



# Article Crisis Map Design Considering Map Cognition

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**Abstract:** Crisis maps play a significant role in emergency responses. Users are challenged to interpret a map rapidly in emergencies, with limited visual information-processing resources and under time pressure. Therefore, cartographic techniques are required to facilitate their map cognition. In this study, we analyzed the exogenous and endogenous disruptions that users needed to overcome when they were reading maps. The analysis results suggested that cartographers' taking the stressors into consideration could promote the cognitive fit between cartographers and users, improving map cognition and spatial information supply–demand matching. This paper also elaborates the course of map visual information processing and related graphic variables to visual attention attributes. To improve the users' map cognition in time-critical emergency situations, crisis map design principles and a methodology were proposed. We developed three fire emergency rescue road maps and performed two evaluations to verify the effectiveness of the principles. Our experiments showed that the principles could effectively facilitate the users' rapid map perception and proper understanding, by reducing their cognitive load, and could improve the quality of the crisis maps to some extent.

Keywords: crisis map; stressors; map cognition; visual attention; design principles

# 1. Introduction

Maps are important because they have the potential to represent large amounts of information regarding an area of interest within a single frame and in a comprehensible manner [1]. During crisis response, it is critical to share and understand complex spatial, thematic, and temporal information in a timely, visual, and compelling way [2]. Crisis maps are often generated during an event and must be interpreted quickly under pressure [3]. They are special-purpose thematic maps on which objects, phenomena, or actions specific to crisis management are highlighted using appropriate cartographic symbols and represented according to their importance [4]. As practical tools in crisis response, maps have intuitive, informative, well-targeted, and topic-prominent characters, providing the users with adequate visualization supports for situation analysis, decision-making, and risk communication.

Map reading is a complex process, in which people interpret various visual representations within the context of their informational needs, goals, knowledge, and experience [5]. Often risk is expressed in the form of maps [6]. During emergencies, all tasks are time sensitive, and the speed with which one can read and interpret a map can make the difference between lives and property being saved or lost [7]. When users read crisis maps in risky and unstable emergencies, they face many stressors, which are events that provoke stress [8]. Timely and accurate information about ongoing events is crucial for users seeking to effectively respond to a crisis [9]. Thus, map reading speed is of paramount importance [10]. Although map images are presented with legends, descriptive text, and



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). explanatory information in some cases, the interpretation of information in the map relies almost wholly on the map image alone [11]. As humans have limited visual informationprocessing resources, combined with time pressure and stress, users' map cognition is greatly hindered. A mechanism called selective attention, or visual attention, in the human visual system directs human vision to parts of interest in a visual scene. These parts are called salient regions, and their saliencies correspond to how much attention can be focused on them [12]. Therefore, cartographers must understand the process of visual information to be handled during map reading and, on this basis, utilize salient regions of the map image to promote the users' rapid perception, proper understanding, and effective map use in time-critical emergencies.

This paper is concerned with cartographic techniques for improving users' map cognition in emergencies, based on visual attention. This study discusses the background regarding previous related studies (Section 2), analyzes users' stressors in crisis map cognition (Section 3), discusses the cognitive fit in spatial information supply–demand matching, illustrates the process of visual information handled in a users' map cognition, and relates graphic variables to visual attention attributes (Section 4). Then, based on the perceptual template model (PTM), crisis map design principles and methods to reduce the users' cognitive workload are proposed (Section 5). Subsequently, three crisis maps are designed and evaluated to show the effectiveness and feasibility of the principles and methods (Section 6), and finally, the conclusions and future work in this field are presented (Section 7).

## 2. Related Research

## 2.1. Crisis Mapping

Crisis mapping is commonly used today to describe the holistic integration and visualization of location-enabled information to support a broad spectrum of humanitarian relief and emergency management activities [13]. It is a new genre of mapping for decision making and risk communication [14]. Cartographers recognized the key role of maps in emergency response a long time ago. At present, most studies aim to improve crisis mapping efficiency, and mainly focus on the important parts of mapping, such as mapping methods and symbology.

The template-based technique has become the major mode of crisis mapping, because of its advantages of a reusable template, high production efficiency, and automatic mapping [15]. Xu [16] proposed emergency thematic map template design principles and formed an emergency thematic map template by module combination. Qian [17] analyzed the design method and principles of a parametric template for emergency mapping and illustrated the fundamental problems with the example of earthquake emergency map template design. Zheng et al. [18] proposed a new rapid emergency map design method using template technology based on the knowledge obtained from a set of questionnaires and eye movement tracking experiments. Besides template technology, there have been numerous other research works about web-based mapping [13,19–22] and remote-sensing-data-based mapping [23–25].

With regard to crisis map symbology, Kostelnick and Hoeniges [26] summarized four general challenges related to the development of crisis map symbology, including methods for developing symbol taxonomies, considerations for designing crisis map symbols, standardization of crisis map symbols, and sharing and promulgation of crisis map symbols. Dymon [3] analyzed the existing emergency map symbology found in various forms, and proposed a theoretical framework for the design of an emergency mapping symbology. Anthony et al. [7] developed a visually enabled, web-based interactive symbol store to help crisis map makers share point symbols. In addition, there exists further studies of map symbols for specific emergency events [27–30].

Although many previous studies have an important guiding significance for improving crisis mapping efficiency, there has been less research on crisis map design from the perspective of map visual cognition. This article contributes to the field of crisis map design, while fully considering users' stressors in map cognition. We sought cartographic techniques that utilized salient regions of the map image to improve the users' map cognition in emergencies.

## 2.2. Spatial Cognition

Spatial cognition is the process whereby people understand the environments in which they are living, including the position, dependence, changes, and principles of matter and phenomenon [31]. Visual cognition is the main form of spatial cognition. The process of spatial cognition follows the general procedures by which a human knows about common things, including perception, representation, memory, and thinking. Two types of spatial cognition must be considered during map making and use: real world cognition for cartographers and map cognition for users, each of which is responsible for an important transformation [32]. The first transformation is an abstraction process from non-cartographic material to a map-presentable form, which is determined by the spatial cognition of the cartographers; the second is the interpretation of spatial information from a map, which is determined by the users. The level of spatial cognition is decisive for the extent and effect of the corresponding transformation, and directly influences the information load and map use.

Map cognition, namely geospatial cognition based on maps, realizes people's understanding of geographical space by reading a map [33]. Map cognition is affected by numerous factors, such as map information load, human visual physiology, reading habits, psychological factors, proficiency, and map use environments. Chen [34] analyzed the necessity for spatial cognition research on electronic maps and summarized the characteristics and main contents of electronic-map spatial cognition. Zheng [35] developed a personalized map cognition factor model and evaluated the suitability of personalized maps.

Some studies have explored the effects of emergencies on users' map cognition abilities. Du et al. [36] pointed out that the psychological constraints on emergency management had an adverse effect on users' map cognition. Zhou et al. [37] concluded that people experienced more difficulty reading maps under time pressure after conducting a wayfinding experiment using eye-tracking and a verbal protocol. Lin et al. [38] examined the effect of repeated exposures to indoor environments on people's indoor wayfinding performance under normal conditions and during a fire emergency, and the results revealed a significant negative impact of mental stress caused by the fire emergency on participants' wayfinding performance. Hammond [39] distinguished two groups of stressors that eventually increase the stress level of users. Exogenous disruptions arise from outside the system, such as fire, noise, heat, and interruptions from external physical breakdowns. Endogenous disruptions emerge from the task situation itself, including time pressure or a computer program with bugs.

#### 2.3. Visiual Attention

Although there is always more information in a scene, the brain can process only a fraction because of its limited computational capacity. Visual attention implements an information-processing bottleneck that allows only a small part of the incoming sensory information to reach the short-term memory and visual awareness [40]. The mechanism of visual attention significantly reduces the amount of data in human visual processing by enabling people to rapidly orientate towards the visual areas that carry more useful information. These specific areas that produce special stimuli in visual processing are considered to have visual saliency.

As a visualization of spatial information, a map is mainly processed by human vision. Visual attention is a crucial concept established in map design and map reading [41]. Fabrikant et al. [42] investigated the relationship between thematic relevance and perceptual salience in static weather map displays. The analysis results of eye-movement recordings showed that the salient display design affected the viewing behavior and response time of test participants. Hegarty et al. [43] concluded that users were more accurate if they

viewed maps that made task-relevant information more visually salient. Swienty et al. [44] proposed attention-guiding geo-visualization principles and methodologies to facilitate a user's attention when reading maps. These studies all explained that saliency-based map design can improve the efficiency of human visual processing.

## 3. Stressors in Crisis Map Cognition

#### 3.1. Relationship between Stress and Cognition

In a crisis, people may be faced with an urgent task requiring quick decision-making [45]. A wrong decision can aggravate the situation and lead to even more significant losses of life and property. Therefore, they are always under a huge amount of stress. Cognitive theories indicate that stress impairs performance by increasing the attention given to negative thoughts [46]. On the one hand, stress weakens cognitive functions, concentration, and logical and abstract thinking. This weakening is caused by a high level of emotional activity, which disturbs information processing [45].

On the other hand, cognitive load also increases the selective attention given to stressors, amplifies stress levels, and is detrimental to the ability to focus attention on other relevant issues [47]. The term cognitive load can be considered as the amount of work required to acquire and use information [48]. Since the working memory is vulnerable to overloading, two types of adverse cognitive load exist: intrinsic and extraneous [49]. The intrinsic cognitive load is related to the complexity of the visual information; it is more difficult to process complex information and this results in a higher cognitive load. The extraneous cognitive load will increase due to distractions or a poor representation of information [50]. After synthesizing the above two aspects, map elements have to be easily understood and interpreted for map use in a crisis situation [51].

## 3.2. Stressors

Based on the stressor theory of Hammond, we analyzed the stressors that affect the users' map cognition under emergencies. The exogenous and endogenous disruptions that users must deal with when reading maps are listed as Table 1.

Stressor	Main Items	Examples
	Emergency events	Earthquake, flood, etc.
Exogonous	Losses	Death toll, property loss, etc.
disruptions	Major hazard sources	Liquid oxygen storage tank, explosions factory, etc.
usiupuons	Significant hidden dangers	Potential landslides, hidden dangers in fire, etc.
	Unfavorable environmental conditions	Rugged topography, heavy rainstorm, etc.
	Ineffective map	Visual overload, inappropriate graphics, etc.
Endogenous	Emergency tasks	Medical rescue, crowd evacuation, etc.
disruptions	Psychological constraints on emergency management	Anxiety, fear, etc.
	User's negative background	Older age, poor map literacy, etc.

Table 1. Stressors affecting users' map cognition under emergencies.

Exogenous disruptions mainly include emergency events, losses, major hazard sources, significant hidden dangers, and unfavorable environmental conditions. In the Emergency Response Law of the People's Republic of China, emergency events are divided into four categories: natural disasters, accidental disasters, public health events, and social security events [52]. Losses refer to a significant amount of damage to life, property, resources, and the environment due to these events, such as the amount of deaths, injuries, and property damage. Major hazard sources refer to the sites or facilities that produce, transport, use, or store hazardous substances for a long time or temporarily, and where the quantity of hazardous substances is equal to or exceeds a critical quantity [53]. Significant hidden danger is a hidden dangerous factor which may cause severe casualties and substantial economic losses. Unfavorable environmental conditions refer to severe external environmental conditions, such as cold weather, snowy ground, or slippery roads.

As a part of objective reality, exogenous disruptions exert detrimental effects on the users' map cognition.

Endogenous disruptions mainly include ineffective maps, emergency tasks, psychological constraints on emergency management, and the user's negative background. The users' cognitive level is affected by the map itself. The lack of cartographic symbols for communication in crisis situations and visually overloaded maps reduce legibility and make orientation and understanding essential crisis information difficult [5]. Successful decision making during emergency situations depends on the availability and relevancy of information, presented in the right time and in an understandable way [54]. Emergency tasks refer to plans and schemes implemented for emergency rescue and loss reduction. Emergency tasks must be performed quickly, accurately, and effectively. The impact of emergency tasks on map cognition is mainly reflected in their complexity and time urgency. Psychological constraints on emergency management refer to the user's highly intense psychological status, usually manifested as excitement, anxiety, fear, or even mental conflict. Such a negative mental status directly affects the user's ability for map cognition. The user's background mainly involves age, spatial abilities, expertise [55], prior knowledge, education level, and cognitive style. Some studies have found that a user's background has different effects on visual cognition. People's reasoning, working memory, and perceptual speed decline with increasing age [56]. Spatial abilities affect performance, as well as memory, especially in spatial tasks [57]. Prior knowledge in a certain field can significantly improve their visual searching ability [58]. In addition, individual differences in human cognitive style affect user performance [59]. They can affect work with a map, at least in the subprocesses [60]. Therefore, the user's negative background, such as older age, poor map literacy, less emergency experience, low education level, or inappropriate cognitive style, can hamper their map cognition ability to some extent.

### 3.3. Cognitive Fit in Spatial Information Supply–Demand Matching

In rapid emergency responses, the spatial information required by users must be transmitted quickly and accurately by cartographers through crisis maps. From the users' viewpoint, their demands are the reliable obtainment of spatial information they need from the maps. From the cartographers' perspective, they aim to transmit the most valuable geospatial information in the most suitable presentation to users by fully considering their stressors. Fast information matching occurs between demand and supply, which involves crisis maps as the carrier. The matching is driven by emergency events and users' spatial information needs. The matching goal is the users' final efficient execution of tasks through an accurate information obtainment in the shortest time.

Supply-demand matching is based on two types of spatial cognition: real world cognition for cartographers, and map cognition for users. These two types of spatial cognition are related and facilitate each other, constituting a complete process of geospatial cognition. The subject of real-world cognition is cartographers. After they generate a mental map by real-world cognition, they produce crisis maps in an understandable way for the users. On the users' side, they obtain spatial information through the development of a mental map during map cognition. The process of spatial cognition and information matching is shown in Figure 1.

Building a mental map from a map is more difficult for the user than for cartographers, who map from the real world [61]. If cartographers completely consider the stressors, their understanding of the real world will become more pertinent and effective. They will form more detailed, specific, and targeted mental maps to guide their map design. This is helpful for users to build their mental maps. As cartographers fully consider stressors, users will form a more accurate mental map, which is similar to the cartographers' after their map cognition. Furthermore, the mental map will allow them a better recognition of the real world they are facing. This shows that efficient supply–demand matching depends on the similarity of the mental maps between cartographers and users. According to the theory of cognitive fit, the similarity between two types of mental maps can be regarded as the

degree of cognitive fit of cartographers and users. The cognitive fit theory suggests that a problem-solving task and the problem representation of that task influence the effectiveness of the problem-solving process [62]. The higher the cognitive fit, the more the usability and readability of the crisis map is enhanced. In other words, the more similar a users' mental map is to the cartographers', the more supply–demand matching it will achieve and the less map reading time will be required by the users.



Figure 1. Cognitive fit in spatial cognition and information matching.

#### 4. Crisis Map Visual Cognition

In contrary to analogue maps, where the production time leads to universality and maximal information saturation, nowadays cartographers should make maps for users with an appropriate amount of information in emergency [63]. In order to facilitate users in obtaining spatial information in the shortest time, it is important for cartographers to design a map that is most conducive to efficient human visual processing. Visual information is transmitted and analyzed along the visual pathway between specific brain structures in the map cognition process. Therefore, it is advantageous to understand the cognitive processes and the underlying functions of visual brain areas in order for cartographers to design cognitively adequate geovisualizations [44]. They can control the information flow using cartographic techniques, to attract users' visual attention and thus improve the users' map cognition by focusing their limited visual resources only on the spatial information they need urgently.

#### 4.1. Crisis Map Visual Cognition Process

Crisis map visual cognition can be divided into three steps: visual perception, visual information processing, and output of the cognitive outcome (Figure 2). Exogenous and endogenous disruptions persist throughout the cognition.



Figure 2. Crisis map visual cognition process.

#### 4.1.1. Visual Perception

Visual perception of crisis maps is mainly realized by the human visual attention mechanism, which can be divided into two processes, i.e., "bottom-up" and "top-down", coexisting in the human brain [64]. During the bottom-up process, attention is attracted exogenously towards stimuli of high physical salience [65]. This process is data-driven selective attention. During the top-down process, attention is directed endogenously to favor the processing of features, objects, or spatial locations that are associated with a task goal, reward, or potential danger [66]. This process is emergency task-driven selective attention. It is evident that emphasizing the task-relevant features in a salient way can improve both "bottom-up" and "top-down" visual perception.

# 4.1.2. Visual Information Processing

Crisis map information is first transmitted to the human retina through the above two forms of visual perception. Then, visual information enters the primary visual cortex. From there, visual information progresses along two parallel hierarchical streams: the ventral stream and the dorsal stream. The ventral stream, sometimes called the "what pathway", is mainly concerned with the recognition and identification of visual stimuli [40], such as shelters, hospitals, etc. The dorsal stream, sometimes called the "where pathway", is primarily concerned with the spatial properties of visual information, such as the rescue path, the scope of the floods, etc.

Studies have shown that map visual variables stimulate the what and where pathways selectively [44,67]. For example, size, color, and transparency can stimulate both the what and where pathways at the same time, while shape only works on the what pathway [44]. These findings provide a basis for cartographers to utilize some visual variables that act on the what and where pathways simultaneously, to attract the users' visual attention rapidly.

## 4.1.3. Output of Cognition

After the above processing, the map visual information is incorporated in the prefrontal cortex and matched with the user's existing domain knowledge. Finally, map cognitive results are output in the form of information, decision-making, and emergency action. Information refers to the desired spatial information the user obtained from a map, such as the effects and distribution of disasters, population transfer routes, and traffic disruptions. Decision-making refers to the user's selection of the most suitable solution from all possible schemes in the current emergency situations, after weighing up decision alternatives. Emergency action refers to the behaviors of the user in crisis response, such as transfer of victims, material distribution, and medical rescue. Obviously, among the outputs of map cognition, information is the basis for decision-making and emergency actions.

## 5. Crisis Map Design Principles and Method

## 5.1. Perceptual Template Model

The PTM is used to describe the internal signal processing mechanism of the visual system. It is a theoretical and empirical framework for directly assessing the mechanisms of attention by systematically manipulating the amount and/or characteristics of the external noise added to the signal stimuli and measuring the modulations of perceptual discriminability (signal and noise levels) in the cognitive processes [68]. The PTM includes five components: a perceptual template with certain tuning characteristics, a nonlinear transducer function, multiplicative internal noise, independent additive internal noise, and a decision process. Selective attention can improve task performance by interacting with a perceptual template [69]. According to the PTM theory, selective attention can be improved by three mechanisms: stimulus enhancement, external noise exclusion, and internal noise reduction. These mechanisms are similar to three aspects of signal processing: amplification, improved filtering, and modified gain control.

# 5.2. Crisis Map Design Principles Based on PTM

We can categorize objects related to a crisis map into three classes: geographic objects for risk data [70], cartographic objects for geographic objects that are portrayed on the map [70,71], and map graphics describing cartographic objects. To ensure a good cognitive fit between cartographers and users and to minimize adverse cognitive loads, we established the following crisis map design principles, based on the above attention mechanisms: (1) map contents should be thematically relevant; (2) relevant contents should be visually salient; and (3) crisis map graphics should be appropriate. The crisis map design principles and the fundamental mechanisms they are based on are illustrated in Figure 3.



Figure 3. Design principles of crisis maps based on PTM.

## 5.2.1. Relevance of Map Contents

As the complexity of emergency maps arises from the large amount of information they hold [70] and as the users search for visual information related to their tasks [72], the cartographers should depict the relevant geographic objects and omit irrelevant ones. The relevance of map contents is the key basis for selecting geographic objects that need to be expressed on the map. This rule corresponds to the mechanism of external noise exclusion in PTM. This mechanism filters external noise in stimulus signals, which focuses the selective attention on specific spatial regions or stimulus features. External noise exclusion only improves the performance at high external noise levels [73]. After the occurrence of a disaster, cartographers are faced with large amounts of spatial, thematic, and temporal information, which can be considered as a high external noise level. The selection of geographic objects is necessary and can be realized with the measure of relevance to disaster semantics (i.e., task relevance) and spatial semantics (i.e., spatial relevance). Cartographers select the relevant geographic objects, from coarse to fine, through a step-by-step analysis. The selection can effectively reduce the users' intrinsic cognitive load and greatly promote their top-down map cognition. The most valuable geospatial information that best fits the users' needs in the current situation is transmitted from the cartographers to the users through information filtration based on the relevance of map contents. Usually, the amount of the cartographic objects is reduced on a small-scale map, according to the relevance of geographic objects, their real-world counterparts, and vice versa.

Task relevance

Task relevance embodies the degree of satisfaction between geographic objects and user tasks. It is an effective method for cartographers to quantify map contents. Geographic objects can be coarsely assessed by the logical operations: "relevant" and "irrelevant". Taking a medical rescue map as an example, the geographic objects with medical and emergency rescue attributes are relevant, such as hospitals and temporary medical rescue places. Relevant geographic objects can be finely categorized into two groups, according to their task relevance: high-demand and medium-demand geographic objects. High-demand geographic objects are closely related to the users' tasks and need to be represented with cartographic objects in the most detailed manner. Sometimes, high-demand geographic objects can be further subdivided into several distinct levels, because of the complexity of the task: first-level geographic objects, second-level geographic objects, etc. While the mediumdemand geographic objects have less task relevance, they still have a certain relationship with the users' tasks. Although their corresponding cartographic objects are not those most directly used by the users, they often play an auxiliary role in emergency situations.

Spatial relevance

In addition to task relevance, geographic objects need to be evaluated by spatial relevance. Spatial relevance refers to the degree of spatial alienation between geographic objects and tasks, which is usually expressed by distance. The closer geographic objects are, the greater the spatial relevance they have. Still taking the medical rescue map as an example, closer hospitals or temporary medical rescue locations have a better availability for medical rescue tasks.

#### 5.2.2. Saliency of Relevant Map Contents

Cartographic objects are used to represent geographic objects on maps. Their expression is determined by the relevance of geographic objects. If cartographers use map visual variables reasonably, making the relevant information more salient, with the irrelevant information being removed or diluted, the efficiency of the users' visual searching and decision-making will be improved [72]. Geographic objects with high relevance and their corresponding cartographic objects should have high visual saliency, but should not be too salient, to avoid the loss of the more global geographic information required for spatial reference and successful orientation and navigation in the physical space [44]. This rule reflects the mechanism of stimulus enhancement in PTM. External noise exclusion filters irrelevant contents to reduce external noise. Stimulus enhancement can improve performance only when the external noise level is low [73]. As stimulus enhancement underlies the performance improvement at the attended location, the thematically relevant contents should be conveyed with cartographic objects in a visually salient manner. The saliency of the relevant content allows users to locate important information on the map more efficiently and rapidly. Moreover, in this way, users' attention can be directed to the critical information, and the users' extraneous cognitive load is reduced.

As discussed in Section 4, some visual variables can guide human visual attention and promote the decoding of map information. Therefore, different visual variables and their combinations can be utilized to express the relevant geographic objects, by enhancing the visuals of their corresponding cartographic objects.

# 5.2.3. Appropriate Map Graphics

Studies have shown that existing crisis maps are not always readable, because of graphic choices which are not always relevant [5]. Thus, the portrayal of cartographic objects with appropriate map graphics is important. This rule is based on the mechanism of internal noise reduction in PTM. Internal multiplicative noise reduction improves the performance at all levels of external noise. Map graphics is a system of symbols consisting of map symbols and of mutual relationships between symbols (syntactic dimension), the relationship of symbols according to the presented objects (semantic dimension), and the relationship of a user with the symbols (pragmatic dimension) [74]. Map graphics include basic geometric and graphic elements (point, line, and area) and cartographic symbols primarily used to depict the position and quality of objects [75]. Map graphics are especially significant for communication in emergencies, because the quick and correct interpretation of maps and increase users' extraneous cognitive loads, because they fail to portray cartographic objects clearly and effectively.

Map graphics should meet various demands. Frangeö laid down the conditions that should be fulfilled to meet these demands [76]. To decrease the users' cognitive overheads, cartographers should refer to these conditions to ensure the appropriate usage of map graphics when crisis maps are designed.

## 5.3. Crisis Map Design Method

We followed the above-mentioned design principles by adopting the design method proposed in [77]. The design includes two major visual layers: the spatial reference that offers the context for the focal information is in the visual background (base map), while the thematic information is in the visual foreground. The contrast of the visual foreground and background should be increased, and the visual hierarchy of related and non-related geographic objects should be highlighted to accelerate visual information processing.

## 5.3.1. Base Map

The base map also shows the relationship between emergency thematic information and the general geographic environment, besides the function of orientation and positioning. The selection of geographic objects to be depicted with cartographic objects on the base map should take their relevance into account. We should not excessively ignore the base map contents, because oversimplification will result in a gap between thematic information and the base map. Similarly, we should not select too much content, because overloading will result in the insufficient prominence of the emergency thematic information. For example, the base map of natural disaster maps generally contains geomorphology, but public health crisis maps do not. This stems from the fact that natural disasters often destroy landforms, while public health emergencies have no relationship with landform, so it can be ignored [17]. Factors affecting content selection include scale and map demonstration methods, except for the relevance of geographic objects. The base map should be designed in the least salient manner, with appropriate map graphics to produce a continuum for the users' visual searching efficiency.

# 5.3.2. Thematic Information Visual Layer

The thematic information visual layer is the primary information source for map users. Geographic objects with high relevance should be encoded using cartographic objects in a salient manner to capture users' visual attention quickly and make their attention moderately persistent. We choose the size and color to improve the visual saliency of cartographic objects, and increase the contrast between the base map and the thematic information visual layer with transparency, because the above three visual variables can stimulate both the what and where pathways simultaneously. In addition, the selected color should be consistent with its symbolism [78]; for example, red should represent danger, whereas green safety.

# 6. Crisis Map Design and Evaluation

# 6.1. Crisis Map Design Case

We used the above-mentioned method to produce a fire emergency rescue road map, which is a spatial information backup for fire crews after fire and traffic accidents occur. The geographic objects depicted with cartographic objects on the base map include schools, shopping centers, parks, rivers, residential areas, etc. Their corresponding cartographic objects as an auxiliary when reading maps should not dominate the visualization, and their visual differences should not be very large. The thematic information visual layer includes the route, fire brigade station, and accident site, etc. These geographic objects should be represented with salient cartographic objects to ensure certain visual differences between the background and foreground. We produced another two maps on the same theme to verify the effectiveness of the fire emergency rescue road map design. Figure 4a shows a non-relevance filtered and non-saliency map. Figure 4b is a relevance filtered but non-saliency map. Figure 4c is a relevance filtered and saliency map. The three maps are shown in Figure 4.



**Figure 4.** Three different fire emergency rescue road maps: (**a**) non-relevance filtered and non-saliency map; (**b**) relevance filtered but non-saliency map; and (**c**) relevance filtered and saliency map.

#### 6.2. Evaluation of the Map

We used two methods to test the design of the three maps. The first was Itti's visual saliency model, aiming at the evaluation of bottom-up map cognition [40]. The second was a map reaction time experiment, targeting the evaluation of top-down map cognition.

## 6.2.1. Model Based Evaluation

Itti's visual saliency model is bottom-up guided. It simulates users' attention focus and visual conversion when they are handling images. The model can not only predict users' gaze paths and attention fixation positions, but also compute their number of visual conversions and reading time. An attention-based map that indicates the most salient regions can be generated from the model. Figure 5 shows the results calculated with the model for the three maps in Figure 4. The areas enclosed by blue lines in Figure 5a1–a3 represent eye fixation positions. The red lines are the predictions of the users' visual scan paths made by the model. Irregular faculae in the attention-based maps, shown in Figure 5b1–b3, denote the most salient regions in the corresponding maps.



**Figure 5.** The scan paths and salient regions computed with the Itti model: (**a1**) the scan paths of the non-relevance filtered and non-saliency map; (**b1**) the salient regions of the non-relevance filtered and non-saliency map; (**a2**) the scan paths of the relevance filtered but non-saliency map; (**b2**) the salient regions of the relevance filtered but non-saliency map; (**b2**) the salient regions of the relevance filtered but non-saliency map; (**b2**) the salient regions of the relevance filtered but non-saliency map; (**b2**) the salient regions of the relevance filtered but non-saliency map; (**b2**) the salient regions of the relevance filtered and saliency map; (**b3**) the salient regions of the relevance filtered and saliency map.

For the map in Figure 4a, information was not relevant filtered and was not visualized in a salient manner. The scan paths, shown in Figure 5a1, not only pass through the cartographic objects related to the users' task, such as the accident site and the fire brigade station, but also the unrelated objects, such as rivers, parks, schools, and residential areas. The salient area, shown in Figure 5b1, shows some uncorrelated objects falling in the salient areas, and they occupy a part of the users' attention and increase the map cognitive load.

Figure 4b is the relevance filtered but non-saliency map. The scan paths, shown in Figure 5a2, pass through the relevant objects, such as the accident site and the fire brigade station, but the scan path is spread throughout the map. Similarly, the saliency faculae in Figure 5b2 cover a big area, which indicates the low efficiency and high time requirement for reading the map.

For the map in Figure 4c, the information was relevance filtered and visualized in a salient way. The scan paths completely pass through the most relevant cartographic objects, as shown in Figure 5a3. This suggests that attention is attracted by the most relevant objects when reading the map. The saliency area calculated by the model, shown in Figure 5b3, coincides with the location of cartographic objects in the thematic information visual layer,

which indicates that the relevant information has a higher saliency and can capture the user's visual attention at the first instance.

The Itti's visual saliency model can also calculate the cumulative query time of cartographic objects and visual conversions by assuming users are reading the maps, as shown in Table 2. The longer the cumulative time, the higher the time cost for map reading. The more the visual conversions, the higher the efficiency in capturing attention. Table 2 shows that (1) the model cannot detect the route in the maps of Figure 4a,b, so their visual conversions are 0. (2) The query time of the cartographic objects in the thematic information layer of the map in Figure 4c was generally shorter than that of Figure 4a,b. (3) The cartographic objects in the map thematic information layer in Figure 4c have more visual conversions than Figure 4a,b. (4) For the map in Figure 4c, the query time of cartographic objects in the thematic information layer was far less than that of the base map. (5) For the map in Figure 4c, the cartographic objects in the thematic information layer was far less than that of the base map. (5) For the map in Figure 4c, the cartographic objects in the thematic information layer have more visual conversions than the base map.

Table 2. Query time of cartographic objects and visual conversions.

Man	Thematic Layer					Base Map	
Map	Accident Site	Fire Brigade Station	Route	<b>Residential Areas</b>	Park	Accident Site	
Figure 4a map	Query time	101.1 ms	160.1 ms	/	290.9 ms	380.4 ms	
	Visual conversions	2	2	0	4	1	
Figure 4b map	Query time	97.7 ms	174.0 ms	/	238.7 ms	297.5 ms	
	Visual conversions	3	3	0	2	1	
Figure 4c map	Query time	94.4 ms	175.8 ms	183.1 ms	573.4 ms	382.5 ms	
	Visual conversions	8	5	6	3	2	

The Note: '/' means Itti's visual saliency model could not detect the route.

The above experimental results show that our proposed crisis map design principles and methods can reduce the users' query time for acquiring relevant information by catching their attention effectively in bottom-up map cognition.

## 6.2.2. Empirical Evaluation: The Reaction Time Experiment

Itti's visual saliency model proves that the map in Figure 4c has a strong "bottom-up" visual guidance attribute. To evaluate the top-down map cognitive effect, we used E-Prime 2.0 software to design an experiment to obtain the reaction time for users reading the three maps in Figure 4.

• Participants

The study sample comprised 60 right-handed students (32 males, 28 females) of the Lanzhou Jiaotong University, aged 21–25 years (M = 24.81; SD = 0.89). They all reported normal or corrected-to-normal vision and no neurological diseases. Before the experiment, we assessed them with a state-trait anxiety inventory form (STAI-Form Y) [79], and the results showed that their scores were lower than the norm.

Experimental materials

Two types of experimental materials were employed: the three maps mentioned above, and 240 s video clips about various historical disasters. The video clips were utilized to induce a state anxiety in the subjects, to simulate their psychological state in emergencies. Before the formal experiment, we recruited another 10 volunteers to validate the video clips for inducing a state of anxiety using E-Prime 2.0 software. The 10 volunteers were required to fill in the STAI-Form Y before and after watching video clips, and their scores were tested by the paired-sample *t*-test. The evaluation results of the video clips are presented in Table 3.

T Matched	$(M \pm SD)$	Ct.I Emer Maar	L	Sia		
Before	After	Std.Error Mean	L	Sig.	Norm ( $w \pm 5D$ )	
$30.45\pm7.18$	$52.70\pm5.82$	-22.25	-18.845	0.000	$45.31 \pm 11.99$	

Table 3. Evaluation of inducing anxiety from the video clips.

The results showed that there was a significant difference in the scores of the STAI-Form Y before and after the induction of a state of anxiety (t(9) = -22.25, p < 0.001), and the anxiety levels of the volunteers were higher than the norm (52.70 > 45.31), indicating the video clips are effective for anxiety arousal.

Procedure

Sixty participants were divided into three groups (A, B, C), with twenty people in each, in which group A and group B both contained eleven males and nine females, and group C had ten males and ten females. The experiment was conducted under quiet and room temperature conditions, according to the paradigm of visual searching. Each participant was asked to wear headphones to complete the test independently on the computer. Before the experiment started, the procedure was explained to the participants. However, no information regarding the study purpose was given, to avoid a response bias [80,81]. In the experiment, the participants were asked to find the targets on the map according to the instruction and then make the corresponding key response. The computer automatically recorded the key response of the participants, and the time unit was milliseconds. To maximize the simulation of emergencies, the subjects were required to respond as quickly as possible, on the premise of ensuring the correct rate.

The experiment consisted of three trials. Each group carried out a trial on the map corresponding to its group name in Figure 4. First, the video clips were shown to each participant to arouse anxiety. Then, we assigned a visual target to each participant, told him/her to search for it on the map in the shortest time possible and click the target with the mouse. Next, we presented a 1000 ms fixation "+" for the participant. Finally, the participant began to search for the targets on the map, including the accident site, the fire brigade station, and the route, and we recorded the time from the map appearance to the mouse click. As the route is a line symbol, the participants were told to click on a position that was close to it as possible. Each participant searched three times and 20 participants in each group completed a trial. The experimental process followed by each participant is shown in Figure 6.



Figure 6. Experimental process of crisis map reaction time evaluation.

• Results

We obtained 180 mouse clicks after three trials. For each map, the mouse click accuracy and reaction time is listed in Table 4. The reaction times of the three groups were tested using a paired-sample t-test, and the results are presented in Table 5. The reaction time of 20 participants in group A, group B and group C is shown in Tables A1–A3 in the Appendix A.

	Group A	(Figure 4a M	ap)	Group B	(Figure 4b M	lap)	Group C	C (Figure 4c N	lap)
Cartographic Objects	Fire Brigade Station	Route	Accident Site	Fire Brigade Station	Route	Accident Site	Fire Brigade Station	Route	Accident Site
Accuracy Average time	100% 1257 ms	85% 1280 ms	98% 1251 ms	100% 805 ms	80% 815 ms	100% 804 ms	100% 675 ms	90% 680 ms	100% 679 ms
Overall average time	12	262.67 ms			808 ms			678 ms	

Table 4. The experimental accuracy and reaction time for each group.

Table 5. Paired samples test of map reaction time.

Datas				61-		
Pai	Pairs		Std.Deviation	Std.Error Mean	τ	51g.
Pair 1	A-B	454.67	217.15	28.03	16.22	0.000
Pair 2	A-C	584.67	240.45	31.04	18.83	0.000
Pair 3	B-C	130.00	94.91	12.25	10.61	0.000

The following conclusions can be drawn from Tables 4 and 5:

- (1) Compared with group A, groups B and C spent less time, because the Figure 4a map tested by group A did not filter the irrelevant contents, whereas the maps tested by group B (t(59) = 16.22, p < 0.001) and group C (t(59) = 18.83, p < 0.001) filtered the irrelevant contents. The reduction of distractors in the Figure 4b, c maps significantly improved the performance of the participants.
- (2) Compared with group B, group C (t(59) = 10.61, p < 0.001) took less time. Although the Figure 4b map filtered irrelevant contents, the geographic objects with high relevance had the same visual saliency with other objects, creating little difference between all cartographic objects on the map. The salient design provided the best performance in group C.
- (3) The fact that group C spent the least time and had the highest accuracy implied the effectiveness and feasibility of our map design principles and methods.

## 7. Conclusions

Crisis maps play a significant role in emergency management. In essence, crisis maps are a special type of thematic map. Their special purpose and environment make their visualization design different from ordinary thematic maps. We studied the design of crisis map from the perspective of map cognition. The stressors, namely the exogenous and endogenous disruptions in emergencies, affect users' cognitive performance, while the cognitive load amplifies stress levels. Considering the stressors when designing a crisis map will promote the cognitive fit between the cartographers and the users during the spatial information supply–demand matching. To create more effective maps for use in emergencies, we established crisis map design principles and a methodology based on the visual attention mechanism and PTM. The outcomes of Itti's visual saliency model and the reaction time experiment verified the efficiency of the principles and methods in both for bottom-up and top-down map cognition.

Recording eye-movement was also important to measure a user's cognitive workload [82] and to investigate top-down driven activities. Swienty et al. utilized Itti's model to pre-evaluate geovisualization designs, then used more precise eye movement recordings to confirm the validity of their approach [44]. In the future, we will also perform eye-movement experiments to perform further evaluation. In addition, we will design more types of crisis map to verify the effectiveness of our proposed principles. **Author Contributions:** All the authors contributed to the crisis map design principles and this manuscript. Ping Du proposed the methodology and wrote the draft of the manuscript. Dingkai Li analyzed the stressors and performed the experiments. Tao Liu analyzed the results of evaluation. Liming Zhang, Xiaoxia Yang and Yikun Li guided the research and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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# Appendix A

De d'élés este Massalaur	Reaction Time of Searching Visual Targets (ms)				
Participants Number	Fire Brigade Station	Route	Accident Site		
1	1241	1316	1126		
2	1239	1208	1266		
3	1237	1341	1270		
4	978	1125	1021		
5	1297	1224	1084		
6	1313	954	1274		
7	1124	1213	1299		
8	1231	1279	1219		
9	1385	1399	1301		
10	979	1246	1098		
11	1293	1141	1222		
12	1310	1421	1277		
13	1115	1355	1220		
14	1296	1287	1295		
15	1430	1424	1223		
16	2145	2012	1789		
17	1281	1225	1282		
18	946	959	1426		
19	1311	1311	1303		
20	989	1160	1025		

Table A1. The Reaction Time of Group A (Figure 4a map).

Table A2. The Reaction Time of Group B (Figure 4b map).

Participanta Number	<b>Reaction Time of Searching Visual Targets (ms)</b>				
Farticipants Number	Fire Brigade Station	Route	Accident Site		
1	729	853	733		
2	828	728	791		
3	870	722	736		
4	798	920	770		

Desti da esta Nicerla e	Reaction Time of Searching Visual Targets (ms)				
Participants Number	Fire Brigade Station	Route	Accident Site		
5	762	901	850		
6	869	753	747		
7	842	844	902		
8	737	728	903		
9	770	877	805		
10	774	844	784		
11	858	740	823		
12	783	885	799		
13	706	756	710		
14	846	728	829		
15	821	758	776		
16	835	837	752		
17	842	884	895		
18	780	856	818		
19	807	709	829		
20	843	977	828		

Table A2. Cont.

**Table A3.** The Reaction Time of Group C (Figure 4c map).

Desti ein en te Namh en	<b>Reaction Time of Searching Visual Targets (ms)</b>				
Participants Number	Fire Brigade Station	Route	Accident Site		
1	661	755	758		
2	624	652	509		
3	756	532	723		
4	693	687	687		
5	804	698	783		
6	637	637	424		
7	633	689	451		
8	534	654	690		
9	603	699	671		
10	651	620	678		
11	740	734	810		
12	783	816	804		
13	549	731	640		
14	558	550	737		
15	784	693	753		
16	711	606	520		
17	654	746	762		
18	815	673	709		
19	617	665	699		
20	693	763	772		

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