Eye Tracking to Explore the Potential of Enhanced Imagery Basemaps in Web Mapping

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Abstract: The research reported here is motivated by the now ubiquitous nature of web mapping services that provide remotely sensed imagery as a basemap option. Despite the popularity of imagery basemaps, few strategies have been suggested to enhance their readability. Here, we describe a controlled experiment leveraging the eye tracking method to explore the potential of enhancing remotely sensed imagery when used for cartographic presentation. Specifically, twenty participants had their eye movements recorded as they visually searched for areas of interest in either an unmodified image (such as typical in web mapping services) or enhanced image (using image processing routines common to Remote Sensing). By interpreting the eye movement fixations and saccades of participants using a combination of qualitative and quantitative analysis, we found that the image enhancements improved both the effectiveness of and efficiency in identifying areas of interest, particularly those previously concealed in more visually complex areas in the image. The results from this study can be used to improve the readability of web maps that employ remotely sensed imagery as the basemap.

Key words: Cartography, Remote Sensing, web mapping, eye tracking, visual analytics, imagery basemaps

Introduction

Developments in web-based mapping over the past decade have increased substantially both the number and variety of maps consumed each day by the general public. The now ubiquitous nature of these web maps has opened many new opportunities for Cartography, such as the possibility of maps that are highly interactive, location-aware, generated on-demand, and portray information in real-time. However, the constraints in form and function imposed by these web mapping services—and the associated shift in map reader expectations given their exposure to these constraints—have pressed academic and professional cartographers alike to revise or rethink many of their time-tested cartographic strategies when designing for the Web. Here, we address one such topic prompted by conventions in contemporary web mapping that is receiving increasing application in cartographic practice: the use of remotely sensed imagery (e.g., satellite imagery, aerial photography, oblique imagery) as the basemap reference frame for map use and interpretation.

Abstraction is central to the design of an effective map; meaningless detail must be generalized from the map display to facilitate clear communication of the represented geographic phenomenon (Robinson et al., 1995). Compared to vector maps, remotely sensed imagery carries more spatial detail and thus may be perceived as more accurate and more useful by map readers (Woodruff, 2007; Niroumand-Jadidi et al., 2011). However, it is known that the information dense quality of imagery can cause difficulties in identifying features of interest from the visual scene, rendering the imagery unusable despite its appearance of accuracy (Roth, 2009). It is for this reason that imagery traditionally was used for information assembly and not basemap presentation within Cartography, with cartographers performing the image interpretation by tracing vectors for the final map product and thus relieving map readers from interpreting the images themselves (Levin et al., 2008; Walter & Luo, 2011). Because map readers now readily have access to imagery through web maps, it is important to explore if some or any of the principles of cartographic abstraction can be applied to such imagery when used as a basemap.

In this paper, we focus on the generalization operator of *enhancement*, or the inclusion of graphic embellishments around or within a feature to maintain or emphasize feature relationships (McMaster & Monmonier, 1989; McMaster & Shea, 1992; Regnauld & McMaster, 2007; Roth et al., 2011). Specifically, we explore the potential utility of applying image enhancements common in Remote Sensing to web maps that employ imagery as the basemap. The eye tracking method was administered in a controlled experiment to capture human visual search strategies for identifying road features in both unmodified and enhanced imagery basemaps. Eye movement fixations and saccades were analyzed using an integrated qualitative-quantitative approach to determine if the image enhancements improved either the effectiveness or efficiency (or both) of identifying road features. While the primary motivation of this work is improvement to the cartographic design of web maps, such investigation into the human visual search strategies for reading imagery basemaps also may be helpful in research and development on automated image interpretation (e.g., Gienko & Chekalin, 2004; Gienko & Levin, 2005; Gienko & Levin, 2007).

The paper proceeds with five additional sections. Related studies employing the eye-tracking method for map reading and image interpretation are reviewed in the next section. The experimental design and analysis are described in the third section. The results of the experiment are described in fourth section and concluding remarks are offered in the fifth section.

Background: Eye Tracking for Investigating Map Interpretation

Vector maps, remotely sensed imagery, and others forms of information graphics are effective tools for supporting thinking because they make use of the most powerful pathway to the human mind: the eye-brain system (MacEachren, 1995). Attention of the human eye is both stimulus- and goal-driven when visually searching a scene, with novices relying more heavily on apparent contrast and experts relying more heavily on known patterns established through past experience (Corbetta & Gordon, 2002; Wright & Ward, 2008). The movements of the eye itself play a functional role in visual perception and are considered a window into visually-enabled cognition (Mast & Kosslyn, 2002). Eye movements therefore provide valuable information about the way in which a visual scene is interpreted or misinterpreted (Liversedge & Findlay, 2000).

The *eye tracking* method describes the use of specialized equipment to record eye movements as participants interpret a visual scene, map-based or otherwise (Marsh & Haklay, 2010). An eye tracking instrument collects information about vision *fixations* (positions onscreen where the eye is paused for an extended period) and *saccades* (movements between fixations), which sometimes are described together as *gazes* (Olivier, 2007; Webb & Renshaw, 2008). While eye tracking has a longstanding tradition in Psychology and Neurobiology spanning the Twentieth Century (Yarbus, 1967; Rayner, 1998), it was not until recent achievements in eye tracking technology that the method has become readily accessible in other domains (Çöltekin et al., 2009). It is important to note that the eye tracking method suffers from the Midas Touch problem, or the inability of a participant to stop using their eyes when not attending to the experimental visual scene, often resulting in many meaningless and potentially misleading gazes when applied for usability or cognitive studies (Jacobs, 1991). However, eye tracking remains appropriate for the research reported here, given the simplified experimental task of visually searching an information dense visual scene to extract and identify features of interest.

Cartographers were early to explore the potential of eye tracking as a method for studying perception and cognition (e.g., Guyot, 1971; Castner, 1973; Jenks, 1973; DeLucia, 1974; Hill, 1975; Steinke, 1975; Dobson, 1977; Castner & Lywood, 1978; Philips et al., 1978; Dobson 1979; Steinke 1979); see Steinke (1987) for a summary of these early applications of eye tracking in Cartography. Despite a subsequent period of several decades during which use of eye tracking was minimal, there is now a renewed interest in the eye tracking method within Cartography, likely due to the aforementioned improved accessibility to state-of-the-art eye tracking equipment. Much of this recent research is motivated by emerging developments in web mapping—as with the research reported here—and primarily focuses upon improving the usability and utility of the interface to the map (e.g., Alaçam & Dalci, 2009; Çöltekin et al., 2009; Çöltekin et al. 2010; Ooms et al., 2010; Manson et al., 2012). Eye tracking also has produced key insights into visual search strategies for interpreting paper topographic maps (Brodersen et al., 2002), cartographic representations of time such as small multiples and animations (Fabrikant et al., 2008; Garlandini & Fabrikant, 2009; Goldsberry & Griffin, 2012), static weather map displays (Fabrikant et al., 2009), and coordinated geographic visualizations (Griffin & Robinson 2010). The emphasis of these studies is on interpretation of vector maps; application of eye tracking for interpreting information-dense displays, like remotely sensed imagery or 3D environments, is limited (for discussion on the potential of eye tracking for remote sensing, see Geinko & Chekalin 2004; Geinko & Levin, 2005; Geinko & Levin, 2007).

Methods

Participants

Twenty undergraduate students (10 females and 10 males) took part in a controlled experiment designed to compare visual search strategies between web maps using unmodified versus enhanced remotely sensed imagery for the basemap. The sample size of 20 generally aligns with other eye tracking studies in Cartography (e.g., Garlandini & Fabrikant 2009; Çöltekin et al., 2010; Ooms et al., 2010). Participants were recruited from the Geography Department of Beijing Normal University through emails and were between the ages of 19 and 21 years old. This sample group was deemed appropriate because the participants were not professionals working in Cartography or Remote Sensing, but had experience using modern computing and web mapping technology; these characteristics are common to the majority of web map users today. None of the participants reported having eye diseases or color vision deficiency; students with myopia were able to participate if wearing corrective glasses.

Materials

Participants were asked to interpret either an unmodified or an enhanced image of Hohhot, China, a city of nearly 3 million inhabitants located approximately 500km west of Beijing. The imagery spanned a 3km by 5km area in Hohhot; the same geographic extent was used for both the unmodified (Figure 1) and enhanced (Figure 2) trial in the experiment. The area was selected because it includes agricultural, industrial, and residential land uses; selection of a portion of the city outside of the city center also ensured that participants would be unfamiliar with the depicted area prior to starting the experiment. The imagery did not include any additional map vectors or labels and was not interactive (i.e., as with typical web-based 'slippy' maps).

In the experiment reported here, we focused exclusively on the identification of road features in the imagery, an important task supported by web maps given the emphasis of many web mapping services on navigation and routing. Specific emphasis on road features was necessary to simplify the experiment, leaving investigation into visual search strategies of other map features discriminable on imagery for follow-up research. In the following, regions within the imagery containing primary roads or a majority of paved surface are described as *areas of interest* or *AOIs.* Three visual enhancement methods known to improve the readability of AOIs (roads) were applied to the unmodified image to generate the enhanced image for the experiment (Lillesand et al., 2004; Jensen, 2005):

1. *Histogram Segmented Stretch*: The histogram segmented stretch routine divides the range of greyscale digital numbers into discrete intervals and equalizes those intervals containing AOIs. This enhancement was applied to clarify bright and dark areas on the image.

2. *Co-occurrence-based Texture Filtering*: The texture filtering routine adjusts the value of individual pixels based on the pattern of values (i.e., the texture) of surrounding pixels; the co-occurrence variation allows for the combination of multiple texture filters into the image processing (e.g., mean, variance, homogeneity, contrast). This enhancement was applied to emphasize high contrast edges in the image.

Figure 1: Unmodified Trial: The unmodified image showing a 3km by 5km section of Hohhot.

Figure 2: The Enhanced Trial: The enhanced image showing the same section of Hohhot after application of three remote sensing image processing routines.

3. *Gaussian Low-pass Filtering*: The Gaussian low-pass filtering reduces the amplitude of pixels with high values (i.e., extremely bright areas), passing over pixels with low values. This enhancement was applied to protect bright (high value) portions of the image and to reduce the amount of detail in homogenous areas.

Apparatus

The Tobii Studio (http://www.tobii.com/) eye tracking technology was used to record the participants' eye movements during the experiment. The Tobii Studio software included Tobii Studio 1.0, installed on an IBM ThinkPad laptop. The Tobii Studio hardware included a Tobii Eye Tracker, with a sampling rate of 120Hz, mounted on a 17-inch TFT display, with a screen resolution of 1280×1024. The sampling rate results in the collection of an eye movement data point every 8.3 milliseconds. The remotely sensed imagery was displayed at full screen in the TFT display, resulting in a screen pixel resolution of approximately four ground meters per pixel. We adopted the Tobii default of 0.84 pixels/millisecond as the minimal velocity threshold for a fixation. The Tobii Studio technology was set-up in a private room in the Beijing Normal University; the same room and apparatus configuration was used for all participants, with participants completing the experiment separately.

Procedure

The experimental task required participants to visually scan the remotely sensed imagery in order to identify road features. Identification is the least sophisticated objective supported by vector maps, remotely sensed imagery, and other information graphics (Crampton 2002), with more complex objectives such as comparison, ranking, association, and delineation thought to be composed of a series of more basic identification tasks (Roth 2011). We chose to focus on the identification objective to simplify the experiment, leaving investigation of higher order objectives for follow-up research.

The 20 participants were divided evenly into two groups, one group receiving the unmodified image and the other receiving the enhanced image. Each group was balanced to include five males and five females. The experiment began with an overview description of the research project and the procedure. Before starting the experiment, each participant completed an eye movement calibration exercise, which calculated the direction and position of the participant gaze onscreen. The participants also were informed at this time that they should attempt to minimize their blinking and keep the position of their head and body stable, as both may impact eye movement recordings.

Following calibration, participants were instructed to identify as many roads in the subsequently displayed image as possible within an eight second time limit. This kind of open-ended or exploratory task in which participants considered all road features at once was chosen over a more closed-ended task in which participants considered features one-at-a-time in order to avoid the need for placing labels on the map or for having prior knowledge about the geographic area. It also was thought that the eye tracking method would be particularly useful in investigating visual search strategies for such open ended tasks, as fixations indicate points in time at which individual roads were identified in the imagery by feature type, but not by feature name (which would require a verbal statement, and thus additional place name information through labels or prior knowledge).

Analysis

Both qualitative and quantitative analytical techniques were applied to interpret participant eye movements during the open-ended identification tasks. Analysis of participant visual search strategies began with the generation and interpretation of visual representations of participant fixations and saccades. Visual analysis of information graphics, when coupled with descriptive and inferential statistics, allows for a nuanced understanding of experimental results; this blended qualitative (visual) and quantitative (computational/statistical) approach is a key tenet of the emerging research thrust of Visual Analytics (Thomas et al., 2005; Andrienko et al., 2002). These qualitative, visual representations were used throughout analysis to aid interpretation of the quantitative, statistical analyses.

Mapping techniques common in cartographic representation often are applied to eye movement data due to the two-dimensional (spatial) nature of onscreen fixations and saccades (Duchowski, 2007). Four map-based visual representations of fixations and saccades were generated for qualitative interpretation of participant eye movements:

1. *Gaze Plot Map*: A gaze plot map shows the eye movements of a single participant for a single image trial, thus providing a graphic overview of each participant's visual search strategy. Gaze plot maps generated using the Tobii software represent fixation locations as proportional circles, colored according to time, and the sequence of saccades between fixations as line symbols. In total, 10 gaze plot maps were generated for both the unmodified and enhanced image, producing 20 in total; Figure 4 provides a pair of composite gaze plot maps showing the gazes of all participants, while Figure 7 shows two individual gaze plot maps from a pair of participants..

2. *Fixation Heat Map*: A limitation of gaze plot maps is that they quickly become cluttered visually, particularly when showing the gazes of more than one participant. A fixation heat map is a composite graphic providing an overview of fixation locations and durations of all participants for a single image trial. Fixation heat maps, and heat maps generally, draw on traditions in Cartography like isoline and surface mapping (MacEachren & DiBiase, 1991). The Tobii software generates fixation heat maps using red for areas in the image on which participants were collectively fixated for long periods of time and green for areas on which participants were collectively fixated for small periods of time; variations in color value (red=darker, green=lighter) allow for the fixation heat maps to be interpreted by individuals with color vision deficiency. Areas receiving no fixations are not symbolized (e.g., Figure 5).

3. *Saccade Heat Map*: While a fixation heat map provides a composite graphic of the fixation locations and durations, a saccade heat map provides a composite graphic of the eye movement trajectories. While most cognitive activity occurs during fixations and not saccades, some aspects of the visual scene are perceived during saccades (Gienko and Chekalin, 2004). The Line Density tool in Esri's ArcGIS software was used to generate the pair of saccade heat maps, using dark green to represent areas with a high density of saccades and light green to represent areas with a low density of saccades. Areas receiving no saccades are not symbolized (e.g., Figure 6).

4. *Time Series Gaze Plot Map*: A limitation of the above three visual representations is that they represent the entire experimental session in a single graphic. Time series gaze plot maps were generated to provide more detail about the step-by-step process of participants' visual search strategies, rather than the overall sum of the fixations and saccades. Time series gaze plot maps follow the small multiple technique (Bertin, 1967|1983; Tufte, 1983), with each gaze plot map in the time series showing the locations (not duration) of all participant fixations and saccades within a uniform, non-overlapping interval of time; we produced partial gaze plot maps at two second time intervals (e.g., Figure 8).

Quantitative analysis of participant visual search strategies was completed by relating fixations and saccades to predetermined AOIs Two *levels* of AOIs on both the unmodified and enhanced imagery were sampled prior to the experiment for subsequent qualitative and quantitative analysis (Figure 3); the level was determined by the AOIs visual complexity in the imagery, or the degree to which the roads were concealed visually in the image by surrounding, complex features (MacEachren, 1982). Level #1 AOIs include primary roads (e.g., multilane highways) that are in open areas and can be recognized easily. In contrast, Level #2 AOIs include networks of secondary roads found in more visually complex areas, such as industrial or residential locations. We anticipated that participants more quickly and easily could identify Level #1 AOIs given their greater prominence in the visual scene. Areas not marked as an AOI may include tertiary roads, but generally include a low proportion of paved areas compared to non-paved areas. To account for imprecision in eye movements, a buffer of 25 pixels (approximately 100 meters) was added for aggregation of fixations to the Level#1 AOIs.

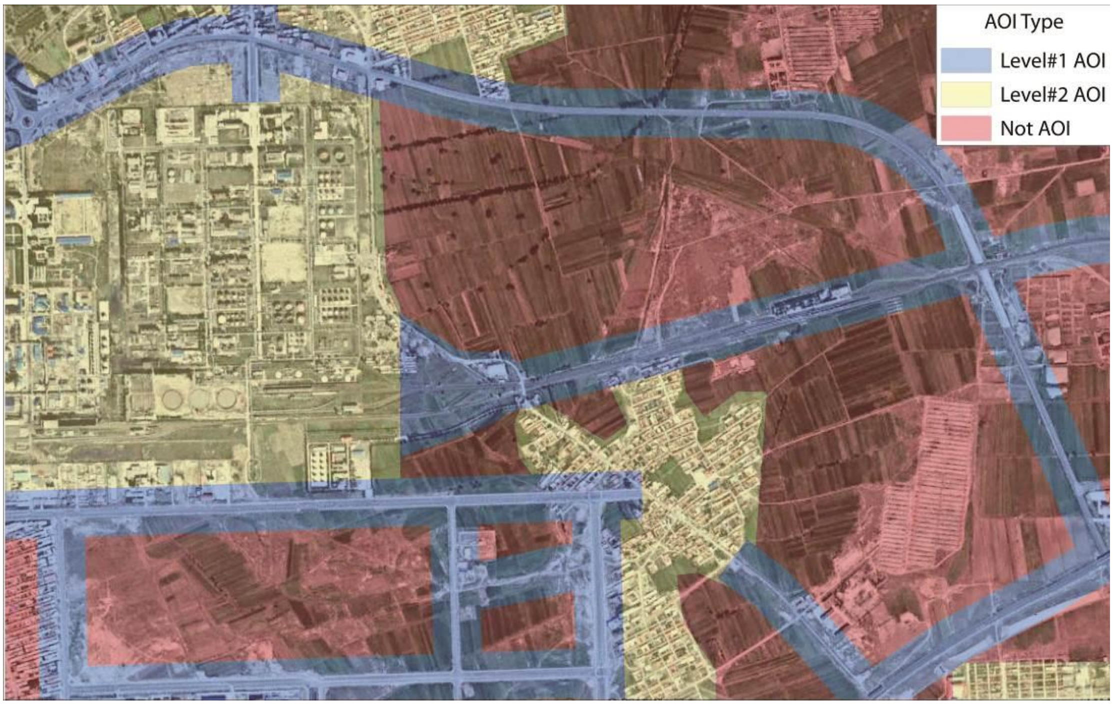

Figure 3. Level #1 and #2 AOIs used for quantitative analysis.

Controlled experiments using eye tracking or other kinds of participant recordings often are analyzed in terms of *effectiveness*, or how well the participant could complete the experimental tasks with the provided materials, and *efficiency*, or how quickly the participant could complete the experimental task with the provided materials (Dobson, 1983). Analysis of effectiveness relied on three broad characteristics of participant visual search strategies: (1) *extensiveness* (the total length of saccades), (2) *frequency* (the total number of fixations and saccades), and (3) *accuracy* (the percentage of all fixations occurring atop AOIs). Analysis of efficiency also relied on three broad characteristics of participant visual search strategies: (1) *duration* (the amount of time spent in fixations or saccades), (2) *productivity* (the percentage of time spent fixated on AOIs, the experimental task given to users), and (3) *time to fixation* (the amount of time spent in a saccade prior to a fixation). Table 1 provides a definition for each of the quantitative metrics used, both for effectiveness and efficiency as well as their application to fixations and saccades. Both descriptive and inferential statistics were calculated for all metrics; two-tailed t-tests were applied to each characteristic to test significance between the pair of remotely sensed imagery trials, with the null hypothesis assuming no difference in effectiveness or efficiency between unmodified and enhanced imagery (Burt et al. 2009).

Table 1. Definition of the metrics used to analyze effectiveness and efficiency.

Effectiveness		Variable Definition
Extensiveness (screen pixels)		
Saccades		
	Total saccade length	The total length of saccades
Frequency (count)		
Fixations		
	All Fixations	The total number of fixations
	On AOI	The number of fixations on AOIs
	Off AOI	The number of fixations away from AOIs
	On Level #1 AOI	The number of fixations on Level #1 AOIs
	On Level #2 AOI	The number of fixations on Level #2 AOIs
Saccades		
	Overall	The total number of saccades
Accuracy (percentage)		
Fixations		
	AOI vs. All	Fixation Frequency (On AOI) by Fixation Frequency
	On Level #1 AOI vs. All	Fixation Frequency (On Level#1 AOI) by Fixation Frequency
	On Level #2 AOI vs. All	Fixation Frequency (On Level#2 AOI) by Fixation Frequency
Efficiency		**Variable Definition**
Duration (milliseconds)		
Fixations		
	All Fixations	The total duration of all fixations
	On AOI	The duration of fixations on AOIs
	Off AOI	The duration of fixations away from AOIs
	On Level #1 AOI	The duration of fixations on Level #1 AOIs
	On Level #2 AOI	The duration of fixations on Level #2 AOIs
Saccades		
	All Saccades	The total duration of saccades
Productivity (percentage)		
Fixations		
	Time on AOI	Fixation Duration (On AOI) by Total Fixation Duration
Time to Fixation (milliseconds)		
Time to All Fixations		
	All Fixations	Fixation Duration by Fixation Frequency
Time to First Fixation		
	On AOI	The time taken to first fixation on an AOI
	Off AOI	The time taken to first fixation away from AOI
	On Level #1 AOI	The time taken to first fixation on a Level #1 AOI
	On Level #2 AOI	The time taken to first fixation on a Level #2 AOI

Results and Discussion

Visual Analysis of Composite Fixations and Saccades

Qualitative, visual interpretation of participant eye movements began with generation of composite gaze plot maps depicting all gazes across participants. Figure 4 shows the collective gazes of all 20 participants on both the unmodified image (Figure 4a) and the enhanced image (Figure 4b). While individual gaze plot maps served as a reference throughout qualitative and quantitative analysis (see the discussion of Figure 7 below), it was difficult to extract much useful information from the pair of composite gaze plot maps given their information density.

The pair of fixation heat maps (Figure 5) provided a clearer overview of participant visual search strategies. There were three qualitative differences in visual search strategies on the unmodified versus enhanced image, as revealed through the two fixation heat maps. First, there were more unconnected fixations on the unmodified image areas compared to the enhanced image, resulting in a more discrete fixation heat map for the unmodified image (i.e., one with many isolated islands; Figure 5a) versus a more continuous heat map for the enhanced image (i.e., one with linear areas of aggregate fixations; Figure 5b). Such a qualitative finding suggests that it was easier visually to follow the linear features in the enhanced image, with the unmodified image evoking more visual pauses along the linear features. Second, the fixation hotspots (i.e., clusters) are relatively 'hotter' (i.e., have a greater fixation duration) on the unmodified image (e.g., Hotspot #1 through #6 in Figure 5a) compared to the enhanced image (e.g., Hotspot #7 & #8 in Figure 5b). This suggests that participants' required a longer period of time to interpret a given AOI in the unmodified image, while participants were able to avoid dwelling on a single AOI in the enhanced version. Third, and most importantly, fixation hotspots are focused primarily on Level #1 AOIs in the unmodified image (e.g., Hotspot #1 through #6 in Figure 5a), while fixation hotspots are found atop both Level #1 AOIs (Hotspot #8 and #9 in Figure 5b) and Level #2 AOIs (Hotspot #7 and #10 in Figure 5b) in the enhanced image. This qualitative finding suggests one of two possible explanations: (1) Participants more quickly were able to identify Level #1 AOIs in the enhanced image, giving them time to switch attention to the more visually complex Level #2 AOIs within the time frame; and/or (2) Participants were not able to identify Level #2 AOIs in the unmodified version, regardless of time.

Saccade hotspots (Figure 6) largely correspond to the areas between fixation hotspots (Figure 5) and reinforce the insight into the visual search strategies of participants derived from the fixation heat maps. Unlike the fixation heat maps, both saccade heat maps are continuous in nature; the increased continuity exhibited in the saccade heat maps is predictable and attributed to the nature of a saccade (a linear feature) versus a fixation (a point feature). Like the fixations heat maps, however, saccade hotspots are found primarily along Level #1 AOIs in the unmodified image (e.g., Hotspot #1 and #2 in Figure 6a), but along both Level #1 AOIs (e.g., Hotspots #3 and #4 in Figure 6b) as well as Level #2 AOIs (e.g., Hotspots #5 and #6 in Figure 6b) in the enhanced image. This qualitative finding again suggests the pair of explanations that participants were able to more quickly identified Level #1 AOIs in the enhanced image, affording them time to interpret Level #2 AOIs, or that the Level #2 AOIs were not discriminable in the unmodified image.

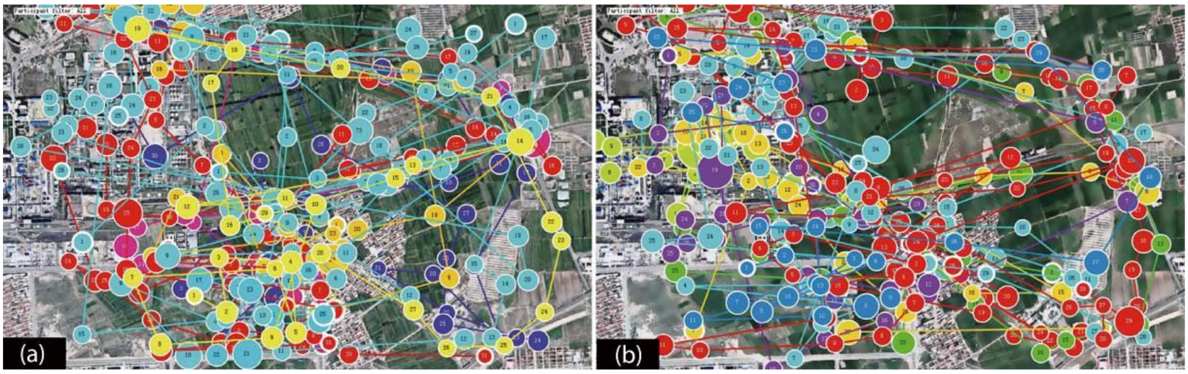

Figure 4. A composite gaze plot map showing the gazes of all participants on (a) the unmodified image and (b) the enhanced image.

Figure 5. Fixation heat map of (a) the unmodified image and (b) the enhanced image. Dark red represents high fixation duration; light yellow represents low fixation duration.

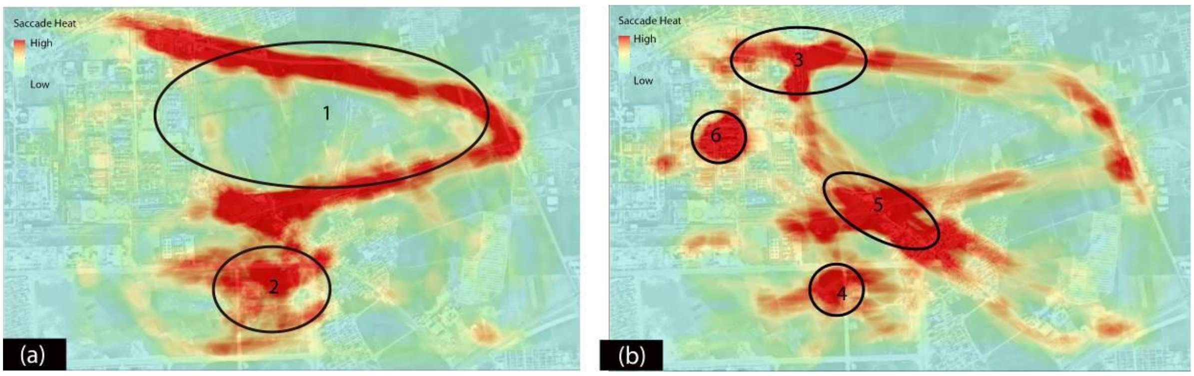

Figure 6. Saccade heat map of (a) the unmodified image and (b) the enhanced image. Dark red represents high saccade duration; light yellow represents low saccade duration.

Visual Analysis of Individual Fixations and Saccades

Qualitative, visual analysis of composite fixations and saccades offered initial evidence that the enhanced image improved identification of AOIs (road features), possibly at both levels of complexity. We generated an individual gaze plot map for each participant to further understand how visual search strategies varied between the unmodified and enhanced imagery. Figure 7 provides a pair of individual gaze plots representative of the difference in visual search strategies between the unmodified and enhanced imagery.

With the unmodified image (Figure 7a):

1. The participant started his or her gaze arbitrarily at the bottom-center of the image atop a Level #1 AOI.
2. The participant then progressed along the Level #1 AOI to the top of the image.
3. The participant then took a sharp right, gazing along a Level #1 AOI until reaching the middle-right of the image; at this point, the participant delayed his or her gaze in its longest fixation.
4. The participant then took a sharp turn back towards the center of the image, gazing along a Level #1 AOI.
5. The participant again fixated upon the original Level #1 AOI as the eight second time limit expired.

With the enhanced image (Figure 7b):

1. The participant began his or her gaze atop the same Level #1 AOI in the bottom of the image.
2. The participant then searched within several non-AOI areas near the initial Level #1 AOI.
3. The participant then turned right across the image, pausing their gaze in a short fixation atop a Level #2 AOI.
4. The participant continued onto a Level #1 AOI at the far right of the image, very quickly following the Level #1 AOI across the top of the image; this saccade included only a few fixations of short duration.
5. The participant spent the remainder of the eight second time limit interpreting the Level #2 AOI in the top-left of the image.

Thus, the interpretation of individual gaze plot maps reinforced that participants spent a greater amount of time identifying Level #1 AOIs in the unmodified image, with participants quickly identifying Level #1 AOIs in the enhanced image (with shorter fixations), leaving remaining time to identify Level #2 AOIs.

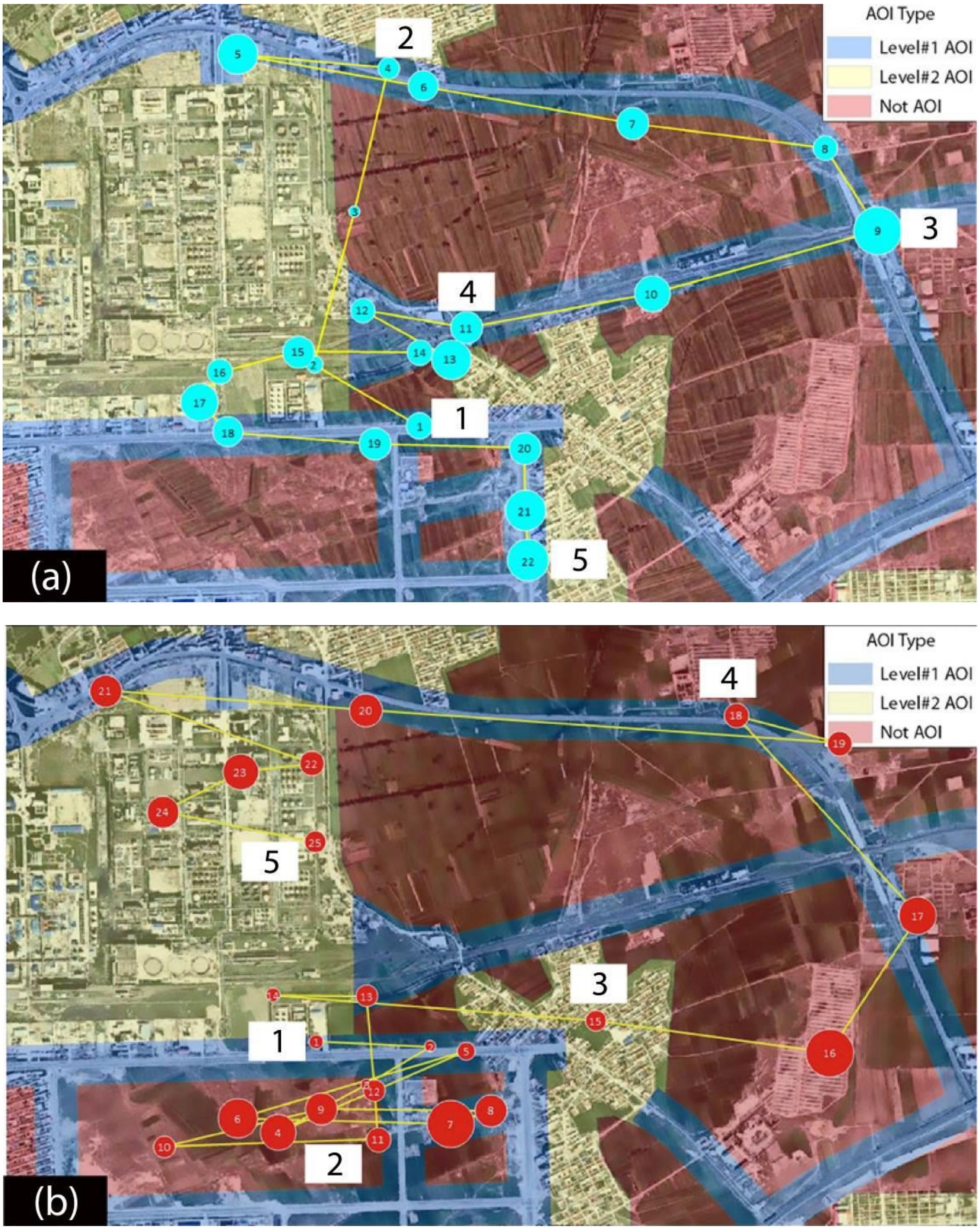

Figure 7. Example single participant gaze plot map of (a) the unmodified image and (b) the enhanced image.

Following qualitative analysis of individual gaze plot maps, we then produced time series gaze plots maps with an interval of two seconds, resulting in two pairs of four gaze plot maps (Figure 8). Time series gaze plot maps partially overcome the visual clutter of composite gaze plot maps, allowing for interpretation of the visual search strategies of individual participants in context to one another, albeit at smaller intervals of time and without information of fixation duration.

During the first two seconds, participants' fixations and saccades on the unmodified image mainly concentrated atop Level #1 AOIs, especially in the bottom-center region of the image (Time Series #1 in Figure 8a). In contrast, participants' fixations and saccades were more commonly found atop visually complex areas in the enhanced image within the first two seconds of the visual search, particularly in the Level #2 AOI at the top-right of the image (Time Series #1 in Figure 8b). During the third and fourth seconds, visual search strategies largely were similar for both the unmodified image (Time Series #2 in Figure 8a) and enhanced image (Time Series #2 in Figure 8b), with an overall emphasis on Level #1 AOIs and in particular the primary road feature running horizontally through the center of the image. Within Time Series #2, participants focused much less on the Level #1 AOI along the top of the image in the enhanced image as compared to the unmodified image. During the fifth and sixth seconds, fixations and saccades on the unmodified image became distributed across a wider geographic area and were located inconsistently across participants (Time Series #3 in Figure 8a). In contrast, fixations and saccades on the enhanced image shifted in part from focus on Level #1 AOIs to Level #2 AOIs (Time Series #3 in Figure 8b). Finally, fixations and saccades on the unmodified image during the final two seconds maintained their wide distribution, with emphasis generally upon Level #1 AOIs (Time Series #4 in Figure 8a). In contrast, the visual search strategies on the enhanced image during the last two seconds almost exclusively focused upon the Level #2 AOIs (Time Series #4 in Figure 8b). Qualitative interpretation of the fixations and saccades through time using two second intervals suggests that while searching is somewhat similar within the first half of the experimental task, the enhanced image allowed participants to switch from Level #1 AOIs to Level #2 AOIs during the second half of the experimental task.

Finally, we supplemented the Figure 8 time series gaze plot maps with time series histograms aggregated across all 20 participants to understand further the relationship between Level #1 and Level #2 AOI visual searching during the eight second time limit. Figure 9 and Figure 10 compare the fixation frequency and fixation duration, respectively, on Level #1 AOIs (Figure 9a and 10a), Level #2 AOIs (Figure 9b and 10b), and non-AOIs (i.e., the remainder of fixations; Figure 9c and 10c) across the two-second intervals shown in Figure 8.

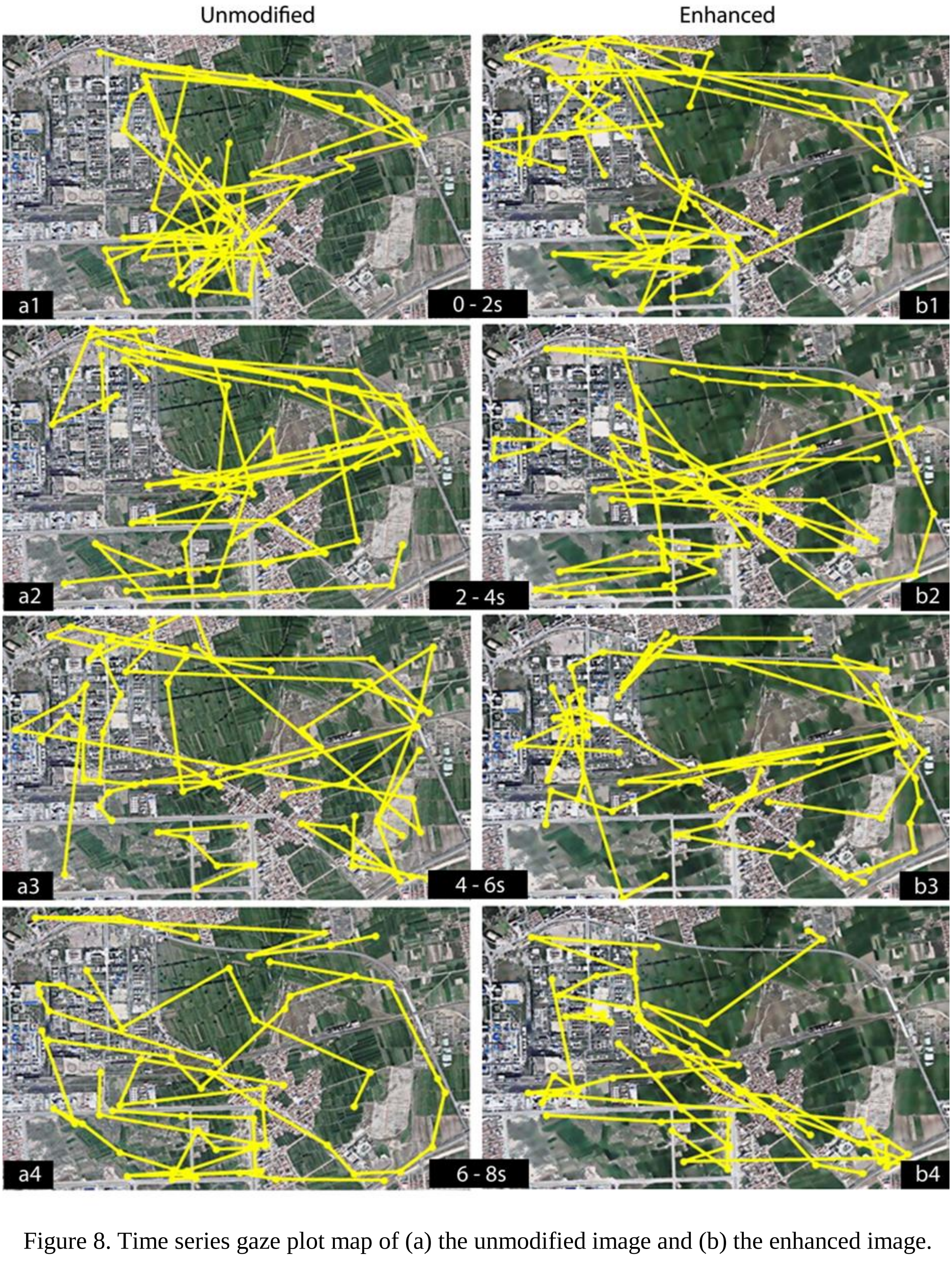

Figure 8. Time series gaze plot map of (a) the unmodified image and (b) the enhanced image.

Across all four two-second time intervals, fixation frequency and duration were higher on Level #1 AOIs for the unmodified image compared to the enhanced image (Figure 9a and 10a). Conversely, fixation frequency and duration were higher on Level #2 AOIs for the enhanced image compared to the unmodified image across the four time intervals Figure 9b and 10b). On the unmodified image, fixation frequency and duration on Level #1 AOIs exhibited a decline through the first three two-second time intervals, but showed a peak in the final two-second time period. On the enhanced image, fixation frequency and duration on Level #1 AOIs peaked in the first half of the experiment, but declined considerably in the second half. Thus, participants more commonly returned to Level #1 AOIs in the final two seconds of the experiment when visually searching the unmodified image, but more commonly maintained focus on Level #2 AOIs when visually searching the enhanced image. This visual search pattern across time further corroborates the qualitative findings above, indicating that participants' attention was guided more effectively to complex areas in the enhanced image as time passed.

Finally, participants fixated equally or less frequently on non-AOIs in the enhanced image across all time intervals and spent less time fixating on the non-AOIs in enhanced image across all time intervals (Figure 9c and 10c). Fixation frequency and duration on non-AOIs between the unmodified and enhanced imagery were near similar in the first two seconds. However, fixation frequency and duration decreased in the third and fourth seconds on the enhanced image, but continued to increase on the unmodified image. Thus, time series analysis of fixation frequency and duration on non-AOIs indicates that participants were able to better hone their visual search strategies away from non-AOIs and towards AOIs using the enhanced image.

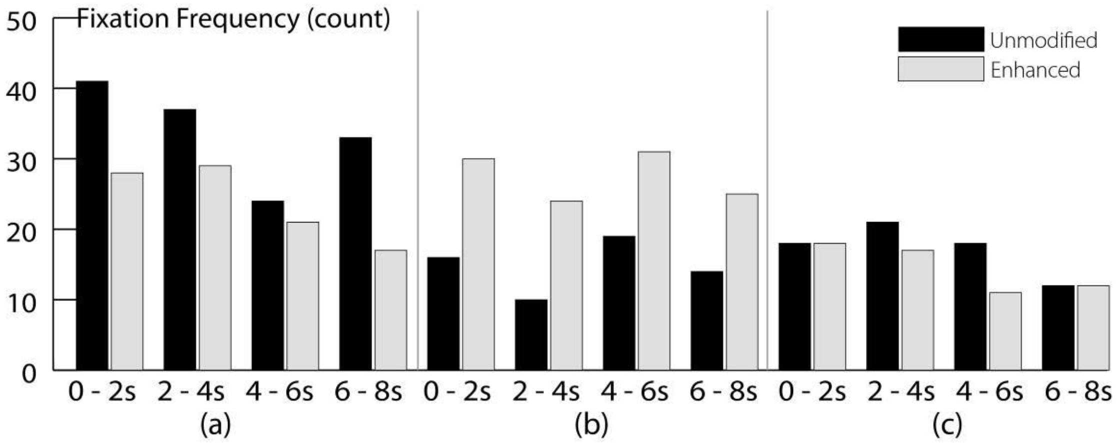

Figure 9. Fixation frequency on the unmodified image (black) and the enhanced image (grey) by (a) Level #1 AOI, (b) Level #2 AOI, and (c) non-AOI.

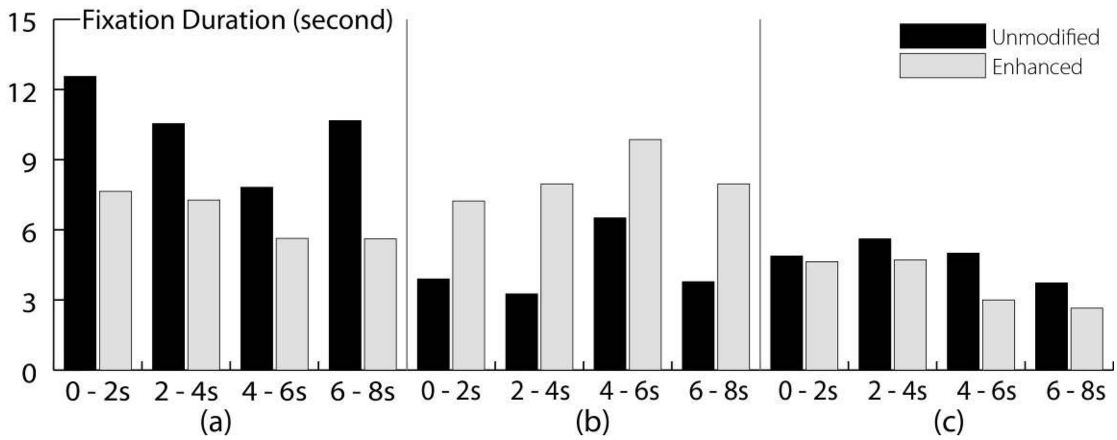

Figure 10. Fixation duration (seconds) on the unmodified image (black) and the enhanced image (grey) by (a) Level #1 AOI, (b) Level #2 AOI, and (c) non-AOI.

Quantitative Analysis of Effectiveness

Following qualitative analysis, a series of quantitative metrics were generated to determine if the identified patterns in visual search strategies between the unmodified and enhanced image were significantly different. Quantitative analysis of fixations and saccades began with investigation into effectiveness, which again was evaluated according to three categories of measures: extensiveness, frequency, and accuracy (Table 2); refer to Table 1 for an overview of the tested effectiveness metrics. Each category of effectiveness metrics is treated in turn in the following quantitative analysis of effectiveness.

Table 2. Descriptive and inferential statistics for effectiveness metrics.

Effectiveness		**Descriptive Statistics**				**Inferential Statistics**	
Extensiveness		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Saccades		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	Total saccade length	4628.50	1023.50	4549.04	1206.96	0.159	0.876
Frequency		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Fixations		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	All Fixations	26.30	2.98	26.30	4.06	0.000	1.000
	On AOI	19.40	4.06	20.50	2.95	-0.693	0.497
	Off AOI	6.90	4.23	5.80	3.05	0.667	0.513
	On Level #1 AOI	13.50	5.48	9.50	5.19	1.675	0.111
	On Level #2 AOI	5.90	3.96	11.00	4.27	-2.771	**0.013**
Saccades		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	Overall	25.30	2.98	25.30	4.06	0.000	1.000
Accuracy		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Fixations		*proportion*	*st.dev*	*proportion*	*st.dev*	*t-score*	*p-value*
	AOI vs. All	0.74	0.14	0.79	0.11	-0.839	0.412
	On L#1 AOI vs. All	0.51	0.2	0.34	0.18	2.022	0.058
	On L#2 AOI vs. All	0.23	0.15	0.44	0.24	-2.438	**0.025**

The first tested effectiveness metric was extensiveness. Fixation extensiveness describes the total number of AOIs receiving a fixation within a single experimental trial; we did not evaluate fixation extensiveness because the AOIs were aggregated into two overall levels of complexity, rather than discretized into a set of mutually exclusive regions (which would be more appropriate for conceptual point features than linear road features). Saccade extensiveness describes the total length of saccades during a single experimental trial, indicating the overall distance that the eye moved during the eight second time limit. The mean saccade length was 4628.50 screen pixels for the unmodified image and 4549.04 screen pixels for the enhanced image, resulting in a t-score of 0.159 ($p=0.876$). Thus, while participants on average scanned a slightly further distance with the unmodified image, this difference was not significant.

The second tested effectiveness metric was frequency. Fixation frequency describes the total number of fixations exhibited during a single experimental trial. Several metrics of fixation frequency were calculated to understand differences in fixations across AOIs: (1) all fixations, (2) fixations on any AOI, (3) fixations away from AOIs, (4) fixations on Level #1 AOIs, and (5) fixations on Level #2 AOIs. The mean frequency of all fixations was 26.30 for both the unmodified and enhanced imagery, resulting in a t-score of 0.000 (p=1.000). This similarity in performance suggests that the participants understood the experimental task (identification of road features) equally well between the unmodified and enhanced trials and that neither trial completely inhibited performance of the task.

There were differences between the unmodified and enhanced imagery in the frequency of fixations both on and off AOIs. The mean fixation frequency on AOIs was 19.40 and 20.50 for the unmodified and enhanced trials respectively, resulting in a t-score of -0.693 (p=0.497). Inversely, the mean fixation frequency off AOIs was 6.90 and 5.80 for the unmodified and enhanced trials respectively, resulting in a t-score of 0.667 (p=0.513). Thus, while the enhanced image did result in more fixations on the targeted AOIs (as indicated in Figure 9c), this difference was not significant.

The largest differences in fixation frequency between the unmodified and enhanced imagery were exhibited across the two levels of complexity. The mean fixation frequency on Level #1 AOIs was 13.50 for the unmodified image and 9.50 for the enhanced image, resulting in a t-score of 1.675 (p=0.111). Conversely, the mean fixation frequency on Level #2 AOIs was 5.90 for the unmodified image and 11.00 for the enhanced image, resulting in a t-score of -2.771 (p=0.013). Therefore, the enhanced image evoked significantly (at alpha=0.05) more fixations on the Level #2 AOIs than the unmodified image. Although not significant (at alpha=0.05), the unmodified image evoked many more fixations on Level #1 AOIs than the enhanced image. Given this result, and the insights revealed through the qualitative analysis above, we conclude that the unmodified and enhanced imagery supported identification of Level #1 AOIs equally effectively, but only the enhanced image supported identification of Level #2 AOIs. Thus, while participants were able to discriminate the more visually complex Level #2 AOIs in the enhanced image, we speculate that participants continued to interpret the same Level #1 AOIs in the unmodified image, unable to switch their visual search to Level #2 AOIs within the time limit.

Saccade frequency describes the total number of saccades exhibited during a single experimental trial. Like the mean frequency of all fixations, the mean saccade frequency was the same for both the unmodified and enhanced imagery (25.30), resulting in a t-score of 0.000 (p=1.000). It is important to note that while the mean fixation and saccade frequencies were the same between the unmodified and enhanced imagery, the standard deviations were much greater for the enhanced image, perhaps indicating that only a subset of participants were able to take advantage of the additional visual cues in the enhanced image (but those that did, were able to visually search the image much more effectively).

The third and final tested effectiveness metric was accuracy, which normalizes fixations and saccades on or off AOIs according to the total number of fixations. Because the mean fixation and saccade frequency was the same for both the unmodified and enhanced imagery, the resulting descriptive and inferential statistics only reinforce insights about effectiveness derived from quantitative analysis of fixation and saccade frequency. The mean fixation accuracy on AOIs was 74% for the unmodified image and 79% for the enhanced image, resulting in a t-score of -0.839 (p=0.412) and thus a non-significant difference (as with mean fixation frequency on AOIs). The mean fixation accuracy on Level #1 AOIs was 51% for the unmodified image and 34% for the enhanced image, resulting in a t-score of 2.022 (p=0.058), a difference that is significant at alpha=0.10, but not alpha=0.05. The mean fixation accuracy on Level #2 AOIs is 23% for the unmodified image and 44% for the enhanced image, resulting in a t-score of -2.438 (p=0.025), a difference in Level #2 AOIs that again is significant at alpha=0.05. The saccade accuracy was not calculated due to the lack of significant differences in saccade frequency and the computational intensity of the underlying line analysis.

Quantitative Analysis of Efficiency

Following quantitative analysis of effectiveness, visual search efficiency was investigated. Like effectiveness, quantitative analysis of efficiency was evaluated according to three categories of measures: duration, productivity, and time to fixation (Table 3). Again, a description of each efficiency metric is provided Table 1. Each category of efficiency metrics is discussed below.

The first tested efficiency metric was duration. Fixation duration describes the total time spend in fixations during a single experimental trial. As with fixation frequency (an effectiveness metric), five variations of this metric were calculated to understand nuances in fixation duration across AOI levels: (1) all fixations, (2) fixations on any AOI, (3) fixations away from AOIs, (4) fixations on Level #1 AOIs, and (5) fixations on Level #2 AOIs. The mean duration of all fixations was higher on the unmodified image (7826.00 milliseconds) compared to the enhanced image (7415.10 milliseconds), resulting in a t-score of 2.905 (p=0.009). Participants therefore spent significantly less time in each fixation (at alpha=0.01) when visually searching the enhanced image compared to unmodified image. When combining this quantitative finding with the insights into visual searching strategies derived from the above qualitative analysis, we speculate that participants more easily identified AOIs (road features) in the enhanced image and therefore could move more quickly to other areas of the image, whereas participants needed to dwell longer on the unmodified image before moving their attention elsewhere.

The differences in fixation duration both on and off AOIs were not significant between the enhanced and modified imagery. The mean fixation duration on AOIs was 5904.40 milliseconds for the unmodified image and 5916.50 milliseconds for the enhanced image, resulting in a t-score of -0.027 (p=0.979). Similarly, the mean fixation duration off AOIs was 1921.60 milliseconds for the unmodified image and 1498.60 milliseconds for the enhanced image, resulting in a t-score of 0.924 (p=0.368). It is important to note, however, that mean duration was significantly reduced for fixations off AOIs compared to fixations on AOIs for both the unmodified and enhanced imagery, again providing an indication that participants understood the experimental task during both trials, particularly the provided definition of an

AOI.

Table 3. Descriptive and inferential statistics for efficiency metrics.

Efficiency		**Descriptive Statistics**				**Inferential Statistics**	
Duration		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Fixations		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	All Fixations	7826.00	274.80	7415.10	352.96	2.905	**0.009**
	On AOI	5904.40	1188.00	5916.50	801.59	-0.027	0.979
	Off AOI	1921.60	111.35	1498.60	925.59	0.924	0.368
	On Level #1 AOI	4159.40	1677.75	2615.90	1520.85	2.155	**0.045**
	On Level #2 AOI	1745.00	1057.70	3300.60	1834.79	-2.323	**0.032**
Saccades		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	All Saccades	174.00	274.80	584.90	352.96	-2.905	**0.009**
Productivity		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Fixations		*proportion*	*st.dev*	*proportion*	*st.dev*	*t-score*	*p-value*
	Time on AOI	0.75	0.14	0.80	0.12	-0.794	0.438
Time to Fixation		***Unmodified***		***Enhanced***		***two-tailed t-test***	
Time to All Fixations		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	All Fixations	300.43	29.68	288.93	52.46	0.603	0.554
Time to First Fixation		*mean*	*st.dev*	*mean*	*st.dev*	*t-score*	*p-value*
	On AOI	254.80	365.33	71.60	226.41	1.348	0.194
	Off AOI	424.80	714.15	1448.89	1775.54	-1.683	0.111
	On Level #1 AOI	379.80	415.34	612.44	470.60	-1.145	0.268
	On Level #2 AOI	1299.00	1723.91	667.90	1365.85	0.889	0.386

Quantitative analysis of fixation duration by AOI level provided further evidence that participants engaged with Level #2 AOIs to a greater degree when visually searching the enhanced image. The mean fixation duration on Level #1 AOIs was 4159.40 and 2615.90 milliseconds for the unmodified and enhanced trials respectively, resulting in a t-score of 2.155 (p=0.045). Conversely, the mean fixation duration on Level #2 AOIs was 1745.00 and 3300.60 milliseconds for the unmodified and enhanced trials respectively, resulting in a t-score of -2.323 (p=0.032). Therefore, the unmodified image evoked significantly (at alpha=0.05) longer fixations on the Level #1 AOIs, while the enhanced image evoked significantly (at alpha=0.05) longer fixations on the Level #2 AOIs than the unmodified image. When paired with the above qualitative and quantitative analyses, this finding reveals two important differences in participant visual search strategies between the unmodified and enhanced imagery. First, participants could identify Level #1 AOIs much more quickly using the enhanced image compared to the unmodified image, showing that the enhancements did improve visual search efficiency of Level #1 AOIs. Second, participants were not able to discriminate Level #2 AOIs in the unmodified image, as the fixation duration on Level #2 AOIs was approximately the same as the fixation duration off AOIs (1745.00 milliseconds for Level #2 AOIs versus 1921.60 milliseconds for non-AOI); in other words, there is minimal evidence that participants would be able to discriminate Level #2 AOIs from non-AOI using the unmodified image, even if the time limit was extended. Thus, the two possibilities offered above in the qualitative analysis (participants identify Level #1 AOIs more quickly in the enhanced image, affording time to identify Level #2 AOIs, and participants could not resolve Level #2 AOIs in the unmodified image) together appear to explain differences in visual search strategies by level of complexity.

Saccade duration describes the total time spend in saccades during a single experimental trial. The mean saccade duration was 174.00 milliseconds for the unmodified image and 584.90 milliseconds for the enhanced image, resulting in a t-score of -2.905 ($p=0.009$). Thus, participants spent significantly (at αlpha=0.01) longer in saccades using the enhanced image compared to the unmodified image. This is an interesting finding, and one that superficially may suggest that participants were often ‘lost’ (i.e., unsure where to look) when using the enhanced image. However, combination of this quantitative finding with the above qualitative analysis suggests that the opposite is true; we instead speculate that the enhanced image afforded a greater amount of time to scan the image, as identification of AOIs required less time at both levels of complexity. It also is likely that participants could scan for longer periods (although not necessarily longer distances, as described above with saccade extensiveness) without incrementally pausing to interpret a feature, given the additional visual search cues provided by the image enhancements.

The second tested efficiency metric was productivity, which normalizes fixation or saccade duration according to the eight second time limit of the experiment to determine the percentage of time spent on the provided experimental task. Because the total fixation duration between unmodified and enhanced imagery was significantly different (see above), it is possible that the normalized productivity metrics could provide additional insight into differences in visual search strategies (unlike the normalized effectiveness metric of accuracy, as the fixation frequency was the same between trials). Participants spent 75% of their time fixating on AOIs (the experimental task) using the unmodified image and 80% of their time fixating on AOIs using the enhanced image, resulting in a t-score of -0.794 ($p=0.438$). Although there was an increase in productivity with the enhanced image, this was not a significant difference. We did not test productivity of Level #1 or #2 AOIs, as this distinction was not explained in the experimental task (i.e., it is only a component of our analysis)

The third and final tested efficiency metric was time to fixation. Two variants of the time to fixation metric were generated, time to all fixations (i.e., the fixation duration normalized by the fixation frequency) and time to first fixation (i.e., how long it took for the participant to fixate upon starting the experiment). The mean time to all fixations was 300.43 milliseconds with the unmodified image and 288.93 milliseconds with the enhanced image, resulting in a t-score of 0.603 ($p=0.554$). The duration per fixation of the enhanced image therefore is shorter than the unmodified image, but the difference is not significant.

The second variant, time to first fixation, was further delineated by type of fixation: (1) time to first fixation on AOI, (2) time to first fixation off AOI, (3) time to first fixation on Level #1 AOI, and (4) time to first fixation on Level #2 AOI. The mean time to first fixation on AOI was 254.80 milliseconds with the unmodified image and 71.60 milliseconds with the enhanced image, resulting in a t-score of 1.348 (p=0.194). Although the mean time to first fixation off AOI in the enhanced image was 1448.89 milliseconds, considerably longer than the 424.80 milliseconds in the unmodified image, the resulting t-score was -1.683 (p=0.111) and therefore did not reflect a significant difficult; this is due to the large amount of variation in first fixation off AOI across participants. The time to first fixation on Level #1 AOI was 379.80 milliseconds and 612.44 milliseconds for the unmodified and enhanced image, respectively, resulting in a t-score of -1.145 (p=0.268). Finally, the time to first fixation on Level #2 AOI was 1299.00 milliseconds and 667.90 milliseconds for the unmodified and enhanced image, respectively, resulting in a t-score of 0.889 (p=0.386). Thus, time to first fixation was not significant between the unmodified and enhanced imagery, regardless of the AOI receiving the first fixation.

Conclusion and Future Work

This article applied the visually enhanced methods on aerial imageries in an eye-movement experiment investigating the potential of the enhanced imagery basemaps for web mapping. Eye-movement metrics to evaluate the effectiveness and efficiency of participants' identification of specific features on aerial imageries were calculated and analyzed. The initial motivation of this work is to improve the cartographic design of web maps. And the investigation into the human visual search strategies for reading imagery basemap also can be helpful in study and practice on automated image interpretation.

We combined the qualitative analysis and quantitative analysis in methodology. Visual analytical approach was used in qualitative analysis. Gaze plot map, Fixation heat map, Saccade heat map and Time series gaze plot map were generated and presented in visual analysis to gain the overview of the participants' interpretation of the image trials. Visual interpretation of fixations and saccades alone provide initial evidence that the enhanced image improved identification of the AOIs. A quantitative analysis of effectiveness and efficiency was followed. Analysis of effectiveness relied on three broad characteristics of participant visual search strategies: Extensiveness, Frequency and Accuracy. Efficiency metrics include: Duration, Productivity and Time-to-fixation. Results show that compared to the unmodified image, participants of the enhanced image has a significantly higher accuracy of identifying Level#2 AOI roads but show insignificant difference searching roads in Level#1 AOI. The visual enhancements not only made the Level#1 AOI recognized easier but also guided the participants' attention to those areas which need more time to interpret. The efficiency evaluation results show that participants of the enhanced image had a much higher efficiency identifying roads on Level#1 AOI and spent much more time on Level#2 AOI because of its visual complexity. The Productivity and Time-to-fixation were also analyzed.

From these results, we conclude that the image enhancements improved both the effectiveness and efficiency in identifying areas of interest, particularly those previously concealed in more visually complex areas in the image. Compared to the unmodified image, the enhanced image is more applicable for basemaps in web mapping involving satellite images when map readers select what features they are interested in. Thus the image enhancement is a practicable method to be applied to the images as basemaps for use and interpretation in web mapping.

Guidelines for applying satellite imagery to web mapping as basemap can be derived from the experiment. Firstly, on one hand, by enhancing specific features of the remote sensing images, map readers' attention will be well guided to the corresponding areas to find the needed information more quickly and conveniently, which improves the readability of the map. For example, by enhancing the linear features such as roads of satellite images when map users intend to find roads information, they can identify the enhanced features more effectively and efficiently. On the other hand, by homogenizing or obscuring unrelated areas of images, map readers' attention can be avoided to focus these areas leaving more time to search needed information although this aspect was not the major motivation of this study. Secondly, as the remotely sensed imagery are now ubiquitous used as a basemap option of web mapping services, generalization of images (such as image enhancement reported here) and many other image processing methods can be considered to be applied to imagery in web mapping design. Combining the traditional abstracted vector maps and remotely sensed imagery processed with certain purposes in web map services to improve effectiveness and efficiency of users' task completion.

There were several constraints purposely introduced into the controlled experiment that inform possible directions for follow-up research. In the future, we can evaluate the effectiveness and efficiency of vector maps and compare them to the enhanced imageries. Thus we can make use of advantages of each other and get better combination of vector maps and satellite images for web mapping cartography. Considering the emerging of more and more interactive web maps, we can also explore different visual search strategies when provided with map interactivity common to the web (e.g., like a search box, panning, zooming, etc.)

Eye tracking method is an effective method for exploring map users' visual interpretation of remote sensing images. This method also can be used for investigating the potential of image enhancement, classification and other processes to reduce the redundancy of information and improve the quality of geospatial images. Combining eye-movement characteristics and remote sensing image has broad prospective applications.

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