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RESEARCH ARTICLE

An augmented representation method of debris flow scenes to improve public perception

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ABSTRACT
Virtual scenes can present rich and clear disaster information, which can significantly improve the level of public disaster perception. However, existing methods for constructing scenes of debris flow disasters have some deficiencies. First, the construction process does not consider public knowledge, which makes it difficult for the constructed scenes to meet the requirements of the public. Second, the scene representation emphasizes visual effects but lacks augmented visualization, leading to scarcity of semantic information and inefficient public perception. In this paper, the optimal selection of scene objects, semantic augmentation through the combination of various visual variables and dynamic augmented representation are discussed in detail. Finally, a debris flow that occurred Shuimo town is selected for experiment analysis. The experimental results show that most people are unaware of the risks posed by debris flow disasters. The public is more concerned about the consequences of a disaster than its spatiotemporal process, especially when the consequences are related to their own interests. Furthermore, an augmented representation can increase the amount of semantic information of scene objects, which is essential for enhancing public understanding of the causes, processes and effects of debris flows and thereby changing people's attitudes and enhancing their risk perception.

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KEYWORDS
Debris flow disaster; public perception; virtual geographical scene; visual variable combination; augmented representation

1. Introduction

Debris flow disasters involve the rapid movement of massive amounts of sediment in mountain areas and are characterized by high velocity, strong striking force, and severe destruction (Wang 2013). The high frequency of debris flow disasters seriously limits the sustainable development of society and the economy (Cui 2014). An important aspect of dealing with debris flows is to change people's conceptions toward disaster mitigation to make the public better able to recognize risk and improve their disaster awareness (Huebl and Fiebiger 2005, Chen *et al*. 2015).

As a means of nonstructural mitigation, disaster education can enrich people's disaster perception. Disaster education can be divided into three main stages: pre-disaster education, during-disaster education, and post-disaster education (Marincioni *et al*. 2012, Liu 2016, Smith *et al*. 2016). Pre-disaster education is a priority for enhancing people's

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Supplemental data for this article can be accessed here.

understanding of disasters, prevention awareness and ability to avoid disasters through education on disaster technology, mitigation measures, government policies, and personal evacuation knowledge. During-disaster education can improve people's flexible response ability, thus reducing the possibility of secondary injury. In addition, it can also help people quickly understand emergency measures, evacuation route selection and how to better rescue themselves and others in an emergency situation. Post-disaster education is a long-term and continuous process, for which a series of tasks, such as psychological counseling and home restoration, need to be continuously implemented to provide affected people a deeper awareness of disasters and improve their prevention capabilities. Traditional media for disaster education, such as books, newspapers, cartoons and videos, have played an active role in promoting the dissemination of disaster knowledge (Kelman 2015), but they rely excessively on 'image and text publicity'. In fact, disaster education specifically related to geographical location can help people better understand the laws governing disaster occurrence and development.

The Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) states that the disaster management department should periodically update and disseminate location-based disaster information to the public based on geospatial information technology (UNISDR (United Nations International Strategy for Disaster Reduction) 2015). In regard to debris flow disasters, the presentation of disaster information mainly includes maps and virtual scenes. A debris flow map, which is usually compiled by professional cartographers, is a powerful tool to help people understand a disaster situation and enhance their awareness of disaster mitigation. To reduce the professionalism of disaster maps and make them more accessible to the general population, panel discussions have been conducted in some studies to enable users to participate in the mapping process, and the contents of disaster maps have been improved by considering their suggestions (Meyer 2012, Liu *et al*. 2018). Although a debris flow map can present basic disaster information such as the inundation area, mud depth, and affected buildings to the public, the capacity of a 2D map to carry information is limited, and it is difficult to support the dynamic visualization of the whole process of debris flow evolution (Kaur *et al*. 2019, Achu *et al*. 2020). Moreover, the public tends to rely on perceptual salience to extract information, and visual phenomena such as flickering, jumping and changing are more visually appealing than a static presentation (Fabrikant and Goldsberry 2005, Xi *et al*. 2016).

As an alternative, virtual geographical scenes can vividly represent the spatiotemporal process of debris flow disasters and display the details of disaster information from multiple angles and an all-around perspective (Macchione *et al*. 2018, Chen *et al*. 2020). Such realistic 3D scenes can enhance the interpretability of disaster data and facilitate mental mapping (Yuan and Hornsby 2007, Lin *et al*. 2013a, Li *et al*. 2015, Qiu *et al*. 2017, Zhang *et al*. 2019). Debris flow scenes presented in 3D can be applied for disaster education to transmit disaster information to the public in a way that is more similar to the real environment (Lin *et al*. 2013b, Chen and Lin 2018, Lü *et al*. 2019). Such a presentation has unique advantages in terms of integrating debris flow information, conveying knowledge of technical prevention measures and risk avoidance for disaster propaganda and education, and integrating disaster models for the dissemination of information regarding the disaster scope and emergency measures. However, the existing studies on the construction of disaster scenes have been oriented toward an expert perspective and have not considered the knowledge level of the general public regarding scene construction. Although the existing methods can be used to describe certain attributes of disaster phenomena and focus on meaningful visual effects, they lack an augmented representation of the whole disaster event process, which can lead to poor readability of disaster information and make it difficult for the general public to understand debris flow information (Dransch *et al*. 2010).

This paper proposes a method for creating augmented representation of debris flow scenes to improve public perception. Public feedback on debris flow disasters is obtained through the questionnaire survey, and the feedback is used to quantitatively analyze public disaster awareness and optimize the selection of scene objects. The combination of various visual variables and dynamic augmented representation of the whole disaster process are considered to construct understandable 3D scenes of debris flow disasters for the public, and thereby improve disaster and risk perception and ultimately change people's conceptions of and attitudes toward disasters. The remainder of this paper is organized as follows. Section 2.1 provides an overall framework of the proposed method. Sections 2.2, 2.3 and 2.4 introduce the unified semantic description of debris flow objects and the optimal selection of scene objects and augmented representation, respectively. Section 3 analyzes the public feedback and develops a prototype system for the augmented representation experiments. Section 4 and Section 5 presents the discussion and conclusions.

2. Methodology

2.1. Multilevel augmented representation framework for debris flow disasters

For the comprehensive presentation of disaster information, this paper proposes a multilevel augmented representation framework for debris flow disasters, as shown in Figure 1.

This framework focuses on the optimal selection and visualization of debris flow objects for the public. The former selects scene objects considering user preferences

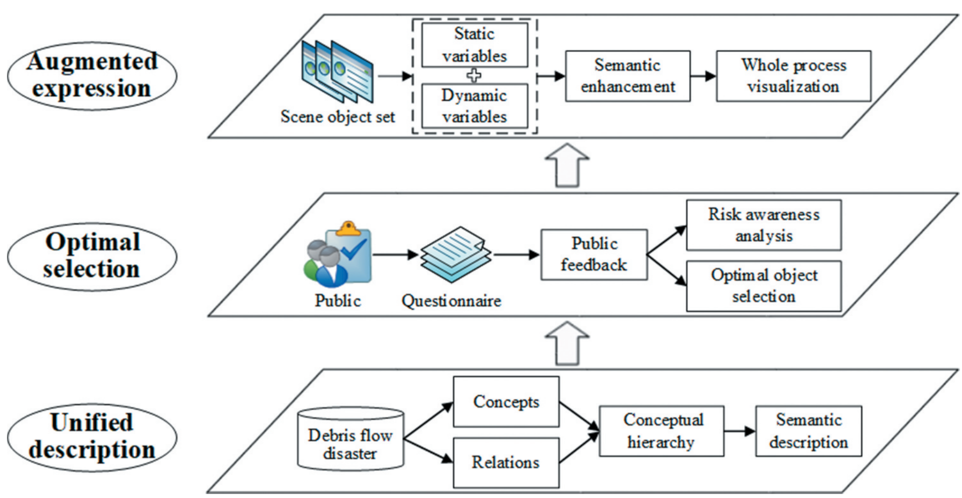


Figure 1. Multilevel augmented representation framework.

and needs, while the latter puts emphasis on improving the transmission abilities of debris flow information. The ultimate goal is to enhance the public's awareness and perception of debris flow disasters and achieve the purpose of disaster education.

With a virtual geographical scene as the basic carrier, the proposed augmented representation uses basic visual variables to form new semantic visual variables (e.g. highlighting, flickering, and deformation) and further combines text with self-explanatory symbols to enable semantic enhancement and the presentation of deep scene information, thereby helping users quickly understand and master key information.

2.2. Classification and unified semantic description of debris flow objects

The first question to be asked in disaster management is 'WHERE? Where is the disaster?' (Bandrova, Zlatanova and Konecny 2012). Therefore, a method of 3D disaster visualization for the public must answer the following three 'what, where and when' questions:

① What is the type of the disaster?
② Where is the disaster?
③ When did the disaster happen?

In addition, virtual scenes of debris flow disasters should present disaster information such as the spatiotemporal process and affected areas. A geographic ontology can clearly define and express the relevant concepts of geographical information science in a unified and formal way and, furthermore, allow this knowledge to be shared at a semantic level (Couclelis 2010). In this paper, a geographic ontology is adopted to describe the definitions and relationships of debris flow objects and to form a conceptual hierarchy of debris flow scenes for the public, as shown in Figure 2.

2.3. Optimal selection of scene objects considering public perception

To incorporate public knowledge into the construction of debris flow scenes, an attempt was made in this study to analyze public disaster awareness and personal preferences through a questionnaire survey. Specifically, the following problems were addressed:

① Quantitative analysis of public awareness of disasters
② Optimal selection of scene objects considering public knowledge

2.3.1. Questionnaire design and evaluation

The questionnaire was divided into two main parts: risk perception and object selection. Based on experience from the field of psychology, we designed the questionnaire using the Likert scale (a 5-point scale, with 5 being the highest rating) to investigate the disaster risk perception of the public and which key debris flow objects should be represented. Some questions were based on the work of Fischhoff *et al*. (1978) and Ho *et al*. (2008), as shown in Table 1.

To allow for different levels of knowledge among members of the public, the questionnaire used simple words (e.g. 3D, animation, and concern) instead of technical terms

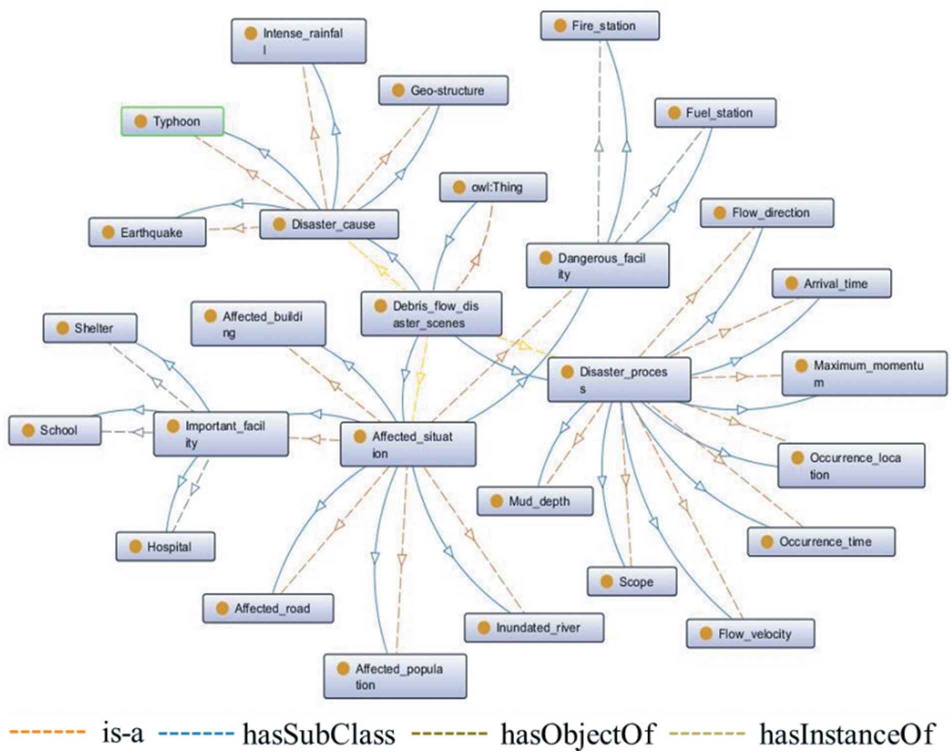


Figure 2. Classification and unified semantic description of debris flow objects.

(e.g. visual scene and visualization) to prevent the survey results from being affected by the influence of unfamiliar terminology.

In this article, reliability and validity indicators are used to evaluate the rationality of the questionnaire. Cronbach's α, which is the most commonly used reliability coefficient, is used to reflect the consistency and reliability of the questionnaire results. To investigate the accuracy and validity of the results, the Kaiser-Meyer-Olkin (KMO) and Bartlett tests are used to evaluate the structural validity of the questionnaire. Many studies have shown that if α is higher than 0.8, the reliability is high, and a KMO value close to 0.9 indicates good validity (DiBiase *et al*. 1992, Broen *et al*. 2015).

2.3.2. Analysis indicators and scene objects selection

This paper adopts indicators such as the mean, interquartile and standard deviation to analyze the feedback. The mean reflects the user's acceptance degree. The interquartile is used to analyze the central tendency of user feedback. The standard deviation indicates the dispersion of the test results and the stability of the preset questions. According to the evaluation standard of the Likert scale, if the mean is between 1.0 and 2.4, the result is disagreement; if the mean is between 2.5 and 3.4, the result is neutral; and if the mean is between 3.5 and 5.0, the result is agreement.

In the analysis of public risk awareness, if the mean value of user feedback is in the range of 1–2.4, the public risk awareness of debris flow disasters is seriously insufficient; if the mean value is in the range of 2.5–3.4, the risk awareness is insufficient; and if the mean

Table 1. Public questionnaire on debris flow disasters.

Types	Item descriptions	Range
Risk perception	① Have debris flow disaster occurred near where you live? A. Yes; B. No ② Do you know anything about debris flows? (1–5) ③ How likely is it that a debris flow will occur near where you live? (1–5) ④ Do you think there are mitigation actions that you can clearly adopt? (1–5)	
Object selection	① When considering the causes of a debris flow, which of the following factors are you most concerned about? A. Earthquake; B. Typhoon; C. Geostructure; D. Intense rainfall (1–5) ② When viewing a 3D animation of the debris flow process, which of the following factors are you most concerned about? A. Occurrence time; B. Occurrence location; C. Scope; D. Flow velocity; E. Flow direction; F. Arrival time; G. Maximum momentum; H. Mud depth (1–5) ③ After a debris flow disaster, which of the following disaster information are you most concerned about? A. Affected building; B. Affected road; C. Affected population; D. Inundated river; E. School; F. Hospital; G. Fuel station; H. Fire station (1–5)	1: Not at all 2: Not much 3: Normal 4: Somewhat 5:Very

value is higher than 3.5, the public has better risk awareness. In the selection of scene objects, we set 3.5 as a threshold value. If the mean value of a scene object is higher than 3.5, we think that most users concern this object, and it will be considered in the construction of debris flow scenes. Otherwise, it will be discarded.

2.4. Augmented representation of debris flow scenes for the public

An augmented representation can effectively associate spatial data with nonspatial attribute data and allow dynamic attribute information to be directly merged with knowledge in the scene to present the essential data over space and time (Li *et al*. 2019b).

2.4.1. Semantic augmentation of scene objects through the combination of various visual variables

Bertin (1983) proposed six basic visual variables, i.e. shape, size, color, brightness, orientation, and texture; however, these are static visual variables, with which it is difficult to fully express the dynamic features and behavior relations of geographical phenomena. Since then, many scholars have incorporated the time dimension into these static visual variables and proposed dynamic visual variables such as time, frequency, duration, synchronization, and order, which can more accurately and intuitively reflect the states and features of spatial phenomena (DiBiase *et al*. 1992, MacEachren 2004).

Combining various visual variables can strengthen the comprehension effect and enable the effective highlighting of target information (Chen 2008, Garlandini and Fabrikant 2009). This paper proposed a means of semantic augmentation for scene objects based on the combination of various visual variables to present more semantic information of debris flow disasters, as shown in Formula 1:

$$M\{S(s_1, s_2, \ldots), D(d_1, d_2, \ldots)\} \overset{f(x_1, x_2, \ldots)}{\longrightarrow} E\{P(x, y, z), A(a_1, a_2 \ldots), R(r_1, r_2 \ldots)\} \quad (1)$$

where M denotes various visual variables; S denotes static visual variables; D denotes dynamic visual variables; f denotes augmented representation characteristics, such as

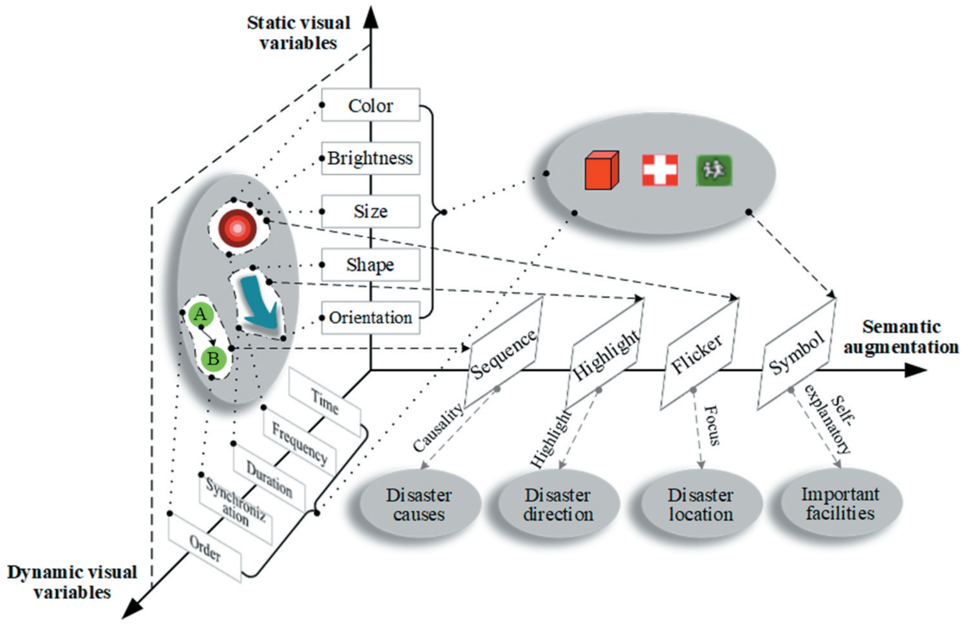


Figure 3. Semantic augmentation model of scene objects.

flickering and highlighting; E denotes the feature information of scene objects; P denotes spatial location information; A denotes attribute information, such as the disaster range and property loss; and R denotes correlation information, such as causality and time.

From a micro perspective, order and synchronization can be combined to represent the cause of a debris flow disaster (e.g. an earthquake). The visual variables of duration, shape and orientation can be combined to realize the movement of arrows that indicate the direction of a debris flow disaster. The visual variables of frequency, color, brightness, and size can be combined to form dynamic diffusion symbols to draw attention to the location of a disaster. From a macro perspective, static and dynamic visual variables can be combined to form different disaster symbols, and the self-explanatory nature of these symbols can help the public quickly obtain semantic information about debris flow disasters, as shown in Figure 3.

2.4.2 Dynamic augmented representation of the whole debris flow process

The complexity and high information density of debris flow scenes place high memory and cognitive burdens on members of the public. However, a reasonable logical sequence can improve the ability of a scene to transmit information. In the framework proposed in this paper, a 'storytelling' method is used to explain the causes and consequences of debris flow disasters in order to realize a dynamic augmented representation of the whole debris flow process, as shown in Figure 4.

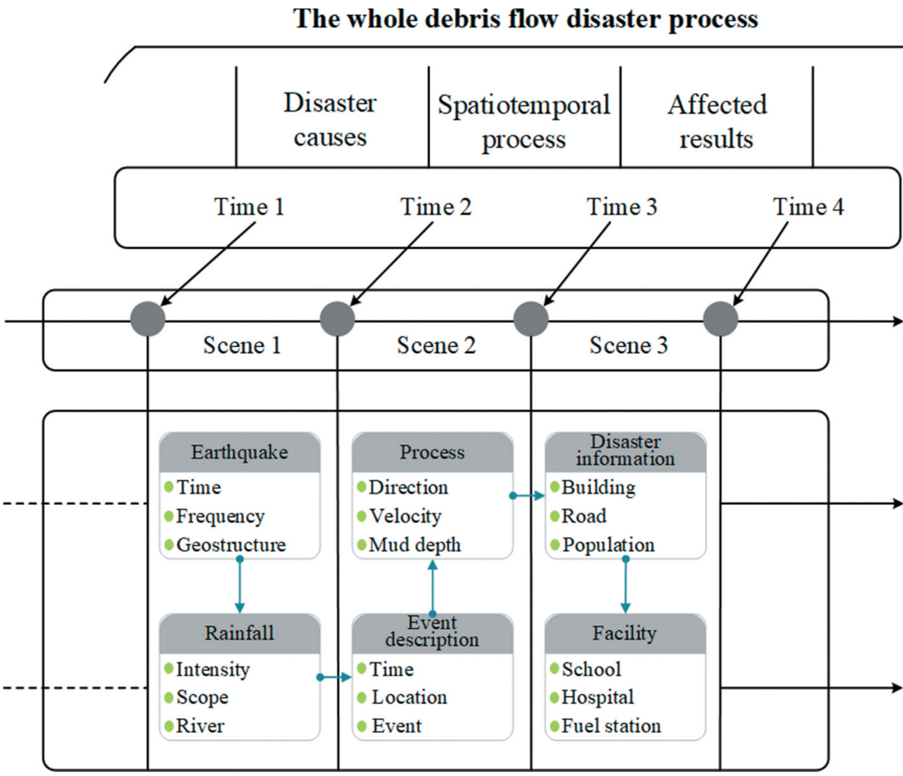


Figure 4. Logical model of the representation of the whole debris flow process.

3. Experimental analysis

3.1 Study area description

The Wenchuan earthquake caused loose soil in the western mountainous area of Sichuan Province, and some towns became prone to frequent debris flow disasters (Huang and Li 2009). In this paper, a debris flow that occurred in Shuimo town was selected as the study area for experimental analysis. Shuimo town is located in Wenchuan County, Sichuan Province (30°55′N~30°58′N, 103°22′E~103°25′E), and there have been many debris flow disasters in its history.

3.2 Selection of scene objects considering public disaster perception

3.2.1 Implementation process

To gather a broadly representative set of respondents to the questionnaire, Wenjuanxing (https://www.wjx.cn/jq/53415183.aspx), a free survey website, was chosen to issue the questionnaire online. The aim was to sample members of the public of different ages, different professional backgrounds, and different regions.

3.2.2 Results analysis

We received 190 questionnaires, and 181 questionnaires were considered valid after excluding invalid and repeated questionnaires. The completed questionnaires came from 26 provinces in China. As shown in Table 2, the Cronbach's α value was determined to be 0.917, which is greater than 0.8; the KMO value was 0.879, close to 0.9; and the Bartlett test results reached highly significant levels. All of these statistics indicate that the data and results collected through the questionnaire are true, valid and reliable.

① Analysis of public risk awareness

The Q1 results showed that a debris flow disaster had never occurred near where 78.45% of the participants lived, indicating that most members of the public do not experience debris flow disasters. The questionnaire results for Q2, Q3, and Q4 are shown in Table 3.

Q = question, M = mean, SD = standard deviation, MD = median, IQR = interquartile range

As shown in Figure 5, the Q2 score (M = 2.71, SD = 1.00) is in interval Z2 (2.5–3.4), close to the upper quartile; the Q3 score (M = 2.35, SD = 1.07) is also in interval Z2 (2.5–3.4), close to the lower quartile; and the Q4 score (M = 2.21, SD = 0.89) is in interval Z2 (2.5–3.4), as well, also close to the lower quartile. In summary, most members of the public have rarely or never received information about debris flow disasters and believe that they will never encounter such disasters; this is because individuals tend to be subject to an 'optimistic bias,' meaning that they believe that negative events are less likely to happen to them than to others (Spittal *et al*. 2005, Marincioni *et al*. 2012, Smith *et al*. 2016). These conclusions confirm the statement of Day (2011) that the public is poorly informed and has low disaster risk awareness. However, all people have the possibility of encountering disasters, even those who live in a plain region with essentially zero risk. Disaster education can strengthen the public's awareness of and ability to avoid disasters. Thus, when disasters are truly encountered, the public can respond more calmly and effectively and will have more opportunity to survive.

② Selection of scene objects

R = reason, M = mean, SD = standard deviation, MD = median, IQR = interquartile range

Table 2. Reliability and validity test results.

		Bartlett's test		
Cronbach's α value	KMO value	Approx. chi-square	df	Sig.
0.917	0.879	3032.098	253	0.000**<0.01

Table 3. Questionnaire results on debris flow risk awareness.

	Disaster perception					
	Q2		Q3		Q4	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	2.71 ± 1.00	3.00 (2–3)	2.35 ± 1.07	2.00 (2–3)	2.21 ± 0.89	2.00 (2–3)

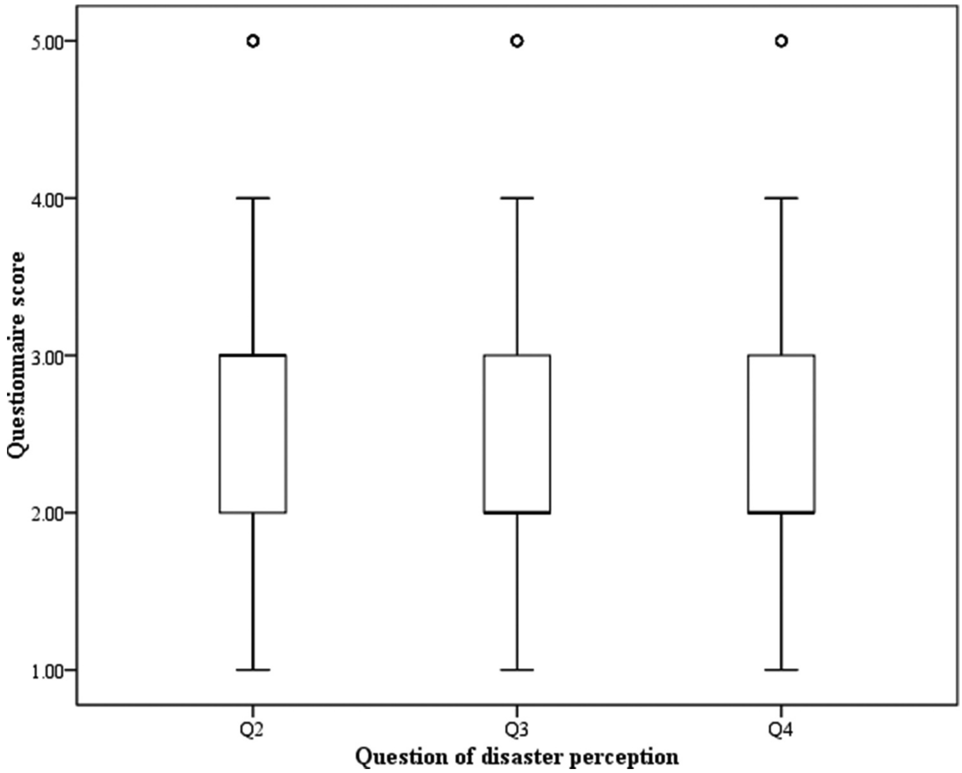


Figure 5. Statistical analysis of public debris flow risk awareness.

Table 4. Questionnaire results on debris flow causes.

	Disaster cause							
	Earthquake (R1)		Typhoon (R2)		Geostructure (R3)		Intense rainfall (R4)	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	3.97 ± 1.05	4.00 (4–5)	3.14 ± 1.24	3.00 (2–4)	4.38 ± 0.83	5.00 (4–5)	4.54 ± 0.81	5.00 (4–5)

As shown in Table 4 and Figure 6, regarding the debris flow causes, the R1 score (M = 3.97, SD = 1.05) is in interval Z3 (3.5–5.0), close to the lower quartile; the R2 score (M = 3.14, SD = 1.24) is in interval Z2 (2.5–3.4), close to the median; and the R3 score (M = 4.38, SD = 0.83) and R4 score (M = 4.54, SD = 0.81) are both in interval Z3 (3.5–5.0), close to the upper quartile. In summary, the public believes that intense rainfall is the most common cause of debris flow disasters, followed by issues related to geostructure and earthquakes, a perception that is consistent with public access to and awareness of news reports. In fact, typhoons may also cause intense rainfall, which may, in turn, lead to debris flow disasters, but because they are not a universal cause, the public has less access to the relevant information.

P = process, M = mean, SD = standard deviation, MD = median, IQR = interquartile range

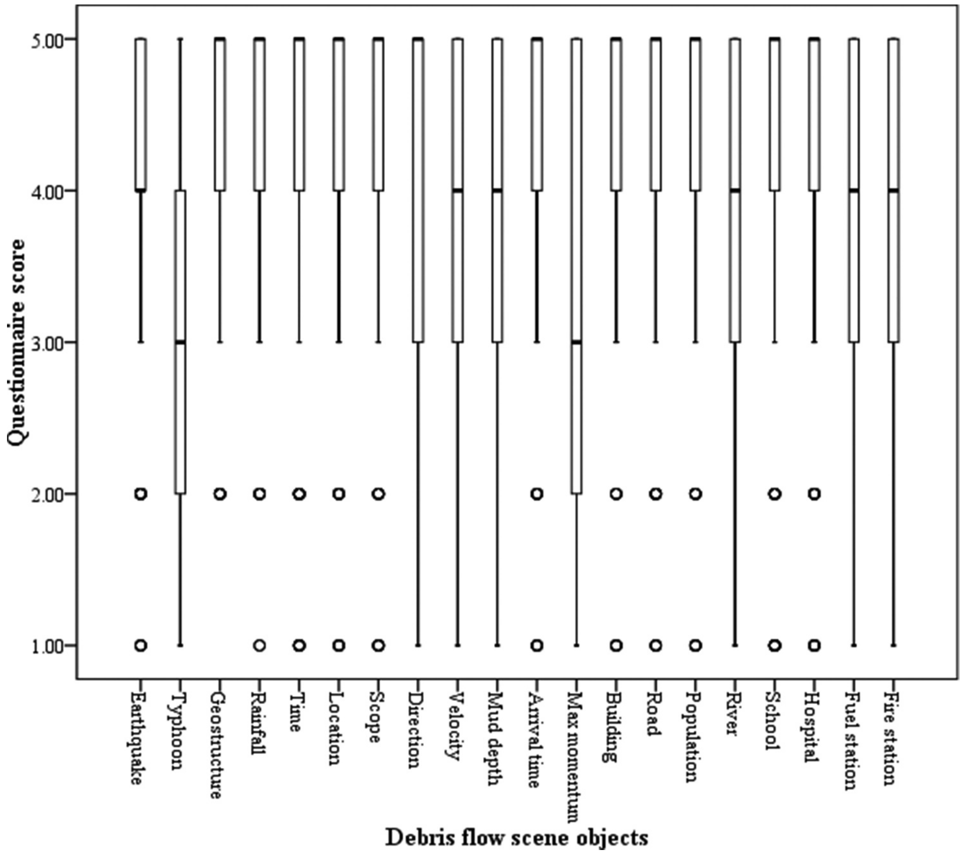


Figure 6. Statistical analysis of the importance of scene objects.

Table 5. Questionnaire results on the debris flow process.

	Disaster process							
	Time (P1)		Location (P2)		Scope (P3)		Direction (P4)	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	4.19 ± 1.11	5.00 (4–5)	4.33 ± 1.04	5.00 (4–5)	4.40 ± 0.95	5.00 (4–5)	4.15 ± 1.15	5.00 (3–5)
	Velocity (P5)		Mud depth (P6)		Arrival time (P7)		Max momentum (P8)	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	3.85 ± 1.30	4.00 (3–5)	3.74 ± 1.24	4.00 (3–5)	4.29 ± 1.02	5.00 (4–5)	3.14 ± 1.43	3.00 (2–5)

As shown in Table 5 and Figure 6, regarding the debris flow spatiotemporal process, the P1 score (M = 4.19, SD = 1.11), P2 score (M = 4.33, SD = 1.04), P3 score (M = 4.40, SD = 0.95), P4 score (M = 4.15, SD = 1.15) and P7 score (M = 4.29, SD = 1.02) are all in interval Z3 (3.5–5.0), close to the upper quartile; the P5 score (M = 3.85, SD = 1.30) and P6 score (M = 3.74, SD = 1.24) are also both in interval Z3 (3.5–5.0), but close to the median; and the P8 score (M = 3.14, SD = 1.43) is in interval Z2 (2.5–3.4), close to the median. In summary, the mean values for P1, P2, P3, P4, and P7 are all higher than 4.0, and the statistical results show a centralized trend, which indicates that most members of the public believe that the representation of time, location, scope, flow direction and arrival time should be prioritized in visualizations of the debris flow process. P5 and P6 have lower mean values than the above elements, and the corresponding statistical results are more scattered, but still in an acceptable range. By contrast, the mean value for P8 is in interval Z2, corresponding to the neutral range, and the concentration of the statistical results is not high. The reason may be that the term 'maximum momentum' is too professional for most members of the public, making it difficult for them to judge whether it is important; therefore, they consider it unnecessary to represent this information.

E = effect, M = mean, SD = standard deviation, MD = median, IQR = interquartile range

As shown in Table 6 and Figure 6, regarding the affected situations of debris flows, the E1 score (M = 4.43, SD = 0.97), E2 score (M = 4.34, SD = 1.02), E3 score (M = 4.33, SD = 1.00), E5 score (M = 4.21, SD = 1.14) and E6 score (M = 4.24, SD = 1.11) are all in interval Z3 (3.5–5.0), close to the upper quartile, while the mean values of the E4 score (M = 3.79, SD = 1.34), E7 score (M = 3.91, SD = 1.22) and E8 score (M = 3.95, SD = 1.24) are all lower than 4.0, close to the lower quartile but still in an acceptable range. In summary, compared with the spatiotemporal process of debris flow disasters, the public is more concerned about the consequences of such disasters.

The objects that may be presented in debris flow scenes are ranked by the corresponding degree of public concern in Figure 7. In addition to the causes of debris flow disasters, the top four objects of concern are the affected buildings, the disaster scope, the affected roads, and the disaster location, followed by the affected population, the affected schools, the affected hospitals and the arrival time of the debris flow; these findings proves that the primary concerns of members of the public are whether their living area will be affected, whether their houses and roads will be damaged, and how to access safe areas. Compared with the above information, the disaster information concerning the characteristics of the debris flow itself (e.g. mud depth and flow velocity) receives less attention. One possible reason is that members of the public have different backgrounds and knowledge structures, and consequently, some of them do not accurately understand the meaning of these professional terms, although this information is essential for experts and decision-makers.

3.3 Dynamic augmented representation of the whole debris flow process

3.3.1 Prototype system for debris flow visualization

Based on WebGL technology, a prototype system for debris flow visualization in the network was implemented. Node.js v6.11.2 was used to build the server side; the browser side was

Table 6. Questionnaire results on affected situations of debris flows.

	Affected situations							
	Building (E1)		Road (E2)		Population (E3)		River (E4)	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	4.43 ± 0.97	5.00 (4–5)	4.34 ± 1.02	5.00 (4–5)	4.33 ± 1.00	5.00 (4–5)	3.79 ± 1.34	4.00 (3–5)
	School (E5)		Hospital (E6)		Fuel station (E7)		Fire station (E8)	
Index	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)	M± SD	MD (IQR)
Score	4.21 ± 1.14	5.00 (4–5)	4.24 ± 1.11	5.00 (4–5)	3.91 ± 1.22	4.00 (4–5)	3.95 ± 1.24	4.00 (4–5)

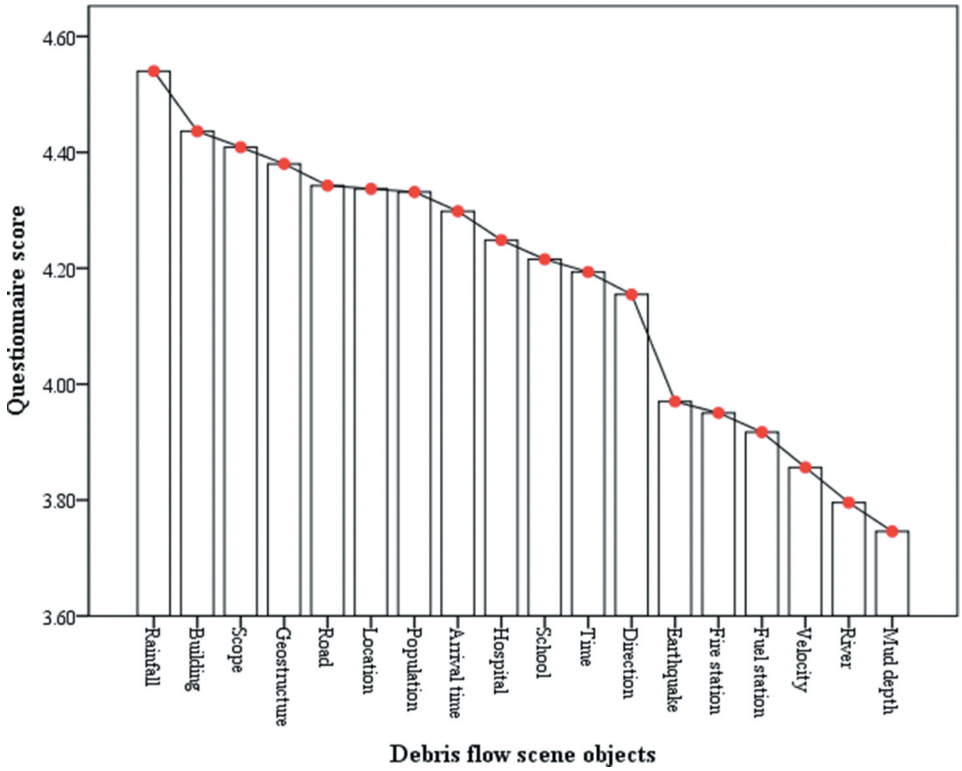


Figure 7. Ranking of the public perception of the importance of scene objects.

built using HTML5, CSS3 and JavaScript; and Cesium.js v1.45, which is a free open-source 3D visualization library, was adopted as the rendering engine. Chrome v80.0.3987.149 was chosen as the web browser to perform debris flow visualization experiments. Figure 8 shows an example of the visualization of a debris flow event in the system.

3.3.2 Instantiation of debris flow scene objects

Based on the results of the analysis presented in section 3.2.2, scene objects are instantiated by combining static and dynamic visual variables, as shown in Table 7. To reduce the cognitive burden placed on members of the public, semantic enhancement of scene objects is achieved through flickering, highlighting, self-explanatory features, etc.

3.3.3 Augmented representation of the whole debris flow process

According to the public feedback and the logical relationship of debris flow evolution, we performed an experiment in which we generated an augmented representation of the whole debris flow process for a chosen disaster event, as shown in Figure 9. For disaster cause visualization, the background information on the debris flow is introduced at a macro level. For example, the viewer is informed that Sichuan has become one of the areas most seriously affected by debris flow disasters in China because of its susceptibility to earthquakes and the prevailing climate conditions. Then, the 3D scene moves to the study area, and shaking is presented to show that the town of Shuimo has suffered three

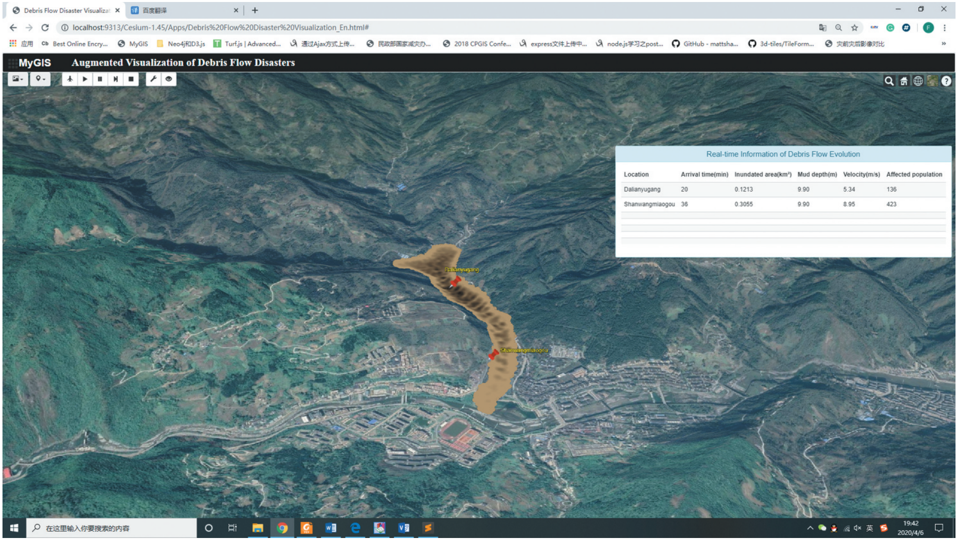
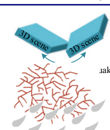
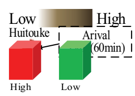
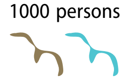


Figure 8. Interface of the prototype system.

Table 7. Instantiation of debris flow scene objects.

Category	Object	Representation description	Example
Disaster causes	Earthquake	Shaking of the 3D scene with selected frequency, amplitude and duration; text annotations representing occurrence time and location	
	Geostructure	Mesh with polylines, color and flickering	
	Intense rainfall	Particle system for real rainfall simulation with	
Disaster process	Time	Text annotations representing occurrence time	12 May 2008
	Location	Symbol annotations representing occurrence location	Shuimo town
	Scope	Inundation boundary with color and flickering	
	Direction	Moving arrows with a background line	
	Velocity	Text annotations representing flow velocity	Velocity (m/s)
	Depth	Continuous gray gradient representing mud depth	 Low High
	Arrival time	Text and symbol annotations representing arrival time	Huitouke Arival (60min)
Affected situations	Building	Simple level of detail (LOD) model with emergency warning colors representing buildings at risk	High Low
	Road	Road lines with emergency warning colors representing roads at risk	High — — Low
	Population	Text annotations representing the affected population	1000 persons
	River	Polygons with gray and blue warning colors representing rivers at risk	
	Facility	Self-explanatory symbols and text representing facilities	 Hospital School Fuel Fire

earthquakes that have loosened the geostructure. The area covered by the yellow mesh is the area affected by earthquakes, and intense rainfall has also raised the river level. All of these causes can induce debris flow disasters.

For visualization of the debris flow process, arrows are used to represent the flow direction, a dotted line indicates the flow route, and a flickering contour line with text annotation is used to emphasize the location and scope of the debris flow. To vividly visualize the spatiotemporal evolution process, a one-to-one mapping and a continuous

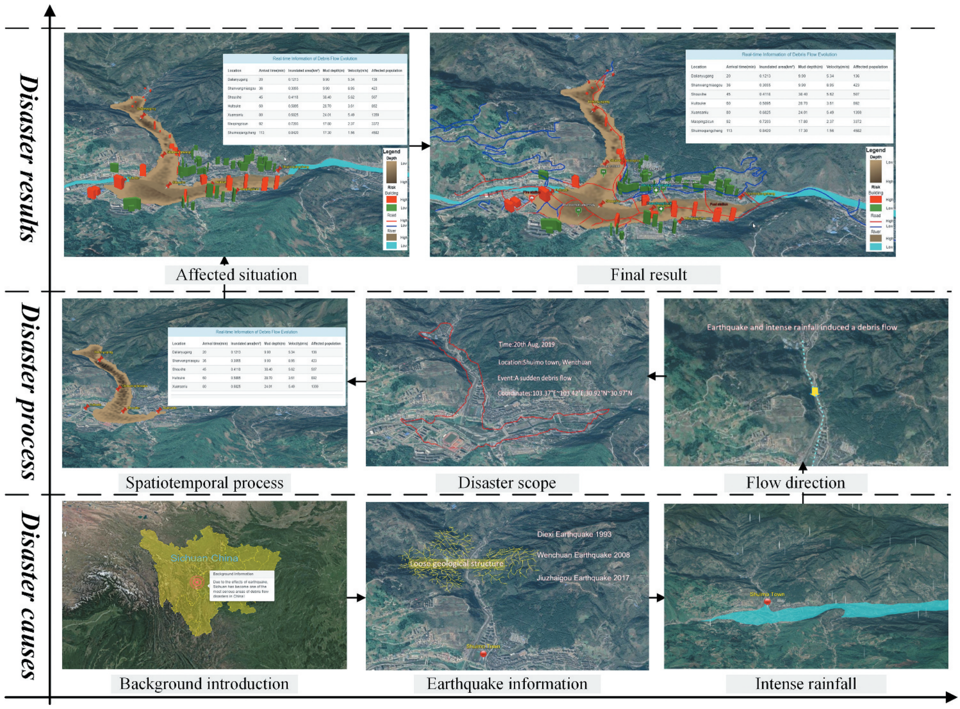


Figure 9. Augmented representation of the whole debris flow process.

gray ribbon are used to show the mud depth value at each moment, and the arrival time, inundated area and flow velocity are simultaneously represented. Regarding the affected situation, the inundated area and the noninundated area of the river are represented by the color gradient corresponding to the debris flow and blue, respectively. For buildings at risk, represented by a simple LOD model in red and green, red indicates a high degree of risk, whereas green indicates a low degree. Red and blue colors are used to indicate that roads are either intact or damaged, and high-risk scene objects are highlighted and flicker to attract attention. Self-explanatory symbols with text annotations are adopted to represent the locations and accessibility of facilities such as schools, hospitals, fire stations and fuel stations. More detailed experimental results of the augmented representation are presented in animated form in a video that is available online (please see https://www.bilibili.com/video/BV1iz411B7xE/and https://youtu.be/_HRsbqLxuEw).

In this way, the whole debris flow disaster process can be presented in a chronological and connected manner guided by causality, logic and context association, thereby enhancing the public perception and understanding of disaster awareness to a certain extent. Static and dynamic visual variables are combined to emphasize important disaster scene objects through visual effects such as flickering and highlighting. The purpose is to enhance the semantic information of scene objects, attract public attention and improve people's risk perception.

3.4 Comparative experiments on debris flow cognition

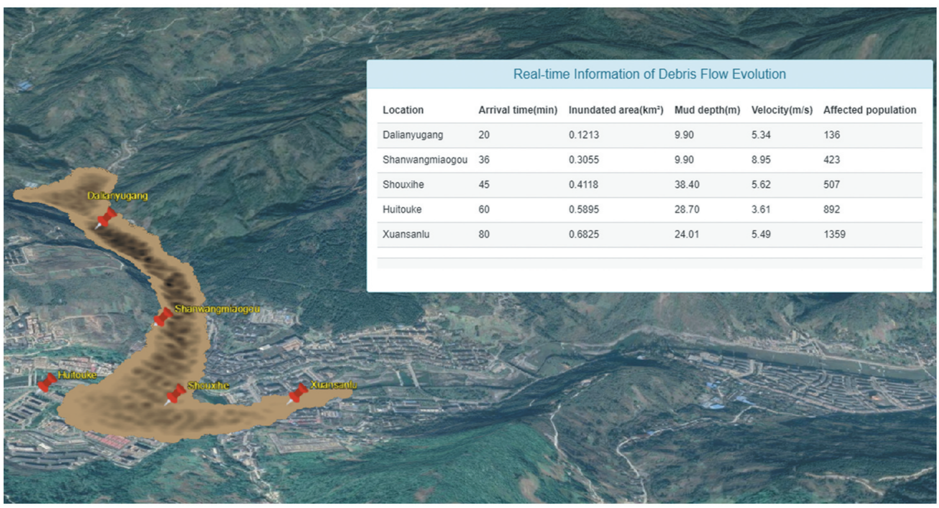
The results of the augmented presentation of the chosen debris flow example were output as a 76-s video, and the visual contents were summarized into a text report of 225 words in length by referencing the disaster emergency plan, as shown in Figure 10. These two materials each contained information about the causes, process and results of a particular debris flow disaster.

3.4.1 Design of the experimental procedure

To include persons of different ages and backgrounds in the cognitive experiments, 168 participants were randomly selected. The 72 participants in group A were asked to observe the augmented representation animation of the debris flow; this group is referred to as the animation group. The 96 participants in group B were asked to read the text report of the debris flow; this group is referred to as the report group.

(1) Implementation process

a



b

The text report of a debris flow disaster

A serious debris flow disaster occurred in Shuimo town, in Wenchuan county, Sichuan province, from 12:00 AM to 7:00 AM on August 20, 2019. The debris flow rapidly moved down the Shanwangmiao gully and Niutanggou gully, moving loose deposits on the slope along the way. The submerged area increased and spread to the downstream reaches of the river. Due to the earthquakes in Diexi, Wenchuan and Jiuzhaigou, the geological structure in the area became loose, and a large number of sources of loose material were formed. A short period of intense rainfall directly induced to the debris flow disaster. This disaster caused the interruption of national highways 213, 317, and 350 and Xuansan Highway, resulting in 3 deaths and 3 missing persons. Thousands of people were evacuated, and more than 100 houses were buried and destroyed. In addition, the comprehensive economic losses amounted to over 100 million RMB.

Figure 10. (a). Animation. (b). Text report. Screenshots of the debris flow animation and text report.

The participants first observed the corresponding experimental materials without prior knowledge of the content of the scene. Subsequently, they answered the following preset questions, and the answer time and accuracy were recorded.

① How many earthquakes occurred in the disaster area?
② Which town was the site of the debris flow disaster?
③ In which order did the following events occur: 1. Intense rainfall; 2. Loosening of the geostructure; 3. Debris flow evolution; 4. Earthquake.
④ How clearly does the experimental material describe the debris flow disaster process? (1. Very clear, 2. Clear, 3. Normal, 4. Unclear, 5. Very unclear)

(2) Analysis indices

The accuracy and finish time were recorded to evaluate and analyze the results of this cognitive experiment, as shown in Table 8. The accuracy indicates the effectiveness of disaster information transmission, and the finish time reflects the ability of the participants to recall the disaster information in the short term (Li *et al*. 2019a).

3.4.2 Analysis of experimental results

The experimental results (Table 9 and Figure 11) show that the accuracy of the answers of the animation group (M = 0.78, SD = 0.19) was significantly higher than that of the report group (M = 0.59, SD = 0.35, $p = 0.000 < 0.01$). The answer accuracy of the animation group was distributed in the interval (0.6, 1.0), and the majority of participants received scores of 100%; in contrast, the answer accuracy of the report group was distributed in the interval (0.3, 0.6), and some participants received scores of zero. With regard to the finish time, the difference between the animation group (M = 72.28, SD = 39.72) and the report group (M = 104.50, SD = 124.35, $p = 0.173 > 0.01$) was not significant.

In general, the finish time of the animation group was shorter than that of the report group, but the finish time of most participants were approximately 1 minute. Compared with the text report of the debris flow, the augmented representation animation could help participants perceive critical details and increase the amount of visually perceived information, thereby helping the participants understand the debris flow disaster at

Table 8. Analysis indices.

Analysis indices	Description
Accuracy	Answer accuracy for the preset questions
Finish time	Average time taken to finish answering the preset questions

Table 9. Descriptive and inferential analysis of the two test groups.

	Descriptive		Inferential		
	Animation group	Report group	Mann-Whitney U test		
	M± SD	M± SD	u	z	p
Accuracy	0.78 ± 0.19	0.59 ± 0.35	1842.50	−5.556	0.000**
Finish time	72.28 ± 39.72	104.50 ± 124.35	3031.00	−1.362	0.173

M = mean, SD = standard deviation, and ** $p < 0.01$

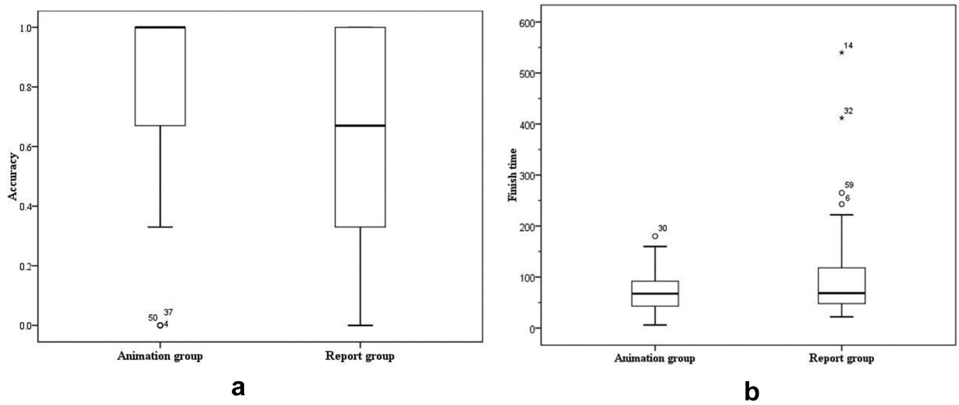


Figure 11. (a). Accuracy. (b). Finish time. Statistical analysis of the two test groups.

a deeper level. However, there was no significant difference between the animation and the text report in terms of the participants' ability to recall disaster information from their short-term memory.

Furthermore, based on the survey responses regarding the clarity of debris flow information transmission, Pearson's chi-square method was used to test the difference in perception between the two groups of participants (Table 10 and Figure 12).

The experimental results show that the difference between the augmented animation and the text report in terms of debris flow information transmission was significant ($p = 0.000 < 0.01$). For the text report, 19.79% of the participants indicated that the text report was unclear or very unclear because there were too many words and a large amount of complex information. For the augmented animation, only 1.39% of

Table 10. Preference comparison of the two test groups.

Comparison	Value	df	p
Animation group/Report group	25.505[a]	4	0.000**

a. Two cells (20.0%) had an expected count of less than 5. The minimum expected count is 3.86.

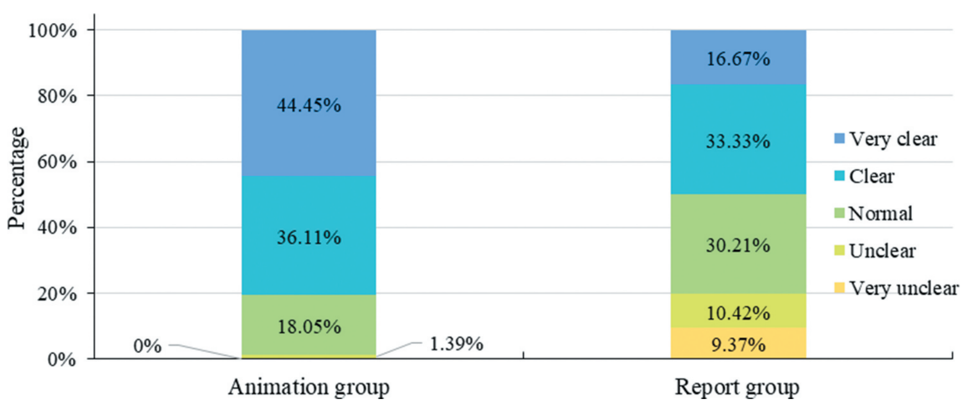


Figure 12. Survey on the clarity of debris flow information.

Table 11. Advantages of the augmented representation method proposed in this article.

Analysis factor	Augmented representation	Text	Picture	Video	Static map + text	Dynamic map + text
Information capacity	High	High	Low	High	Medium	High
Semantic information	Detailed	Simple	Simple	Simple	Simple	Simple
Intuitiveness	High	Low	Medium	High	Medium	Medium
Readability	High	Low	Medium	Medium	Medium	Medium
Visual content	High	Low	Low	Medium	Medium	Medium
Whole process visualization	Supported	Not supported	Not supported	Supported	Not supported	Not supported

participants stated that the debris flow information was unclear. In addition, 44.45% (36.11%) of the participants thought that the description of the debris flow disaster process provided by the augmented representation was very clear (clear), much higher than the corresponding percentage for the text report group. These analysis results show that the augmented representation of the debris flow had a more efficient ability to transmit disaster information. In summary, an augmented representation of debris flow is intuitive and can effectively transmit disaster information. Thus, it has great potential for improving the public's ability to perceive disaster information.

3.4.3 Advantages of augmented representation

Finally, to highlight the innovative nature and advantages of the method proposed in this article, the augmented representation method of debris flows and other visualization methods for disaster information are compared and analyzed in Table 11. The analysis results show that the proposed method has the advantages of rich scene content, a better representation effect, high readability, and support for the dynamic visualization of the entire disaster process.

4. Discussion

In this paper, we have made some attempts to develop a presentation method that can improve the public's perception of debris flow disasters. However, there is still room for further discussion, and we hope that our work can inspire readers to apply further creative thinking to address the challenges raised here.

First, a geographic ontology was used to describe the definitions of debris flow scene objects and their complex semantic relationships. However, this debris flow scene ontology covers only the causes, processes and effects of debris flows, whereas disaster education is a long-term and continuous process with a broader scope; other information about technical measures for disaster prevention and disaster recovery (e.g. resettlement, land use types and assisting enterprises) is also of great significance for public education. Thus, we will continue to improve the debris flow scene ontology to capture additional types of semantic information to support all stages of disaster education.

Second, a particular debris flow event was selected as an example in this paper to guide the development of the augmented representation method. In contrast to flood disasters, debris flows frequently occur in mountainous areas with little extensive infrastructure. From an objective perspective, we considered only certain important types of facilities (e.g. schools and hospitals) and certain dangerous facilities that may cause great harm (e.g. fire stations and fuel stations, etc.), but this does not mean that other types of infrastructure are not important (e.g. police stations, armed police, and transport facilities). In fact, the locations of such disaster mitigation facilities are very helpful to users seeking shelter or the assistance of search and rescue forces. Therefore, the representation of disasters in urban areas should provide more information about critical infrastructures.

Finally, the target audience of the augmented representation method proposed in this article is the general public. In fact, different members of the public may have different levels of understanding and different requirements for the information presented by debris flow scenes due to differences in age, occupation, education level, and knowledge structure. Based on the proposed augmented representation method, qualitative and quantitative analyses of the relationships between different population groups and the contents and visual presentation of disaster scenes can be conducted to enable the personalized customization of disaster scenes for diverse users with distinct requirements, which is a research direction worthy of further investigation.

5. Conclusions and future works

Visualizations based on 3D scenes have the potential to improve the disaster management process and present rich and clear disaster information, significantly improving the level of public perception and understanding of disaster events (Bandrova, Zlatanova and Konecny 2012). This paper has proposed an augmented representation method of debris flow scenes to improve public perception. First, a geographic ontology was adopted to define debris flow objects and describe their relationships, and a unified semantic description was given. Second, we designed a debris flow questionnaire that was presented to members of the public to quantitatively analyze public risk awareness. The statistical analysis results showed that most ordinary people have a low risk awareness of debris flow disasters. In addition, it was found that irrelevant or unimportant objects could be filtered out based on public knowledge, thereby reducing the 3D scene contents. Third, various visual variables were combined to enhance the semantic information of scene objects, and the whole debris flow process was dynamically visualized based on the causality and context of debris flow disasters. The aim was to make it easier for the public to recognize the causal relations, evolution and results of debris flow disasters, thereby changing their conception of disasters and improving their risk awareness and perception. The main contributions of this article are summarized as follows.

(1) The construction of debris flow scenes in 3D considering public knowledge. The public knowledge can be incorporated into the process of selecting scene objects for presentation through questionnaire surveys and feedback analysis. This method can help transform the dissemination of disaster information from one-way communication guided by experts to two-way communication with public participation, thereby improving the public's ability to perceive disaster risk.

(2) Augmented public-facing representation of the whole debris flow process. There is evidence that the public tends to rely on perceptual salience to extract information; thus, static and dynamic visual variables can be combined to create augmented forms of visual expression, such as flickering, highlighting, and self-explanatory features. These forms of expression can enhance the semantic information conveyed by and the self-explanatory nature of a visual representation. At the same time, the whole debris flow process can be presented in a chronological and connected manner by considering causality, logic and contextual association, thereby expanding the public's understanding of the causes, evolution, and results of debris flows and thus improving disaster awareness.

In the future, sound should be incorporated into the augmented representation video, and eye tracking will be utilized to quantitatively analyze public visual preferences, thereby further reducing the cognitive burden for the general public.

Data and code availability statement

The data and codes that support the findings of this study are available at figshare.com under the identifier https://doi.org/10.6084/m9.figshare.13040702.v1.

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