of return effect (Klein, 2000; Samuel and Kat, 2003, Los, 2004). Wright and Richard (2000, 2351) indicate, "Inhibition-of-return is the process by which visual search for an object positioned among others is biased toward novel rather than previously inspected items. It is thought to occur automatically and to increase search efficiency." This suggests map readers should have a natural inclination not to return to locations they have already considered with focused attention. This bias toward novel information may have a dark side if previously considered locations or objects on a dynamic map later happen to contain important information. Cartographers could perform an experimental study that would test the hypothesis that new target objects on a dynamic map would be found more quickly if it occupied a previously unoccupied location rather than a location previously occupied by a non-target map symbol.

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Visual Marking: A concept related to inhibition of return has been called *visual marking* (Watson and Humphreys, 1997; 1998). Watson and Humphreys (2000) found that probes falling on old locations were more difficult to detect than probes falling on new locations. They concluded there was an intentional rather than an automatic bias against old items. Olivers and Humphreys (2003) considered if the inhibition of old locations could carry over from trial to trial. They used a preview task that had the old items differ in color from new items. Later trials presented without the preview were faster when the trials had items with the same color represented in earlier preview trials. Cartographers might be able to determine if visual marking is an automatic bias or a learned strategy using a search task on a dynamic map. An automatic bias should have the same effect on early and late trails, while a learned strategy should affect early trials less than late trials.

Inattentional Blindness: When salient and distinctive objects unexpectedly appear on a dynamic map, studies have shown such objects may frequently be missed when an observer is focusing attention on some other object or event (Simons and Charbis, 1999; Simons, 2000; Mack, 2003). These studies make a distinction between explicit attention and implicit attention capture. In a dynamic map reading context, studies of explicit attention could consider the likelihood that potentially relevant, but unexpected map symbols will be noticed, while studies of implicit attention could consider the likelihood that expected, but irrelevant map symbols can be ignored. An explicit attention capture would imply an awareness of the map symbol, while an implicit attention capture would imply an impact on the performance of a task without explicit awareness. Lavie (1995) argued the cognitive load associated with a perceptual task determines the amount of implicit processing associated with unattended objects. Only attended objects are processed with higher cognitive loads, but unattended objects are also processed with lower cognitive loads. Most *et al*. (2001) reported the likelihood of attentional capture for a suddenly appearing object was increased if its luminance was similar to attended objects and dissimilar from ignored objects. It was argued that subjects developed an attentional set for luminance and were able to ignore other dimensions, e.g., shape, that might also distinguish the suddenly appearing object from other objects.

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Contextual Cueing: Another example of implicit spatial learning related to map reading has been called *contextual cueing* and demonstrated by Chun and Jiang (1998; 1999; 2003). The basic argument is that a consistent spatial context can be implicitly learned, and having this knowledge will make visual search more efficient. Chun (2000, 171) suggested, "contextual information provides useful constraints on the range of possible objects that can be expected to occur with that context" and "contextual information allows perceivers to benefit from the fact that the visual world is highly structured and stable over time." Jiang and Wagner (2004) argued the memory of individual distractor locations and configurations of distractor locations are learned in *contextual cueing*. They reported the search for shape targets could be improved by *contextual cueing*, the relative locations of objects were learned, and the knowledge transferred to rescaled, displaced, and perceptually regrouped displays. Other research has strongly suggested spatial contextual information is implicitly learned during the performance of search tasks and that these long-term memories can persist for some time (Chun and Jiang, 2003). Olson and Chun (2002) reported evidence that the implicit learning of spatial context information is constrained by perceptual grouping. They indicated that grouping by spatial proximity significantly reduced search times, but grouping by non-spatial features such as color did not produce a similar benefit.

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Change Blindness: Map readers are likely to fail to detect changes in dynamic maps for a number of reasons. Changes on a dynamic map might occur during eye-movements, blinks, and blank screens or in locations away from focused attention (Simons, 2000). Simons and Levin (1997, 261) defined *change blindness* as, "the inability to detect changes to an object or scene." Their review of the *change blindness* literature suggested the visual system encodes the many details of perceptual experiences for an instant, but does not integrate more than the gist of the details from view to view. This is done to provide the viewer with stable impressions over time rather than chaos, but causes viewers to miss many changes. Changes to centrally attended objects are more likely to be noticed, but are also often missed. Simons and Levin (1997, 267) suggested, "attention is necessary, but not sufficient, for change detection." Cartographers might use a dynamic map that featured potential change blindness situations to consider if specific changes were missed while accurate general impressions were being learned.

On the bright side, Thornton and Fernandez-Duque (2002, 99) reviewed converging evidence and concluded, "that changes can be registered by the visual system and can influence behavior even in the absence of conscious awareness." This suggests map readers viewing dynamic spatial displays may implicitly learn information from the experiences that could influence decision making even though they were not conscious of the learned information.

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Attentional Blink: Map readers may also fail to attend to information on dynamic maps when information comes in rapid succession. In a map-reading context, a second target map symbol that is presented at the same location within half a second of a first target map symbol is likely to be missed because of an *attentional blink* (Raymond *et al*. 1992; Shapiro *et al*. 1997; Kellie and Shapiro, 2004). The typical experimental design used to study *attentional blink* is called rapid serial visual presentation (RSVP). A sequence of frames is presented as a continuous series that contains one or two frames with targets and blank frames (masks) or other non-target objects. Subjects are required to view the sequence and determine if the target or targets are present or absent. A review of explanations for this effect found a common theme indicating the second target was missed because a limit resource was not available to process the second target (Shapiro *et al*. 1997). Awh *et al*.(2004) reviewed literature that reported the *attentional blink* effect for a variety of target types that included letters, numbers words, shapes, colors, and orientations. They conducted a number of *attentional blink* experiments that used faces as targets and reported faces sometimes could be identified accurately as second targets without the *attentional blink* effect. It was argued that stimuli with spatial patterns such as faces are processed using both holistic configural information and individual feature information. If the feature channels were occupied processing the first target, the configural channel would still be available to identify the second target. Cartographers could easily study this notion because maps and some map symbols also have both spatial patterns and features.

Folk *et al*. (2002) were able to demonstrate what they called a *spatial blink.* Their results indicated that even when one is certain that a target will appear in a specific location in a dynamic display, the appearance of a distractor stimulus at a peripheral location captures attention if the distractor stimulus shares a feature such as color with the target. If someone is set to consider the presence or absence of a red target at a particular location, the shift of attention to another location having a red stimulus increases the likelihood a briefly presented target will be missed.

"Kahneman et al.'s *object file theory argued that when a new object appears and captures our attention, we create a temporary object file in working memory to keep track of the object."*

Kahneman *et al.'s* (1992) object file theory argued that when a new object appears and captures our attention, we create a temporary object file in working memory to keep track of the object. When this viewed object appears to change locations, as in an apparent motion animation, or changes features over time, the data associated with the file is reviewed. This could result in the data encoded about the object being updated if changes are appropriately small, or a new object file being created for a second object if the changes are sufficiently large.

Raymond (2003) claimed that new objects not new features trigger the *attentional blink*. Her experimental results indicated that an *attentional blink* occurred when the first and second targets were different objects, but not when they were the same object with different features. This would be the expected result if the resources needed to create a new object file in working memory were significantly greater than the resources needed to update the data for one object file. Cartographers could easily test this expectation with object files representing map symbols on a dynamic map.

Kellie and Shapiro (2004) morphed one object (smoking pipe) into another object (cooking pot) to test the hypothesis that this process would give the impression of a single object being smoothly transformed and, therefore, not create an *attentional blink*. This was verified and explained by the notion that only one object file needed to be created and updated when viewing the morph animation. When the same frames created for the morph were presented in a scrambled order, this created a demand for more object files, and created an *attentional blink* effect. An inverse relationship was reported between object file contiguity and the magnitude of the *attentional blink* effect.

VISUAL ATTENTION RELATED TO MAP-READING PROCESSESS

Cartographers have considered visual attention as part of processes such as the discrimination between figure and ground, spatial search for map symbols, and object selection processes (Dent, 1972; Lloyd, 1988; Nelson, 1999). Such processes generally reflect hierarchical organizations in both space and time. An early temporal and broad spatial process is the discrimination of the figure (the important area or areas on the map that need to be viewed) from the background (the unimportant area or areas on the map the do not need to be viewed). A serial search for a target map symbol is a middle-level process in space and time. A serial search process would occur after figure-ground segregation and throughout the area of the map that is considered the figure. Objects such as map symbols are selected during later stages of processing, grouped, and narrowly viewed to access meaningful information.

Figure and Ground: The earliest visual processes generally used when reading maps are discriminations of figures from backgrounds. "These visual processes are important because figures form the basis of much visual processing — humans are more likely to recognize and act upon figures than backgrounds" (Vecera *et al*. 2004, 20). Cartographers have discussed the importance of their responsibility to help map readers quickly and accurately distinguish figure from ground. Earlier discussions by cartographers have emphasized both the importance of creating visual hierarchies on maps, and the effects of principles argued by *Gestalt* psychologists (Ellis 1955; Wood, 1968; Dent, 1972). For a discussion of specific *Gestalt* principles related to map reading see MacEachren (1995). A number of early studies noted that figure-ground ambiguity on maps might occur when there is competition between effects, such as value and texture, that differentiate one area on a map from another (Dent, 1972, Head, 1972, Lindenberg, 1975). MacEachren and Mistrick (1992, 91) considered the role of brightness in figure-ground assignments and reported, "neither light nor dark areas are seen as figure if all other things are equal, and that knowledge of which area is land does not dictate that land will be seen as figure." The inability of labels to affect figure-ground segregation would seem to support models that postulate figure-ground assignments precede the focused attention required to read labels.

"The earliest visual processes generally used when reading maps are discriminations of figures from backgrounds."

Theories that argue for hierarchical stages in vision support the notion that the assignment of figure and ground is completed in parallel across the entire visual field before higher-order processes such as focused attention or object identification are initiated (Neisser, 1967; Marr, 1982; Biederman, 1987). Peterson and Skow-Grant (2003) referred to the notion that figure-ground assignment always precedes access to object memories as the *figure-ground first assumption*. The *figure-ground first assumption* leads to two important predictions. First, memory for a shape should not affect a figure-ground assignment because the assignment is assumed to precede any visual attention processes that could be used to match objects in memory. Studies, however, have produced results that indicate object memories are accessed before the assignment of figure and ground is completed (Peterson, 1994; Vecera and O'Reilly, 1998). Peterson (1999) argued object recognition occurs prior to figure-ground segregation. It was hypothesized that pre-figural processes operate on edges to recognize objects, and that this recognition then affects the assignment of figure and ground. Vecera and O'Reilly's (1998) computational model based on parallel distributed processing is slightly different. The model hypothesizes top-down information from internally stored object memories and bottom-up information from the edges present in the visual field are simultaneously processed to affect figure-ground assignments. This view argues for a biased competition between the "bottom-up information carried by the physical stimulus and top-down information based on observer's goals" (Vecera, 2000, 353).

"Theories that argue for hierarchical stages in vision support the notion that the assignment of figure and ground is completed in parallel across the entire visual field before higher-order processes such as focused attention or object identification are initiated."

"Studies, however, have produced results that indicate object memories are accessed before the assignment of figure and ground is completed."

If figure-ground assignments are assumed to precede object processing, it is also predicted that exogenous cues directing visual attention would not influence the initial figure-ground assignment on a map when it first appears to be viewed. For example, if an area on a map has a built in figure bias cause by a *Gestalt* principle such as *good continuation* or *closure,* precueing a background location on the map as the map initially appears on a Web page should have no influence on the initial figure-ground assignments. In other words, precueing the ocean could not shift the initial figure assignment from a continent to the ocean if the map was designed using *Gestalt* principles to show the continent as figure and ocean as background.

Vecera and O'Reilly's (1998) alternate theory suggests original *Gestalt* principles biasing figure-ground assignment can interact with visual attention to affect the initial figure assignment. An experiment to test the theory showed a display with convex and concave shapes that had different colors and a common boundary (Vecera *et al*., 2004). *Gestalt* principles would predict the convex shape would appear as the figure and the concave shape would appear as the background. A significant interaction effect indicated that the biased response for the convex shape as figure was reduced when the concave shape was precued. This result was interpreted to mean that "exogenous spatial attention can compete with image-base *Gestalt* cues in figure-ground assignment (Vecera *et al*., 2004, 25). This indicates that a cartographer presenting a map on a Web page could enhance the likelihood that subjects would segregate the region intended as the figure by marking it with a precue as the page loads.

"This indicates that a cartographer presenting a map on a Web page could enhance the likelihood that subjects would segregate the region intended as the figure by marking it with a precue as the page loads."

Global Precedence: Another interesting hierarchical effect has been called *global precedence* (Navon, 1977). See Kimchi (1992) or Navon (2003) for reviews of the *global precedence* literature. The original hypothesis was that global information is available earlier than local information. The basic issue was whether one sees the forest before one sees the trees. Compound stimuli were typically used in these studies. Examples could be large letters made from small letters or a large state made from small states (Figure 4). Other designs have considered global information in photographs as low-frequency information and local information in photographs as high-frequency information (Loftus and Hartley, 2004). For example, an original aerial photograph (Figure 5b) of an orchard might be separated into global information that shows broad homogeneous regions (Figure 5a) and local information (Figure 5c) that shows the details of linear features.

The general finding was that letters could be identified faster at the global level than at the local level (Navon, 1977). Distracting information related to global shapes also was found to affect the processing of local shapes, but distracting information related to local shapes did not affect the processing of global shapes (Miller and Navon, 2002). Navon (2003) suggested two issues are important. He called one the *disposition issue* and the other the *prevalence issue*. He suggested the *global precedence* effect is a competition between two constituents. The *disposition issue* is concerned with whether or not human perceptual systems have an inherent predisposition to favor global constituents. The *prevalence issue* is concerned with whether or not most real world global patterns are able to win biased competitions with local constituents.

Global precedence should be particularly interesting for those who make and use real world graphics such as maps. If the human perceptual system has an inherent predisposition to process global information first, then map readers should process the patterns on maps made by the cartographic symbols before they process the individual symbols *ceteris paribus*. The *prevalence issue* is somewhat in doubt for map reading because cartographers cannot control the nature of global patterns on maps as well as they can control the nature of local map symbols. Similar to processes that segregate a figure from the background, the biased competition between the global pattern and local objects in the figure has been argued by some to take place before attention is focused, and by others as directed by attention (Navon and Pearl, 1985; Rock and Mack, 1994). Since the degree to which the global configuration is well organized and matches a familiar pattern in memory seems to affect the advantage of the global pattern,

"Global precedence should be particularly interesting for those who make and use real world graphics such as maps."

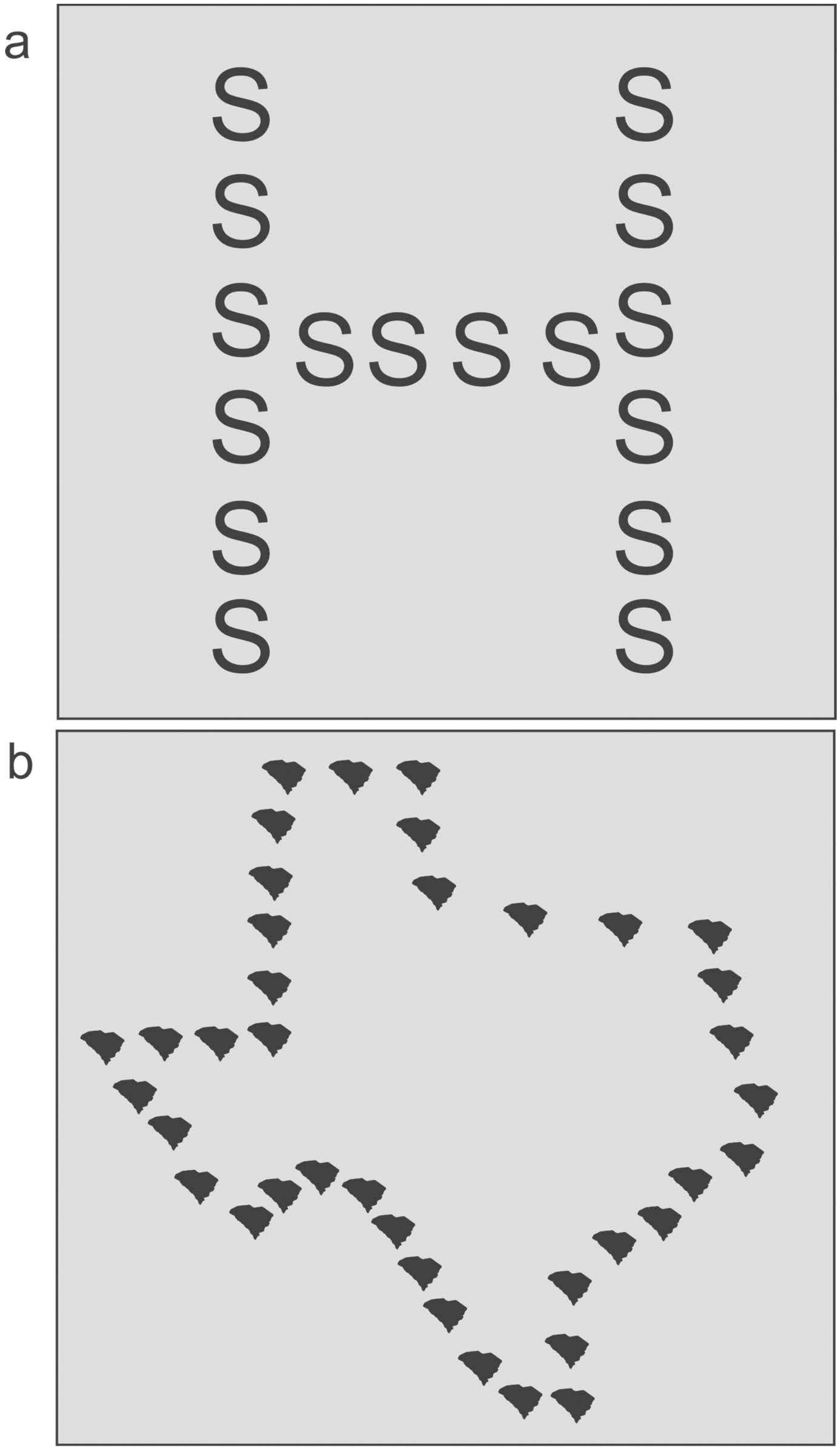

Figure 4. Compound figures showing a large letter pattern made from small letter objects (a) and a large state pattern made from a small state objects (b).

both bottom-up information (*Gestalt* principles) and top-down information (templates in memory) appear to impact the competition (Navon, 2003).

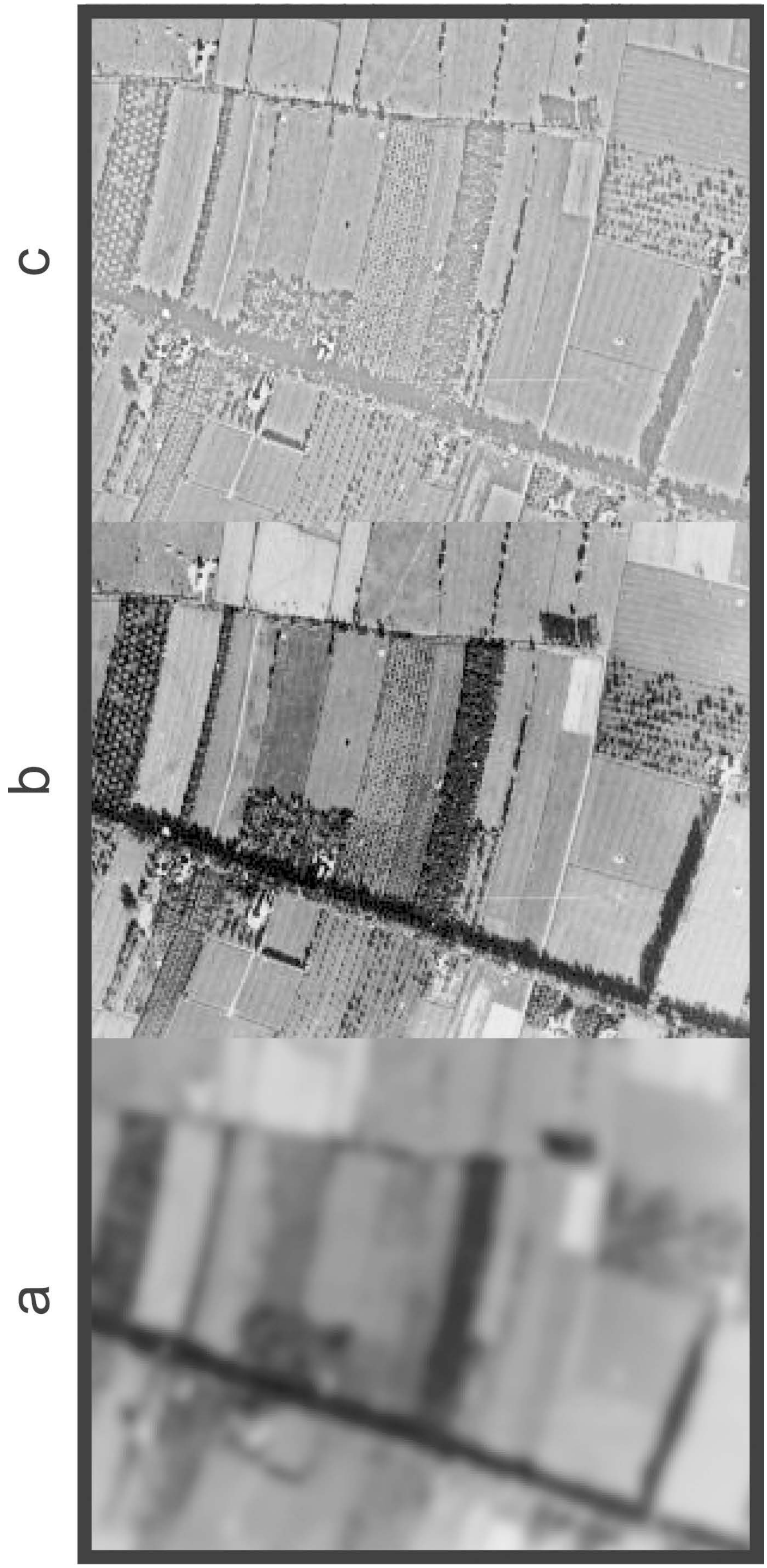

Figure 5. Aerial photograph of an orchard with images showing low-frequency (a), all (b), and high-frequency (c) information.

Loftus and Hartley (2004, 104) identified studies that offered different theoretical perspectives for "the relations between global and local information — the relative time courses over which they are acquired and the means by which they combine into overall perception of the scene." Studies that argue for an *independence theory* take the position that both global and local information can be acquired from a stimulus, such as a map, after it appears and that the order of acquisition is not important (Parker *et al*., 1996). An *independence theory* is distinguished from *global-to-local* theories in that the latter argue for an order to the processing. Sanocki (2001) distinguished between *global precedence* theories that argue the processing of global information precedes the processing of local information, and *interactive* theories that argue that global processing not only precedes but also affects the processing of local information. Morrison and Schyns (2001) have also pointed out that global and local processing have been referred to in two ways that may not be the same (Figures 4 and 5). Some studies have defined global and local scales in terms of the sizes of areas or objects (Sanocki, 1993) while others have used low and high spatial frequency and defined global and local scales in terms of course and fine textures (Olds and Engle, 1998). Studies defining spatial scale using these methods have supported different processing theories. Those defining scale by spatial frequency generally have supported the g*lobal precedence* theory while those defining scale by size have generally supported the *interactive* theory (Loftus and Harley 2004).

*"Studies defining spatial scale using these methods have supported different processing theories. Those defining scale by spatial frequency generally have supported the g*lobal precedence *theory while those defining scale by size have generally supported the* interactive *theory."*

Visual Search: Cartographers have considered many ideas related to visual search in their discussions of map reading. Dobson (1985) made a distinction between search processes driven by the map, which he call *visual search guidance*, and searches driven by higher level cognitive processes, which he called *cognitive search guidance*. The former can be impacted through the map design decisions made by the cartographer and the latter can be impacted through education processed related to map reading.

Based on a number of theories proposed by cognitive scientists, cartographers have conducted experiments on the visual search processes used with maps (Treisman and Gelade, 1980; Duncan and Humphreys, 1989; Cave and Wolfe, 1990). These theories have considered the role that attention plays in visual search in different ways. For the current discussion, consider a base map with a number of map symbols on it. One of the symbols may be the target symbol and the target may have unique features or share features with distractor symbols. The person searching the map is shown the target symbol before seeing the trial map, and must respond as to whether the target is present or absent. Treisman's (1988) *feature integration theory* argued for two distinct stages in a visual search process. An initial pre-attentive parallel stage provided an initial processing of the available information into separate feature maps. Features are locations on dimensions such as red on the color dimension or horizontal on the orientation dimension. If a target map symbol has a unique feature, its presence can be detected quickly during this initial stage without focused attention. When this happens the target is said to pop-out of the map. If the target map symbol does not have a unique feature that distinguishes it from distractor map symbols, a second stage uses focused attention to consider each possible map symbol until the target is found or all possible distractor map symbols have been eliminated from matching the target.

"If a target map symbol has a unique feature, its presence can be detected quickly during this initial stage without focused attention. When this happens the target is said to pop-out of the map."

Other theories for visual search make different assumptions. Duncan and Humphreys' (1989; 1992) *attention engagement theory* made no distinction between parallel and serial stages of processing and argued the similarity between the target and distractors and the similarity among the distractors dictated the difficulty of the task. The search was easy when there was a great contrast between the target and distractors and when distractors were homogeneous. A search should be very difficult when the target was very similar with distractors and the distractors were very dissimilar from each other.

"The search was easy when there was a great contrast between the target and distractors and when distractors were homogeneous. A search should be very difficult when the target was very similar with distractors and the distractors were very dissimilar from each other."

Nelson (1994) tested the predictions of the *attention engagement theory* in a map-reading context by having subjects search for a target color among distractor colors on bivariate choropleth maps. Results indicated that some colors (red and yellow) could be detected significantly faster than other colors. A larger contrast between the target and distractor colors also produced significantly faster reaction times, but the contrast among the distractor colors did not significantly affect reaction times. It was also noted that it was impossible to create maps that have both a small contrast between the target color and distractor colors and a large contrast among distractor colors.

Guided search theory considered visual attention the critical factor in explaining visual search processes and proposed attention was guided by a combination of bottom-up information from a stimulus like a map and top-down information in the searcher's memory (Wolfe, Cave, and Franzel, 1989; Cave and Wolfe, 1990; Wolfe, 1994; Wolfe and Gancarnz, 1996). Cartographers should be interested in what features can guide attention and their relative strengths (Wolfe and Horowitz, 2004). Lloyd (1997) reported parallel searches that produce a pop-out effect for target map symbols with a unique color, shape, size, or orientation when targets were present, but only color produced a pop-out effect when the target was absent. Conjunctive searches that had targets sharing color or shape with distractors also produced a pop-out effect. Conjuntive searches that had targets sharing color and orientation, however, produced a classic serial self-terminating pattern with reaction times increasing with number of distractors.

A number of studies have performed search experiments with choropleth maps that required map readers to search for targets that were adjacent polygons filled with specific colors (Brennan and Lloyd, 1993; Bunch, 1999; Bunch and Lloyd, 2000). It was generally reported that both top-down and bottom-up information influenced search efficiency. With complex choropleth maps, the search for color boundaries was relatively difficult and pop-out effects were not the typical result. Targets with higher luminance red and yellow colors generally resulted in significantly faster search times. Processing time significantly increased with the similarity of the target colors and distractor colors and significantly decreased with the similarity among the distractor colors on test maps (Bunch and Lloyd, 2000).

"Targets with higher luminance red and yellow colors generally resulted in significantly faster search times."

Other studies have also considered the processes used to search for point symbols on maps. Lloyd (1988) examined reaction time patterns to determine if map readers used similar search processes when they determined if a pair of pictographic symbols were present or absent on cartographic and cognitive maps. Subjects who were presented the target symbols first and searched for them on a visible map appeared to use a serial self-terminating process. This was indicated by a pattern showing reaction times increasing linearly as the number of symbols on maps increased. The slope of the relationship between reaction time and number of symbols was approximately twice as steep for absent responses than it was for present responses. Other subjects were presented the map to learn first, the map was then removed, and then the two target symbols were presented. Subjects determined if the symbols were present or absent on the map they had memorized. These subjects appeared to use a parallel search process when considering cognitive maps they had encoded into memory. This was indicated by a pattern of reaction times that did not increase for either present or absent responses as the number of symbols on maps increased. The qualitatively different patterns for the two groups of subjects clearly indicated different search processes were being used to search visible cartographic maps and memories of these same maps.

Nelson *et al*. (1997, 30) considered the search for multivariate point symbols represented as Chernoff Faces and concluded, "research results demonstrated that hierarchical relationships could be manipulated within these types of symbol to increase search efficiency." Visual searches with these complex point symbols proved to be relatively difficult. Subjects appeared to use serial searches in some cases even when the target had some unique feature that should have promoted a pop-effect. It was also reported that search efficiency varied by the type of feature involved in the search. The searches for targets were most efficient when head size was the unique feature and least efficient when mouth orientation was the unique feature. Conjunctive searches that involved a search for a whole and a part, for example head and eyes, were more efficient than conjunctive searches that involved a part and another part, for example nose and mouth.

"The qualitatively different patterns for the two groups of subjects clearly indicated different search processes were being used to search visible cartographic maps and memories of these same maps."

Selection and Grouping of Objects: As Palmer *et al*. (2003, 311) defined it, "perceptual grouping refers to the processes that are responsible for determining how the part-whole structure of experienced perceptual objects (such as people, cars, trees, and houses) are derived from the unstructured data in retinal images." Groups of symbols on maps could be added to the examples above. Cartographers represent symbols on maps so their characteristics suggest to viewers they belong in groups. Without organizational clues, the symbols would not appear to be differentiated or appear to be part of a single group (Figure 6a). Basic *Gestalt* principles based on common colors (Figure 6b), sizes (Figure 6c), orientations (Figure 6d), or motions (Figure 6e) could be used to assign individual symbols into separate groups.

Cognitive research has also been done on familiar cartographic situations such as grouping based on symbols being in a common region (Figure 6g) or having common connections (Figure 6h) (Palmer, 1992; Palmer and Rock, 1994). Palmer and Brooks (2004) discuss common fate principles involving point and line symbols that affect the selection of figure and ground. Examples can be shown for a map with two regions separated by a common boundary. If the boundary shares some key feature with the symbols in one of the region, such as color (Figure 6i) or orientation (Figure 6k) most people select that region as the figure. If the color (Figure 6j) or orientation (Figure 6l) of the boundary is not shared by the symbols in either region, then neither region has an advantage for figure selection.

The perceptual grouping of map symbols can have an important effect on map reading. Efficiencies can be accomplished in visual processing if objects having similar features can be considered all together as a group rather than as many individuals. For example, if one is searching for a red map symbol, all the green map symbols can be put into one category that can be suppressed as a group (Duncan and Humphreys, 1992).

"The perceptual grouping of map symbols can have an important effect on map reading. Efficiencies can be accomplished in visual processing if objects having similar features can be considered all together as a group rather than as many individuals."

Nelson (1999; 2000a; 2000b) conducted studies based on selective attention theory that documented how map readers responded to bivariate point symbols. She focused on ideas related to the measurement of the perceptual grouping of features on an image, and how map readers acquire information from multiple dimensional map symbols. Symbols that are defined on two dimensions such as size/shape or hue/value, can be categorized according to how the dimensions interact. *Separable* dimensions can be attended to independently of other dimensions. *Integral*

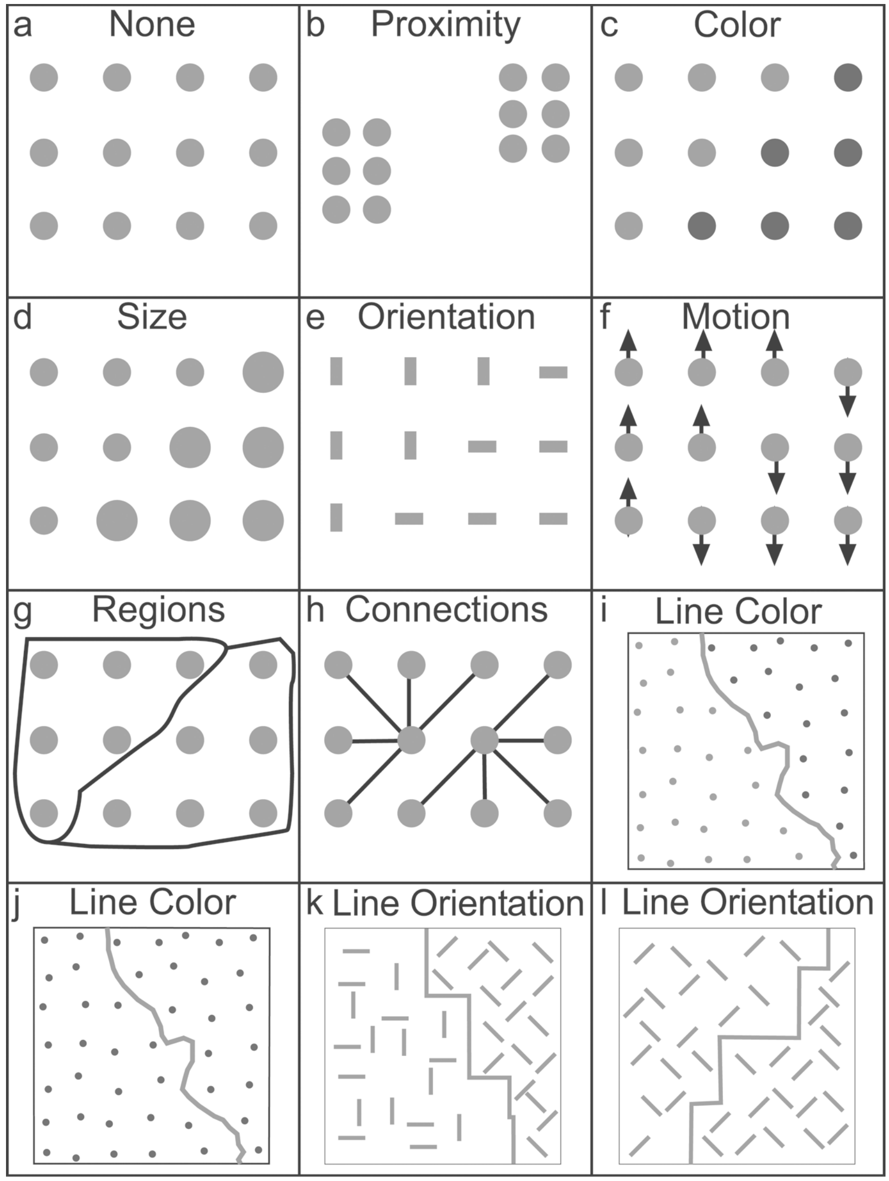

Figure 6. Visual grouping with map symbols. Simple examples show no differentiation (a), and two groups based on proximity (b), color (c), size (d), orientation (e), and motion (f). More complex examples show two groups based on common regions (g) and connections (h). Figure selection (i) and no figure selection (j) based on common line and texture color and figure selection (k) and no figure selection (l) based on common line and texture orientation. (see page 95 for color version)

“Configural *dimensions can be attended to independently, but they can also interact to form an emergent property that takes precedence over the original dimensions.”*

dimensions cannot be attended to without processing other dimensions. *Configural* dimensions can be attended to independently, but they can also interact to form an emergent property that takes precedence over the original dimensions. Speeded-classification tasks were designed to make subjects classify symbols according to stated rules. The rules required subjects to attend to one, either, or both dimensions while filtering out an irrelevant dimension. The results of the experiments were then applied to the design of bivariate thematic maps. These three studies serve as the best example of how cartographers can use knowledge of the visual attention processes used by map readers to design more effective maps (Nelson, 1999; 2000a; 2000b).

Wolfe (2000) reviewed the visual attention literature and identified four ways attention relates with vision. These relationships can be expressed as questions related to cartographic design and map reading and serve as a structure for discussing some possible future map reading studies related to attention. The first relationship considered is *vision before attention.* An important question is, "what information is available for processing before attention selects a location or object?" This issue is related to design decisions that cartographers can make that affect the map reader's selection of figure and ground, or processes that can help the map reader quickly select a layer of information of particular interest in a hierarchy, for example a global pattern or a local object. A series of experiments could consider alternate design choices for maximizing the segregation of figure from ground, or causing global or local information to be processed first. *Gestalt* principles are known to be useful bottom-up methods for affecting figure-ground selection with traditional paper maps, but other methods might be available with electronic map viewed on a monitor. A region, map symbol, or feature could be marked pre-attentively before, or as a map appears on the monitor (Peterson, 1994; Vecera and O'Reilly, 1998). It might also be possible to use high-frequency or low-frequency signals to prime the selection of global or local information on a map (Loftus and Hartley, 2004). Experimental methods could be used to determine effective methods for directing attention to one or more locations that need to be considered quickly in a dynamic presentation.

ATTENTION ON FUTURE MAPS

"Gestalt *principles are known to be useful bottom-up methods for affecting figure-ground selection with traditional paper maps, but other methods might be available with electronic map viewed on a monitor."*

The second relationship is *vision with attention.* The important question here is, "how does focusing attention affect the information selected for processing?" Attention for most map reading tasks can be directed by information on the map and information in the map reader's memory. Competitions may be taking place among locations, features, and objects on the map, and between bottom-up and top down information. The construction of animated maps offers a bigger challenge to cartographers, but there are more resources available to influence the direction of attention on dynamic maps. Studies of efficient processing could test specific hypotheses related to the best methods for directing attention to appropriate locations, features, or objects on a dynamic map. Visual search studies done by cartographers have been restricted to static maps and have considered searches for point symbols and polygons. The dynamic maps that appear on automobile navigation systems need to be searched quickly and accurately so the map reader can acquire important navigation information. Interactive maps may require one to process information quickly and make choices that affect the nature of the next view of the map. Cartographers designing these maps are required to respond to new attention phenomena, for example *inattention blindness*, *change blindness*, or *attention blink*, with these maps.

"Interactive maps may require one to process information quickly and make choices that affect the nature of the next view of the map."

The third relationship is *vision after attention.* An important question is, "does attention leave any lasting effects after it has been directed away from a stimulus?" Map reading studies related to the *inhibition of return* and *visual marking* would fit into this category. Both of these effects suggest map readers should have a bias against attending to previously attended information. This bias for novel information, whether it is automatic or intentional, could impact the visual processing of animated maps. Studies should consider both the positive and negative impacts of these effects. A bias toward novel information might increase or decrease performance for a vigilance task. If a subject were to monitor a dynamic map and report when a particular map symbol appeared, target symbols at new locations or having new features should be more likely to capture attention. The same map reader may find it more difficult to notice target symbols that appear at previously attended and rejected locations or with previously attended and rejected features.

The fourth relationship is *vision without attention.* The important question is, "what is the fate of stimuli that are never selected for attention?" This is a very intriguing question. One possibility is that this information has absolutely no effect on map-reading processes. This, however, is not the only possibility. Unattended information may be learned implicitly without conscious effort and it may influence the processing of the information being processed with focused attention. *Contextual cueing* could prove to be a promising technique for cartographers interested in studying the lasting effects of spatial patterns on their maps. Chun and Nakayama (2000, 77) argued, "Implicit memory traces, not available to conscious awareness, are laid down during visual processing. Visual processing benefits from the accumulation of information provided by the spatial and temporal context of past views." Any spatial patterns that are repeated during map reading and explicitly learned could prove to enhance performances on map-reading tasks. Most *contextual cueing* studies have used a visual search task, but other types of tasks may show an enhanced performance if done in a familiar context rather than a novel context. Studies could be done that present one layer of mapped information as a consistent or inconsistent context and consider a task being completed with another layer of information.

"Contextual cueing *could prove to be a promising technique for cartographers interested in studying the lasting effects of spatial patterns on their maps."*

A simple example could be a map that illustrated rivers in one layer and cities in another layer. The task could be to determine if a city map symbol with particular features were present on the map. The target city might be a red circle and distractor cities might be red squares and blue circles. The city locations would be fixed, but the target and distractor symbols would be randomly assigned to the locations. If half the trials had a river layer that was the same and the other half had novel river patterns, trials with the repeated context should have a faster mean reaction time than trials with the ever-changing context.

This paper has reviewed a number effects related to visual attention that cartographers should consider as they design their maps. These effects have been studied in non-mapping contexts, but need initial studies to establish if the effect on performance extends into a map-reading context. An understanding of how map readers direct attention and how visual attention impacts the performance of map reading tasks should be an important goal for those who wish to produce effective maps. Cognitive experiments conducted within the context of real cartographic maps that test hypotheses related to visual attention should provide the knowledge needed to accomplish this goal. The results of such studies can demonstrate consilience in the information sciences and frame productive questions for future research.

"An understanding of how map readers direct attention and how visual attention impacts the performance of map reading tasks should be an important goal for those who wish to produce effective maps."

NOTES

[1]Non-professionals using mapping software also make many maps. Although these are maps, the people who have access to the conventional wisdom of professional cartographers and who may be motivated by consilience research agendas did not design them.

[2]If the map is considered as a work of art, it should be produced to be aesthetically pleasing. If economic efficiency is the main concern, the map should be produced quickly and inexpensively.

[3] Wilson (1998) argued the physical sciences and biology in particular have achieved a high degree of consilience. He also argued that progress in the

social sciences has been much slower. Wilson does not discuss geography as part of either the physical or social sciences. Because of the disciplines diverse nature, geography should be able to contribute to greater consilience in physical, social, and information sciences.

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