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Using eye tracking to evaluate the usability of animated maps

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Cartographic animation has been developed and widely used in geo-visualisation and many other areas in recent years. The usability of animated maps is a key characteristic affecting map users' effectiveness and efficiency in accomplishing tasks. In this paper, an eye tracking approach was proposed as a visual analytics method to evaluate the usability of animated maps by capturing participants' eye movement data and quantitatively analysing the accuracy (effectiveness) and response time (efficiency) of users' task completion. In the study, a set of animated traffic maps represented by three important visual variables (colour hue, size and frequency) was used for the usability evaluation. The experimental results showed that the usability of these three visual variables for cartographic animation affects the usability of animated maps. Red, yellow, and aqua were found to convey map information more effectively than other colour hues. Size was found to be more usable than colour hues for both animated maps and static maps. Usability was not found to be proportional to the playback rate of animated maps. Furthermore, the usability of the frequency, colour hue, and size was found to be related to the display's size. We hope that the analysis approach presented in this paper and the results of this study will be of help in the design of cartographic animation displays with better usability.

usability, eye tracking approach, animated maps, visual variables

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With the growth of time-series spatial data and the wide application of dynamic geo-visualisation, cartographic animation has been developed and used in many areas. Digital maps and map systems, such as map animation, multicomponent map interfaces, web maps and virtual globes, are increasingly becoming more interactive and dynamic. The usability of animated maps influences the effectiveness and efficiency of cartographic animation information communication between the map maker and the map user. Visual variables are commonly used to describe the various perceived differences in map symbols that are used to represent static and dynamic geographic information. The usability of visual variables directly influences the effectiveness and efficiency of users' task completion when using animated maps. This paper seeks to answer the questions of how visual variables for animated maps affect people's understanding of geographic information and how the usability of animated maps should be evaluated.

Several studies have been conducted to evaluate the usability of maps (Andrienko et al., 2002; Alaçam et al., 2009; Manson et al., 2012). Many methods have been applied to assess the usability of visual variables of map symbols. Efforts to evaluate the usability of visual variables for static maps have also been made (Clarke, 1989; Leung et al., 2002; Lai et al., 2004; Opach, 2005).

Visual variables are commonly used to describe the various perceived differences in map symbols that are used to represent geographic information. For traditional static map

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*Corresponding author (email: dongweihua@bnu.edu.cn) symbols, the notion of a visual variable (which includes luminance, texture, colour, orientation, shape, and size) was developed by Bertin (1967; translated into English in 1983) and subsequently modified and extended by other scholars (McCleary, 1983; Morrison, 1984; Dibiase et al., 1992). For cartographic animation displays, scholars have proposed some visual variables that are unique to animated maps, such as duration, rate of change and order (Ehlschlaeger et al., 1997; Hearnshaw et al., 1994; DiBiase et al., 1992; Slocum et al., 2005). These visual variables are extended to include the display date (the time at which the change is initiated), frequency (the number of times identifiable forms are displayed) and synchronisation (the correspondence of two or more time series) (MacEachren, 2004; Slocum et al., 2005). Wolfe et al. (2004) summarised decades of experience in visual research and attention studies in the fields of psychology and neuroscience. The thinking is that colour, size, and direction are definitely visual variables that can attract and guide people's visual attention when these variables are displayed as static stimuli, but the usability of colour values (brightness) as a visual variable is debatable. For animated maps, colour hue, size, and frequency are commonly and widely used as visual variables. Therefore, in this study, these three visual variables were considered in the evaluation of usability.

The eye-tracking method utilises an eye tracker that collects data on eye movements, which are reflections of humans' inner processes of map interpretation. The information recorded by the eye tracker includes fixations (the coordinates of the eye on the screen for certain durations), saccades (rapid movements between fixations) and durations (the times spent on fixations or saccades) (Olivier, 2007; Webb et al., 2008). The eye tracking method was first applied to psychology and neurobiology and later applied in cartography and Geographical Information Science (GIS) (Rayner, 1998). In recent years, the use of eye tracking in cartography has become more sophisticated. Cartographers have employed eye tracking methods in perceptive and cognitive studies (Steinke, 1987). Many of these studies have focused on improving the design of the map interface (Çöltekin et al., 2009, 2010; Ooms et al., 2010) and participants' visual search strategies and map interpretation (Ooms et al., 2012a, 2012b). Most of these studies have used eye tracking with static stimuli (Brodersen et al., 2002; Fabrikant et al., 2008, 2010; Garlandini et al., 2009); studies involving interactive or animated stimuli have been surprisingly rare (Cöltekin et al., 2009). Because most eye tracking software is geared towards static stimuli, the associated analysis tools and methods are also focused on static stimuli. However, the current methods of conducting and analysing eye tracking experiments are ill suited for these types of maps. Therefore, visual analytics approaches with dynamic stimuli need to be developed.

In this study, we employ eye tracking to evaluate the usability of animated maps by quantitatively analysing the user's accuracy and response time for task completion with respect to three important visual variables (i.e., colour hue, size, and frequency).

1 Design of the experiment

1.1 Visual variable selection for animated maps

As mentioned above, visual variables (e.g., luminance, texture, colour, orientation, shape, size, etc.) for static maps are well discussed in literature. Among these visual variables, luminance (or brightness) is still debatable as a visual variable. Colour hue and size are more commonly and widely used in animated maps than the others (e.g., texture, orientation, shape). In addition, display frequency is a key variable for animated maps. Therefore, in this study, we chose these three visual variables (colour hue, size and frequency) as the test variables to evaluate the usability of animated maps, leaving the investigation of the other visual variables to follow-up research. In addition, the selection of the three variables is consistent with the observation of Wolfe et al. (2004) that visual variables, including size, colour value, frame rate and display format, have been proven in psychophysical studies to be able to guide visual attention and are used in state-of-the-art visual saliency models (Itti et al., 1998).

The tested maps can be divided into two categories, depending on the display size. The large display size (1280×1024 pixels) is the default screen of current desktop computers, and the small display size (480×320 pixels) is based on commonly used mobile phones and the screens of in-car navigation systems. For a given display size, different traffic flows were distinguished by different colours. Red to purple represents large to small traffic flows, respectively. The other method was to use line width to represent traffic flow, keeping the colour the same. Additionally, the line width was divided into 7 classes in comparison with the previous classification.

Relevant studies (Dang, 1998) indicate that in theory, for common map users, the largest classification number is between 5 and 7 for a monochrome map and between 8 and 11 for a colour map. Up to the largest theoretical classification number, the amount of information increases with the increasing classification number and strengthening of visual usability. However, once the largest theoretical classification number is exceeded, the amount of information decreases with the increasing classification number and the weakening of visual usability. Therefore, colour and width were both divided into 7 classes to produce better visual usability.

Another aim of this experiment was to explore the usability of different frequencies when the colour hue (or line width) is a certain value. The variation ranges of the frequencies were narrowed based on different situations. For example, for classification by colour, we selected 4, 5, 6, 7, and 8 frames per second as 5 groups to test large-display-size maps and 0.5, 1, 2, 3, and 4 frames per second to test small-display-size maps. For classification by line width, we selected 8, 9, 10, 11, and 12 frames per second to test large-display-size maps and 4, 5, 6, 7, and 8 frames per second to test small-display-size maps. Thus, the most effective frequency for each situation could be determined.

1.2 Participants

Fifty people (30 females and 20 males) aged 18 to 21 participated in the experiment. The sample size of the experiment was generally align with other eye tracking experiment (e.g., Garlandini et al., 2009; Çöltekin et al., 2010). These participants were undergraduate students from Beijing Normal University (BNU), with background in Education, Social Sciences, Arts, Business, Economics, Geography and Psychology. None of them suffer from colour blindness or colour weakness; they all have normal colour vision. They are all regular Internet users. The selection of these undergraduates was appropriate because they were not experts in the areas of cartography or geographic information system but did have basic skills in map use, as do most map users today. None of the participants was familiar with the traffic situation in Hong Kong, which was the experiment area selected to avoid the possible influence of participants' familiarity with the experiment materials.

1.3 Apparatus

We used the Tobii Studio (http://www.tobii.com/) to record the participants' eye movement data. The hardware used was the Tobii Eye Tracker (Tobii T120), which is a 17-inch TFT display with a screen resolution of 1280×1024 and a sampling rate of 120 Hz. The software used was Tobii Studio 1.0, installed on a ThinkPad laptop for direct and high-precision analyses. The equipment was set up in a quiet, private room at BNU to create a comfortable experiment environment. The participants accomplished the required task by themselves without assistance from others.

1.4 Material

In this study, 24-hour traffic flow data from HongKong was used to generate the animated maps. The maps were created based on the attribute values of the data by classifying the traffic flow on different roads at the same time and outputting the information in chronological order. The maps were divided into two categories: 1280×1024, which was the standard setting for the Eye Tracker screen and is representative of large-scale maps, and 480×320, which is representative of vehicle-mounted GPS and mobile phone screens. The resolution ratios of the small-scale maps were low when displayed on the Eye Tracker.

We dragged a group of 24 hours of dynamic traffic pictures into the timeline as the animated stimuli. Because the pictures were selected at random, it was necessary to sort them into a proper order and to give each picture a display time, which should be in inverse proportion to the frequency. Thus, an animated map (or a piece of a map) was created. Figure 1 provides examples of heat maps for 10:30 AM in HongKong.

1.5 Procedure

Before the test, we introduced the experiment briefly to the participants. The participants were then asked to sit in front of the Eye Tracker, which was connected to the computer in advance. Every participant took two change detection tests to find a comfortable posture and increase the accuracy of the instrument.

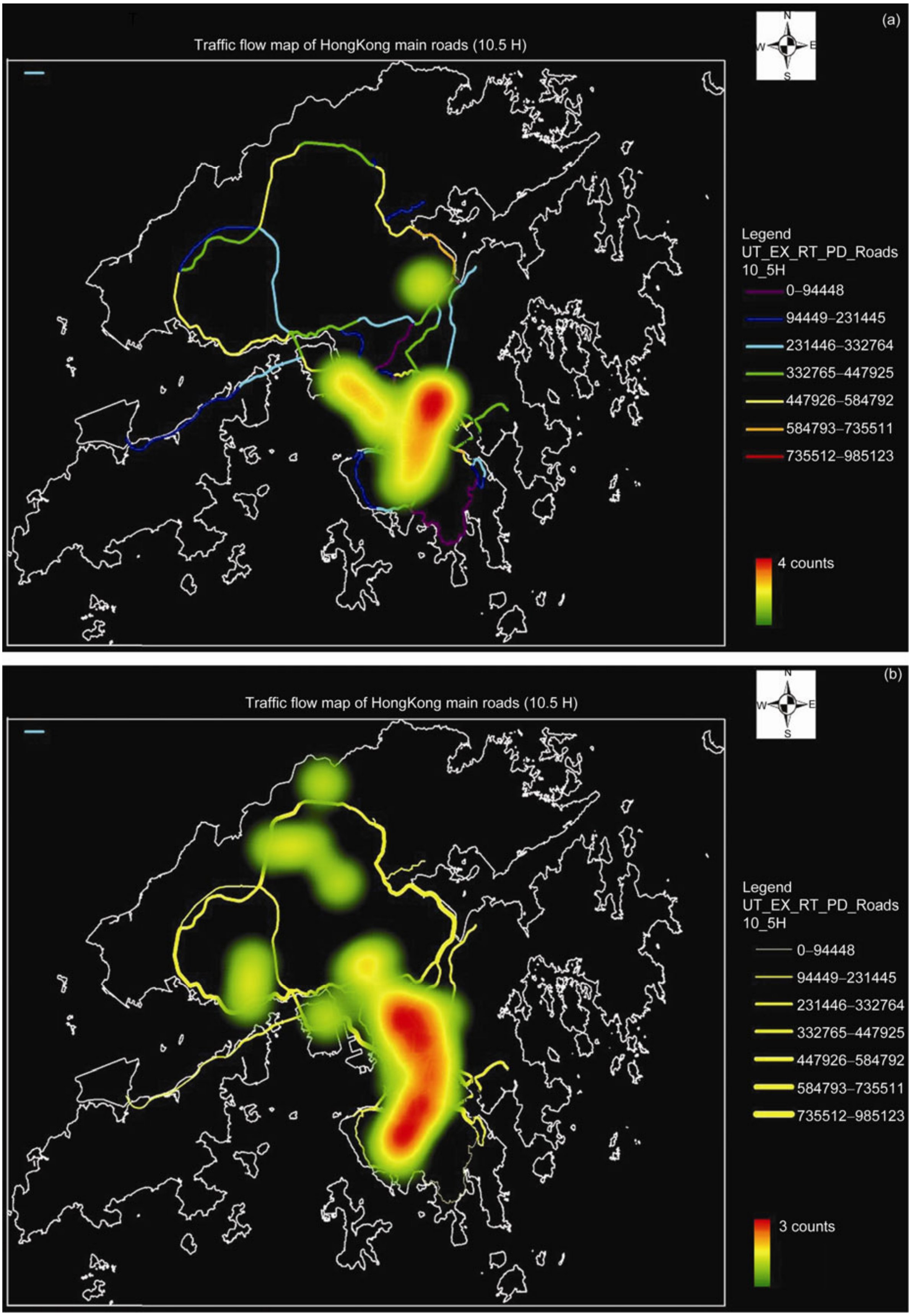
When the experiment began, the participants' task was to find the place of maximum flow and observe its changes over time. During the experiment, participants were tested through different means of expression, such as line colour and line width, at a constant frequency (6 fps for this group). To avoid the influence of visual fatigue and inertial thinking, the course followed a certain principle in sorting, alternating the appearance of large and small animated figures or alternating line widths and colour significations, thus making the cognitive outcomes of the participants more credible.

1.6 Usability evaluation method

Eye tracking provides the ability to record eye movements in an unobtrusive manner by relying on specialised equipment. In this experiment, we focused on exploring the eye tracking method to test the effectiveness and efficiency of three visual variables (colour hue, size and frequency) in evaluating the usability of animated maps. The effectiveness and efficiency of the visual variables can be measured by two quantitative indicators: accuracy (effectiveness) and response time (efficiency).

There are numerous ways in which to measure eye movement, such as duration, the number of fixations and saccades, time to first fixation, etc. We used the built-in areas of interest (AOI) tool in Tobii Studio to calculate the statistics of the eye movement data and generate *heat maps* (also shown in Figure 1). The goal of the data analysis was to collect quantitative data and then analyse the matching degree of the AOI. Therefore, the selected indicators included the accuracy and response time used for entering the target area for the first time.

The accuracy R is defined as number of fixations distributed in the appointed AOI as a percentage of the total number of fixation points:



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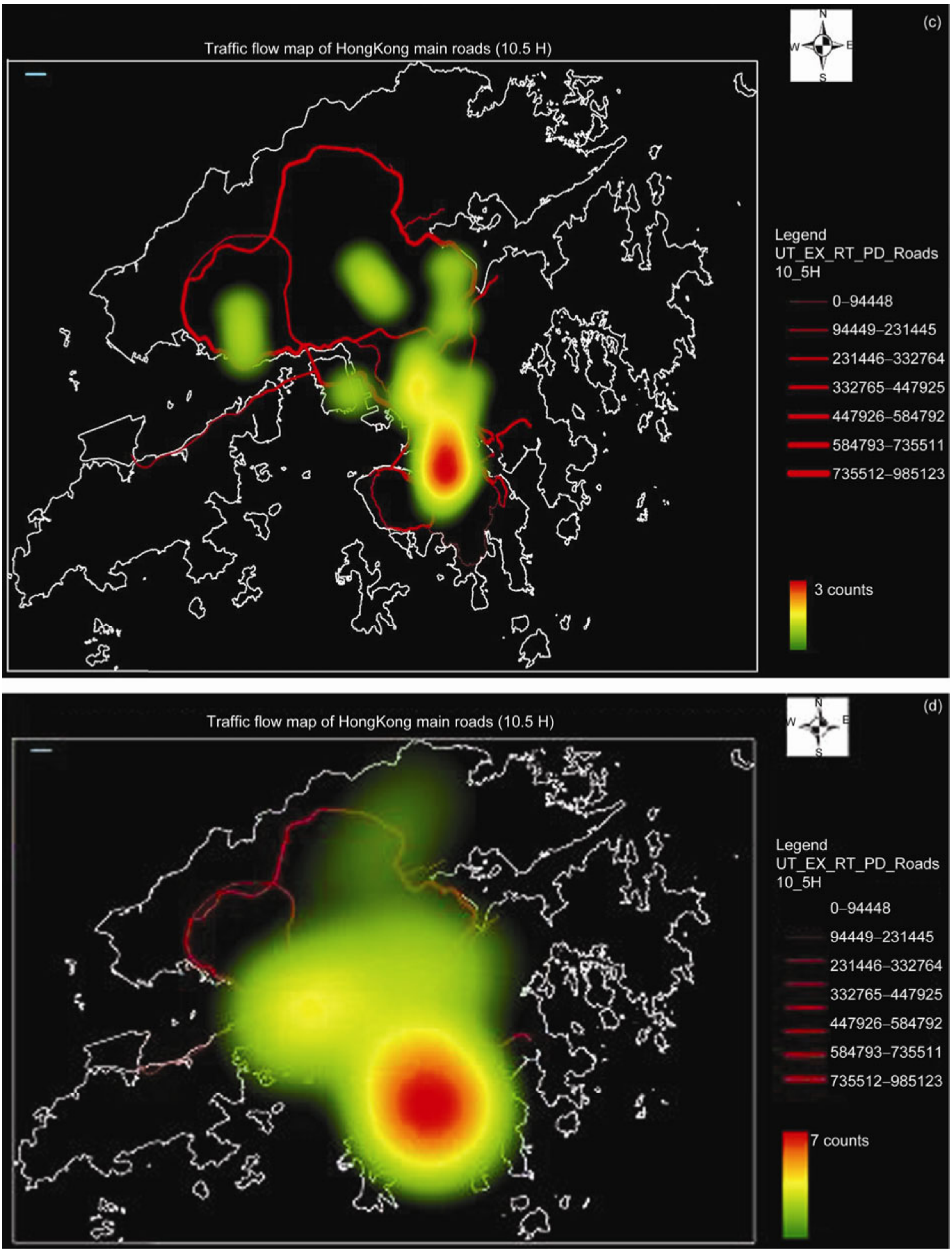

Figure 1 Eye tracking data for the HongKong traffic flow map at 10:30 AM of the day. Maps (a), (b), (c), and (d) are heat maps. In map (a), different traffic flows are distinguished by different colours (notably, in map (a), red is used to represent the maximum traffic flow). Map (b) uses line width to classify traffic flow while keeping the same colour in one map. Map (c) represents the map on a large scale, while map (d) represents the map on a small scale. (a) Heat map using color; (b) heat map using line width; (c) heat map using line width of large size map; (d) heat map using line width of small size map.

$$R = \frac{N_a}{N_t} \times 100\%, \tag{1}$$

where N_a is the number of fixations distributed in the designated AOI and N_t is the total number of fixations in a certain view. The number of fixations can be obtained from the software.

For response time, which is measured by the time spent before the first fixation locates in the AOI, it is not appropriate to use the participants' response times separately because everyone's response time is different. We used the average response time of all participants to measure efficiency:

$$T_a = \frac{\sum_{i=1}^{n} T_i}{n}, \tag{2}$$

where T_a is the average response time, T_i is the i-th participant's response time, and n is the total number of participants.

2 Analysis of results

2.1 Size (line width)

The experiment results were used to examine the usability of size (line width) for animated line symbols, based on the participants' values of R and T during the entire process. Based on the accuracy (see Figure 2), it can be observed that when a large-display-size map was presented through width, green was the most usable colour hue, followed by aqua, in an identical classification of width. Combined with efficiency (measured by response time), users showed a greater preference for aqua.

Each map used one colour to represent line features, and the seven test maps are in the same width classification. The experimental results (see Figure 3) show that using different widths to present traffic flow was a superior method in most cases. The invalid value shown in Figure 3(a) resulted from the special data represented by certain maps and can be disregarded. The visual usability and differences were not remarkable. From the results for the large- and small-display-size maps, we can see that the accuracy of the small-

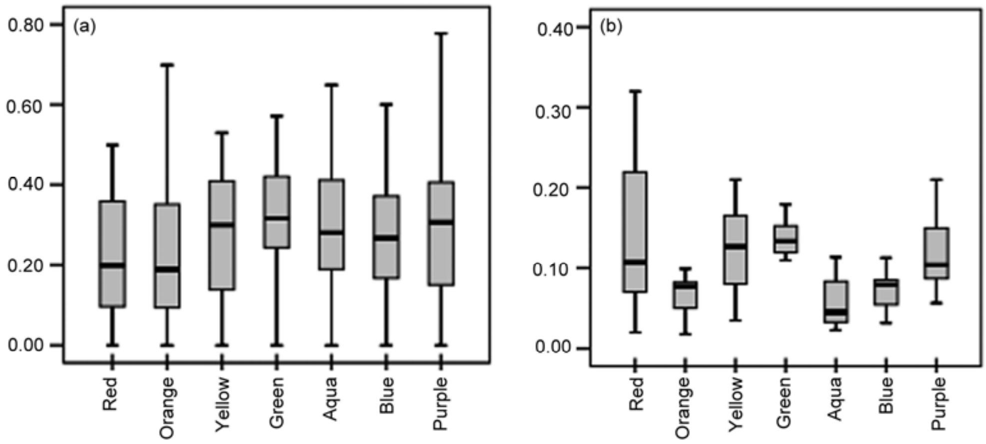

Figure 2 Comparison of accuracy and response time represented by line widths for the large-display-size map. (a) Accuracy; (b) response time.

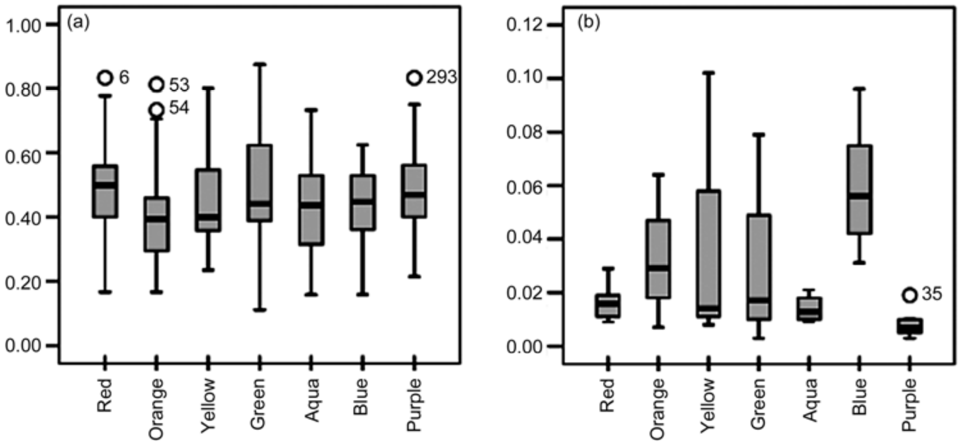

Figure 3 Comparison of accuracy and response time represented by different line widths in the small-display-size map. (a) Accuracy; (b) response time.

display-size maps was consistently above 40 percent, while most of the accuracy results for the large-display-size maps were between 20% and 30%, which indicates that the usability of size (line width) was more obvious in the small-display-size maps.

2.2 Colour hue

Using the same line width, we set different colour hues based on different traffic flow data segments. We used one of the seven colour hues (red/orange/yellow/green/aqua/blue/purple) to represent the maximum data segment, based on the traffic flow data. For example, if red represents the maximum, then the seven data levels are represented by red-orange-yellow-green-aqua-blue-purple. If orange represents the maximum, then the seven data levels are represented by orange-yellow-green-aqua-blue-purple-red, and so on for the other colours.

The results (see Figure 6) show that R was influenced by different colours and can vary greatly. According to the trend, the colour orange's ability to convey information was the weakest in the large-display-size map; it had the lowest R and highest T. The participants confirmed that if the background was black, orange was the most difficult colour to identify; blue tended to be more distinguishable.

According to the boxplot (see Figure 4), red and purple were the most usable colour hues for representing the maximum traffic flow data, while orange was the least usable.

Combined with the response time results, these results suggest that when red represents the maximum flow data, people need the least amount of time to grasp the information. These results are consistent with previously observed patterns of human visual perception (Berin et al., 1991). According to psychological-visual research, colours that have high brightness and a high degree of saturation are more striking, so they differ greatly from other colours in visibility. Therefore, people prefer to choose these colours as the main identifiable characteristics to distinguish different features.

Therefore, taking both R and T into consideration, we found that when the line width was the same in the large-display-size map, red was the most usable colour hue, followed by purple, and that orange was the least usable colour hue.

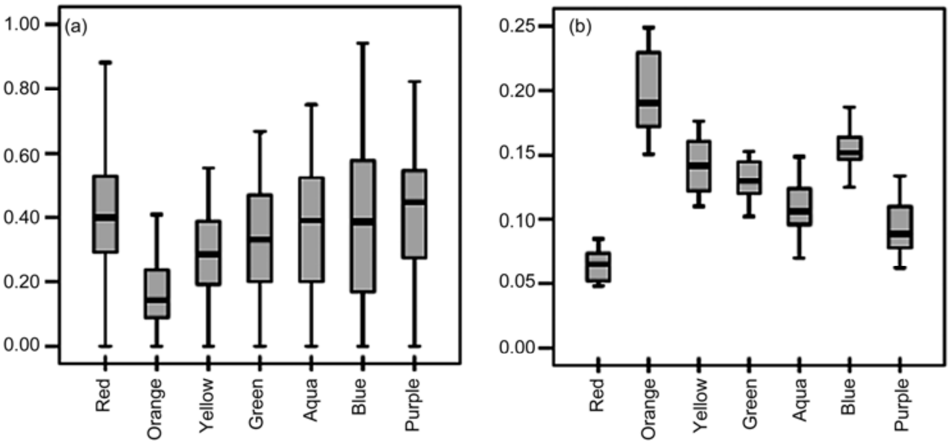

Figure 4 Comparison of accuracy and response time represented by different colours in the large-display-size map. (a) Accuracy; (b) response time.

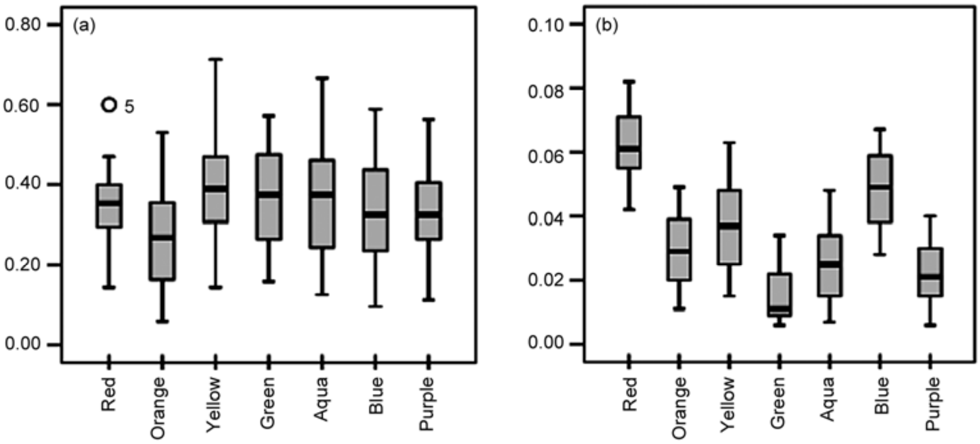

Figure 5 Comparison of accuracy and response time represented by different colour hues in the small-display-size map. (a) Accuracy; (b) response time.

As we can see from the results (see Figure 5), the accuracy was highest for yellow, followed by aqua and red, which were similar but slightly lower in accuracy than yellow, and in the same manner, orange had the lowest *R*. The response times shown in Figure 5(b) suggest that people need the least amount of time to identify green. Generally speaking, except for orange, the usability of these seven colours was similar, and among these colours, yellow and green were the most usable.

From the results summarised above, red was judged to be the most usable colour hue for representing traffic flow data in the large-display-size map, while yellow was judged to be the most usable in the small-display-size map. For both maps, orange was the least usable.

2.3 Frequency

We also designed an experiment to examine the usability of frequency based on a fixed size (line width). For this experiment, we used red to represent traffic flow data in both the large- and small-display-size maps.

Figure 6 shows that the accuracy rate was highest when the frequency was 6 fps and next highest when the frequency rate was 7/8 fps. When the frequency was 5 fps, the least response time was required, followed by 6 fps.

For small-display-size maps, with respect to accuracy (see Figure 7), when the frequency was 1 fps, the map was the most usable. With respect to response time, however, when the frequency was 3 fps, the participants need the least amount of time. When the frequency was 0.5 fps, the response time was the highest, but the accuracy was not. These results indicate that the usability of the frequency was not consistent with the change of rate. In addition, we came to the conclusion that a frequency of 2 fps was the most usable. During the process, we found that the participants gradually lost focus on the targets when the frequency was 0.5 or 1 fps or lower, indicating that these frequencies were not visually usable.

In the same manner, another experiment was performed to examine the usability of the frequency with fixed colour (yellow) and size (line width) for both large- and small-display-size maps.

The results (see Figure 8) show that the accuracy was the highest when the frequency was 10 fps, but this was not the most efficient frequency because the response time of 10 fps was the maximum. Taking both the accuracy and response time into account, 8 fps was the best frequency under these conditions.

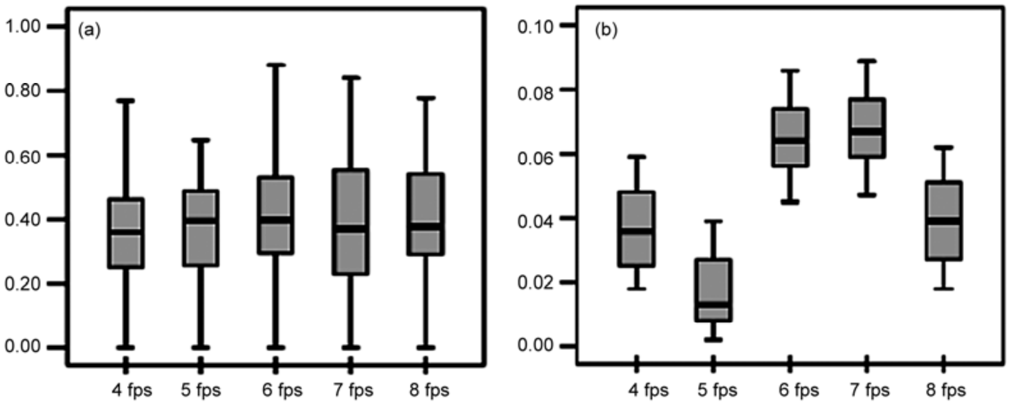

Figure 6 Results of different frequencies represented by colour (red represents the maximum) and fixed line width in the large-display-size map. (a) Accuracy; (b) response time.

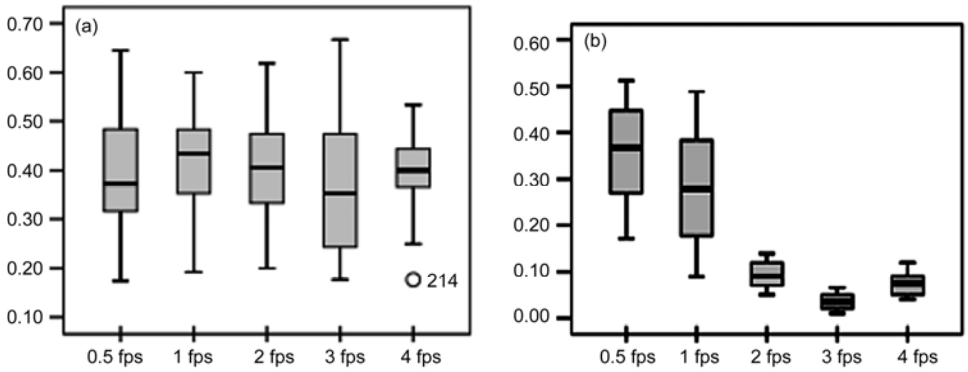

Figure 7 Result of different frequencies represented by colour (red represents the maximum) and fixed line width in the small-display-size map. (a) Accuracy; (b) response time.

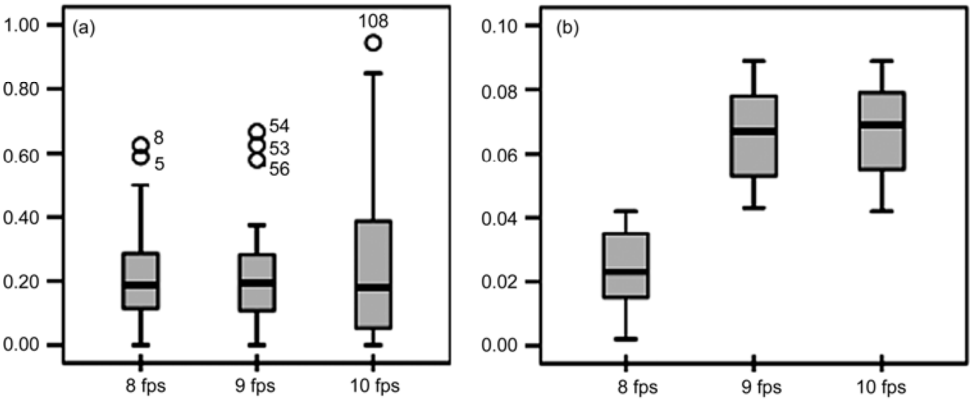

Figure 8 Results of different frequencies represented by line width and fixed colour (yellow) in a large-display-size map. (a) Accuracy; (b) response time.

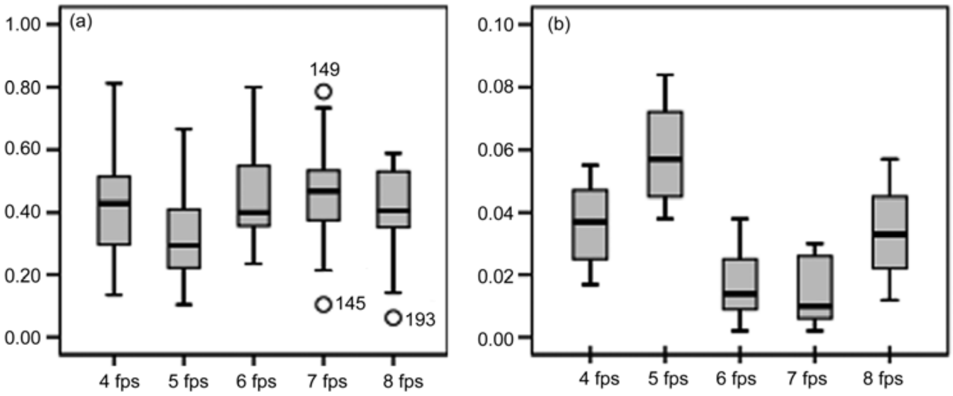

Figure 9 Results of different frequencies represented by line width and fixed colour (yellow) in the small display size map. (a) Accuracy; (b) response time.

Table 1 The most effective colours and line widths in the large- and small-display-size map

	Represented by colour hue	Represented by line width
Large-display-size map (1280×1024)	Red	Aqua
Small-display-size map (480 × 320)	Yellow	

As shown in Figure 9, frequencies of 6 and 7 fps had the highest accuracy. The map with a frequency of 7 fps had shorter response times than the map with a frequency of 6 fps. Therefore, 7 fps was judged to be more usable under these conditions.

3 Discussion

(1) Effective colour hue: The human ability to distinguish colours is not the same at different wavelengths. For example, at some parts of the spectrum near 480 and 580 nm, the human eye can see colour differences of 1 nm change, while at other parts of the spectrum, the human eye can distinguish a difference of approximately 1–2 nm changes. Therefore, the human eye is most sensitive to aqua (480 nm) and yellow (580 nm). Red has the longest wavelength in the visible light spectrum. This physical characteristic makes red bright and eye-catching. Purple, which has the shortest wavelength in the visible light spectrum, has the opposite tendencies. The experimental results suggest that red, yellow, and aqua are the most effective colours for conveying map information (see in Table 1), which is consistent with human intuitive visual perception.

(2) Effective size (line width): Through several comparisons, we found that the effects of traffic flow data represented by line width indicating quantities in addition to colours were better than those represented by colour only. These results are consistent with the findings of Bertin's research on static visual variables. This experiment's results showed that the inclusion of static visual variables representing quantitative gradation in animated maps was still applicable; that is to say, gradation represented by line width was more useful than gradation represented by colour, and the combination of the two was much more useful. This phenomenon was due to line width having a strong sense of quantity, so it is given priority in conveying quantitative changes.

(3) Effective frequency: Visual data and psychophysical experiments show that the human vision system has some

certainties of selectivity with respect to response time and frequency. When the flash frequency is too low, people feel things are static; at 8–16 Hz, people sense flashing; at 10–16 Hz, people sense flickering; at 20–50 Hz or more, the human eye regards flashing as a continuous light source, at which point the target's movements or changes will be imperceptible. In this experiment, the frequency ranged from 0.5 to 12 fps. Thus, the process of change will have a flash or flicker effect. Under the condition of flash/flicker, the size (line width) of the visual variable was the most effective for change detection, and it can effectively guide the animated map viewer's attention. As shown in Table 2, the experiment's results suggest the more effective frequencies that are suitable for visual perception differed for the two different display sizes. Thus, we should select appropriate frequencies based on the actual situation.

Only two common display sizes were included in the test, namely 1280×1024 and 480×320, so the results may be limited in applicability to those two sizes. However, other relevant research has shown that the smaller the size of a map is, the lower the frequency should be (Dong, 2012).

In addition, the experiment confirmed Bertin's (1967; translated into English in 1983) research on stable visual variables, that is, maps perform better when colour and line width are combined to represent different values on a map.

4 Conclusions

In this study, an eye-tracking approach was used to evaluate the usability of cartographic animation with three important visual variables: colour hue, size, and frequency. In the process, dynamic traffic maps were designed for a cartographic animation experiment. Accuracy (effectiveness) and response time (efficiency) were proposed for use in quantitatively analysis of users' eye movement data in Section 1.

As discussed in Sections 2 and 3, the main contribution of the research include: (1) The experimental results show that red, yellow, and aqua are more effective at conveying map information than other colour hues, which is consistent with human intuitive visual perception. (2) Furthermore, size (line width) is more accurate and effective than colour hues for animated maps in conveying quantitative changes, as with static maps. (3) The usability of frequency was not proportional to the playback rate of the animated map. Notably, the usability of frequency, colour hue and size were related to the display's size. For example, higher frequencies were more effective on a large-format display, such as 1280×1024 pixels with colour expression, while for a small display size, such as 480×320 pixels with colour expression, lower frequencies were more effective. We hope that the analysis approach presented in this paper and the results of this study will be useful in the design of animated maps with better usability.

Table 2 The most effective frequencies of different colours, line widths and sizes in the large- and small-display-size map

	Represented by colour	Represented by line width
Large-display-size map (1280×1024)	8 fps	8 fps
Small-display-size map (480 × 320)	2 fps	7 fps

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