THE FORMAL REPRESENTATIONS OF THE AUTOMATED CONSTRUCTION OF MAP SYMBOLS

GONG XINYU

PhD

The Hong Kong Polytechnic University

2024

The Hong Kong Polytechnic University
The Department of Land Surveying and Geo-Informatics

The Formal representations of the Automated Construction of Map Symbols

GONG Xinyu

A thesis submitted in partial fulfillment of
the requirements for the degree of Doctor of Philosophy

August 2023

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

_____________________________ (Signed)

_________GONG Xinyu______(Name of student)

Abstract

Map is one of the three ancient communication means, including natural language and music, and cartography is "the art, science, and technology of making maps". Traditional mapping, conducted by well-trained professional cartographers, mainly focuses on improving the accuracy of maps. However, in some tasks (e.g., planning routes with schematic metro maps), accuracy is not the main concern of maps. Accuracy is just one of the indicators designed to describe usability (i.e., the degree to which a product is able or fit to be used by specific users when performing specific tasks in a specific environment). Personalized maps (i.e., mapping by users based on their unique interests and experience) emphasize user engagement and interactivity with maps rather than accuracy. Users nowadays care more about the usability and the aesthetics of the maps, and they tend to make their maps in different scenarios. Compared with traditional maps, personal maps have further expansions in information dimension, granularity, hierarchy, expression, and semantics against the background of spatiotemporal big data and show a more all-encompassing connotation and characteristics. There has been an increasing demand for personalized mappings, such as in urban informatics and the tourist industry.

Automated construction of map symbols plays an important role in facilitating personalized mapping. In the studies about the construction of map symbols, the basic elements and construction methods of map symbols have been discussed. However, the formal representation of map symbols has not been considered deeply, which is believed to be fundamental to the automated construction of map symbols and thus to the mathematization of cartographic theory. This project aims to develop the formal representation of the automatic construction of map symbols. In our understanding, constructing formal representations of map symbols is a complex process, and the first step in this process is to formally represent their structures. To achieve this goal, four strategies are therefore proposed in this project, (1) to employ Chinese characters' structures for representing map symbols, (2) to employ the existing basic operators for representing map symbols, (3) to employ the metric and color modifications for representing map symbols, and (4) to investigate the effects of topological properties on map symbol perception.

The structures of words can be formally described in natural language. In its hieroglyphic representation, Chinese writing resembles two-dimensional map symbols. This study evaluates the feasibility of using the structures of Chinese characters to represent the structures of map symbols. Two experiments were performed in this regard: a descriptive-statistics-based analysis and a questionnaire-based satisfaction evaluation. The results of the experiments reveal that (1) nearly 80% of map symbols fit perfectly onto the structures of Chinese characters and (2) over half of the experimental participants thought that the structures of map symbols could be represented adequately by those of Chinese characters. These results indicate that the structures of Chinese characters can represent the structures of map symbols, but more operators are required.

Secondly, the representation problems of these two types of map symbols (i.e., the map symbol didn't or imperfectly fit the structures of Chinese characters) were solved by employing additional basic operators and proposed some metric and color modifications. To validate these proposed solutions, experiments have been carried out. The results indicated that almost all the map symbols can be formally represented with additional operators and metric and color modifications. The percentages of map symbols that didn't fit structures of Chinese characters solved by these operators and modifications are 2.4% and 20.1% respectively. The percentage of map symbols that imperfectly fit them solved by these operators and modifications are 8.7% and 8% respectively.

A component-based approach is employed to analyze the effects of topological properties of map symbols on the interpretation. An experimental evaluation performed included four main sections: the effect of frame shape, the effect of interior, the effect of contrast between frame and interior, and user preference of frame shape. Experimental results show that frame does have effects on symbol interpretation, and people prefer circle and square (i.e., two kinds of frame shape) in most cases; interior has limited effects on symbol interpretation; and contrast between interior and frame has significant effects on the interpretation of some symbols. Our research helps to better understand how map symbols interact with map readers.

In summary, this study aims to develop formal representations of map symbols. To achieve this, the feasibility of structures of Chinese characters, the basic mathematical operators, and the metric and color modifications for representing map symbols were evaluated. Experiments have been carried out and results indicated that these operators and modifications are feasible for automatically constructing map symbols. The topological properties were proven to have an effect on map symbol perception. This work could not only enrich cartographic theory but also prompt the mathematization of map symbol construction. Of course, the automatic construction of map symbols is a rather complex problem, and further development is still needed.

Publications Arising from the Thesis

Gong, X., Lan, T., & Ti, P. (2023). Metric and Color Modifications for the Automated Construction of Map Symbols. *ISPRS International Journal of Geo-Information*, 12(8), 331.

Gong, X., Li, Z., & Liu, X. (2022). Structures of Compound Map Symbols Represented with Chinese Characters. *Journal of Geovisualization and Spatial Analysis*, 6(1), 6.

Acknowledgments

First, I would like to express my deepest gratitude to my supervisor Prof. Li Zhilin. Prof. Li gave me the opportunity to study under his guidance. He taught me how to do research and how to overcome difficulties in my daily life. I pretty much appreciate his valuable comments., unconditional support, and his patience. I would also like to express my deepest gratitude to my chief supervisor, Dr. Xintao Liu for his invaluable advice, patient guidance, and financial support.

Second, I would like to thank the members in my group: Dr. Ti Peng, Dr. Lan Tian, Dr. Shi Zhicheng, and Dr. Peng Qian, for their helps during my PhD career. Special thanks to all my friends in Hong Kong Polytechnic University, I wish everyone a good future. I would like to thank my parents. Without their understanding and support, I am not able to complete my research. Finally, I especially want to thank my boyfriend Dr. He Yuhao, for his encouragement and support in my life. Everything will be better in the future.

Table of Content

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Background and Motivation

1.1.1 The popularity of personalized mapping

Traditional mapping, which is conducted by well-trained professional cartographers, mainly focuses on improving the accuracy of maps. However, in some tasks (e.g., planning routes with schematic metro maps), accuracy is not the main concern of maps (Lan, et al., 2019). Accuracy is just one of the indicators designed to describe usability (i.e., the degree to which a product is able or fit to be used by specific users when performing specific tasks in a specific environment). Personalized maps (i.e., mapping by users based on their unique interests and experience) emphasize user engagement and interactivity with maps rather than accuracy. users nowadays care more about the usability and the aesthetics of the maps, and they tend to make their maps in different scenarios (Li, et al., 2022). Compared with traditional maps, personal maps under the background of spatiotemporal big data have further expanded information dimensions, granularity, Compared with traditional maps, personal maps under the background of spatiotemporal big data have further expanded information dimensions, granularity, levels, expressions, of semantics, expressions, and semantics (Wang, 2017; Liu, Fang, Guo, & Gao, 2014 and Wang et al., 2022), presenting a more all-encompassing connotation and characteristics. A framework of personalized mapping and some examples of personal maps are illustrated in Figure 1.1 and Figure 1.2.

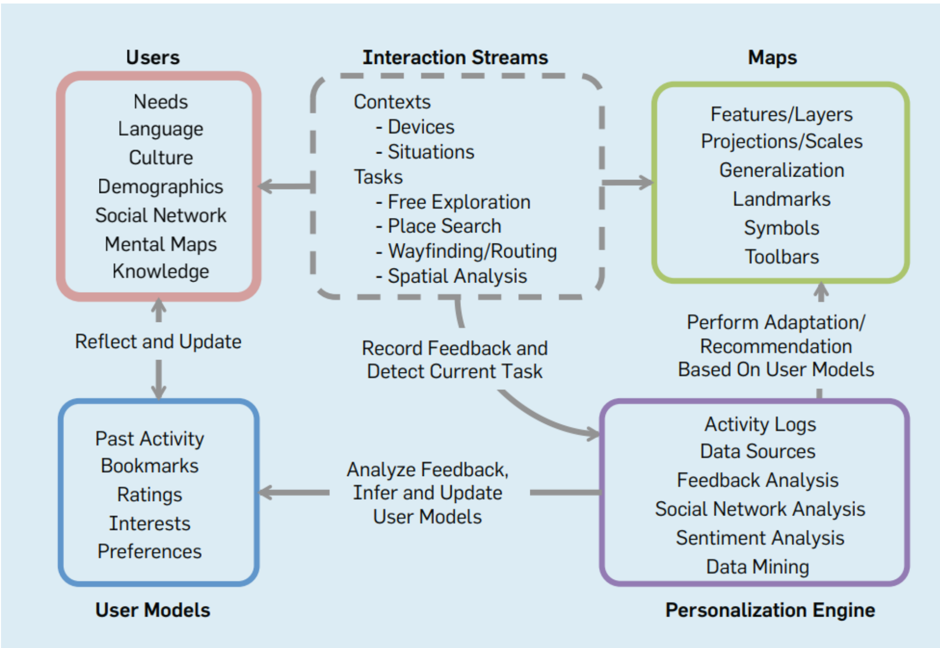


Figure 1.1 A framework of personalized mapping (Ballatore and Bertolotto, 2015).

Figure 1.2 Some examples of personalized mapping.

Advances in information and communication technology over the past two decades have generally increased the popularity of electronic maps, which are developed with the support of computers and smart devices. Some examples are illustrated in Figure 1.3 and Figure 1.4. There has been an increasing public demand for personalized mappings, such as in urban informatics (Torrens, 2022) and the tourist industry (Jancewicz and Borowicz, 2017). As a means to further promote personalized cartography for the public, there is a growing need for the automatic construction of map symbols.

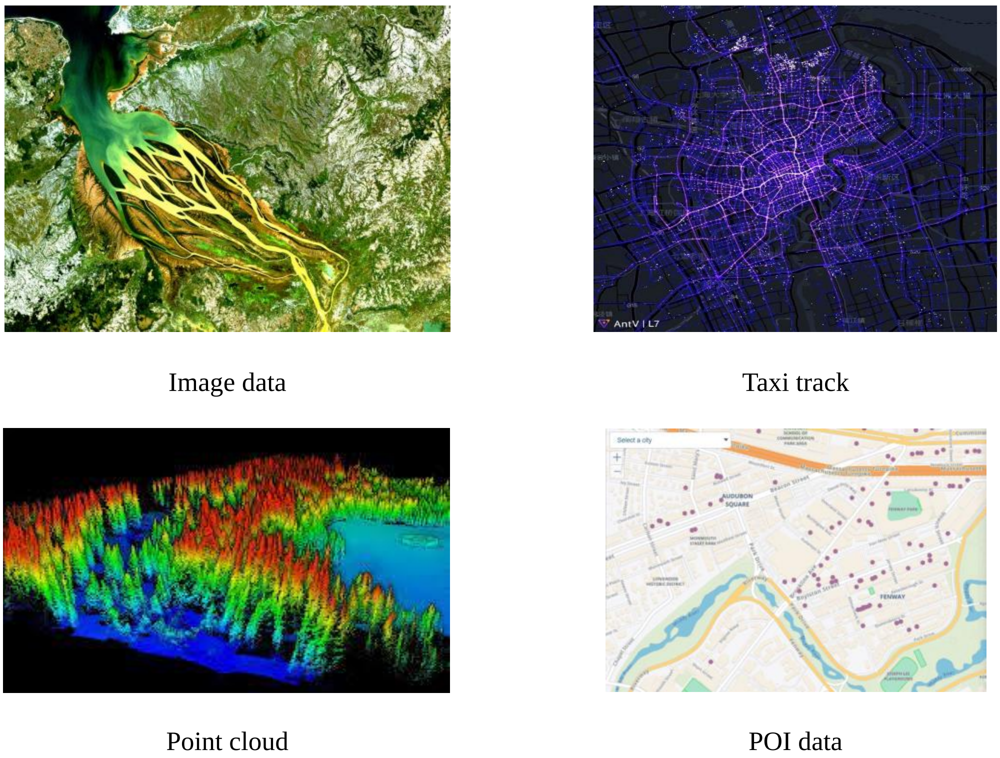
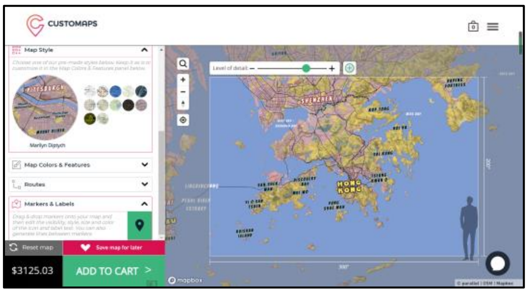


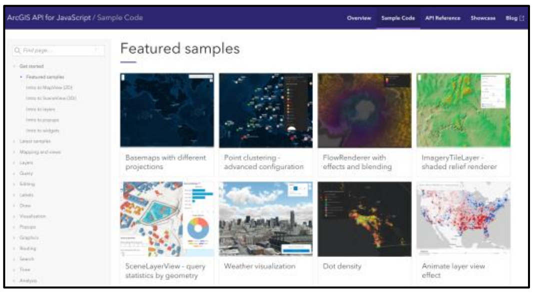
Figure 1.3 Data diversity.

Figure 1.4 Device diversity.

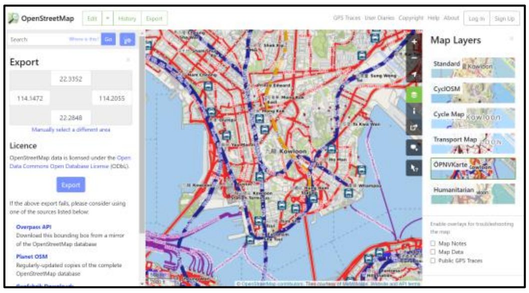
~~The demand for automated map symbol-making customization to support the personalized mapping of users is increasing.~~ Some commercial companies, such as Baidu, ArcGIS, and MapBox, have developed a series of data visualization components with rich visual representation (see Figure 1.5). They also provide users with secondary development interfaces to meet their needs for personalized mapping. For example, MapBox provides more than ten map styles: basic, bright, streets, doors, dark, light, satellite, satellite streets, traffic day, traffic night, and empty. Users can design their map styles based on these styles. Such a method can significantly improve personalized mapping.



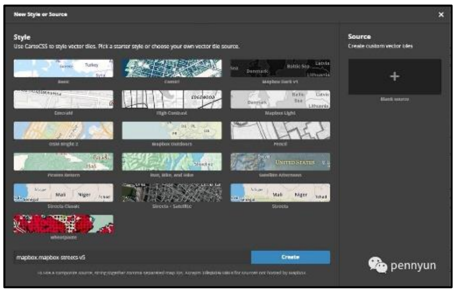
Customaps



ArcGIS API for JS



Open street map



Mapbox

Figure 1.5 Some secondary developing platforms of maps.

1.1.2 The construction of map symbols

Symbols are the basic elements of maps. According to their complexity, map symbols can be classified into three categories: geometric symbols, associative symbols, and pictorial symbols (MacEachren, 1995). Both pictorial and associative symbols are highly iconic because they are recognized to be related to the referent. Pictorial symbols are directly similar to their referents, while associative symbols closely resemble activities or objects that are related to the referent, but not the referent itself. Geometric symbols are abstract shapes that bear little or no resemblance to a referent.

Geometric symbols   Associate symbols   Pictorial symbols

Figure 1.6 The classifications of map symbols (MacEachren, 1995).

The study of symbols is not only a classic problem of cartography, but also a new problem raised with the continuous progress of the map itself. Jacques Bertin published his pioneering book <Semiology of Graphics> in 1967, which caused a sensation. Since then, scholars have established visual variables (e.g., Bertin, 1983; Robinson et al. 1995), Dynamic variables (e.g., Dibiase et al., 1992; MacEachren, 1994), and screen variables, perspective variables, and screen variables (Li and Kraak, 2002). The primary visual variables consist of three geometric variables (size, orientation, and shape) and three colour variables (hue, saturation, and value). The secondary visual variables are for patterns. Figure 1.7 shows examples of these visual variables, which define the forms of map symbols. The form of a map symbol refers to the shape, visual appearance, or configuration of an object.

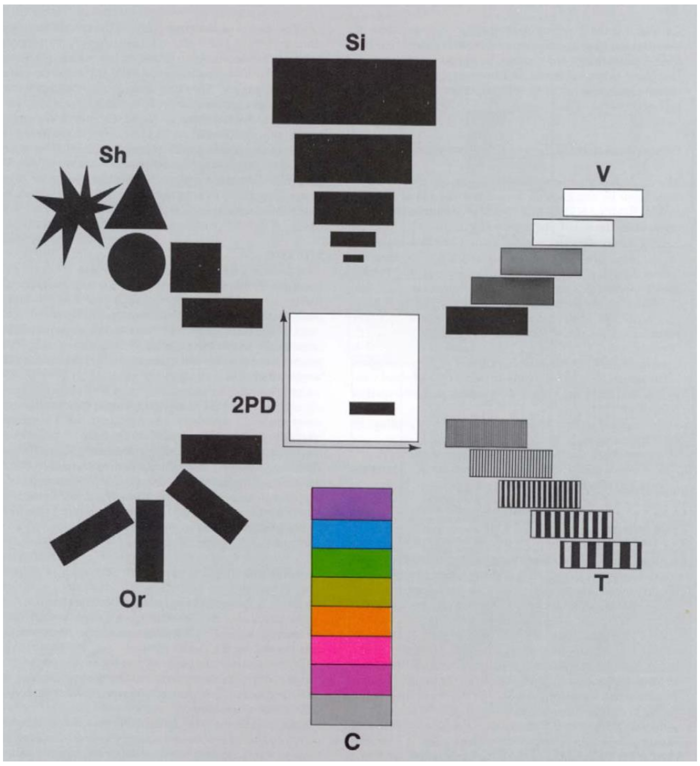
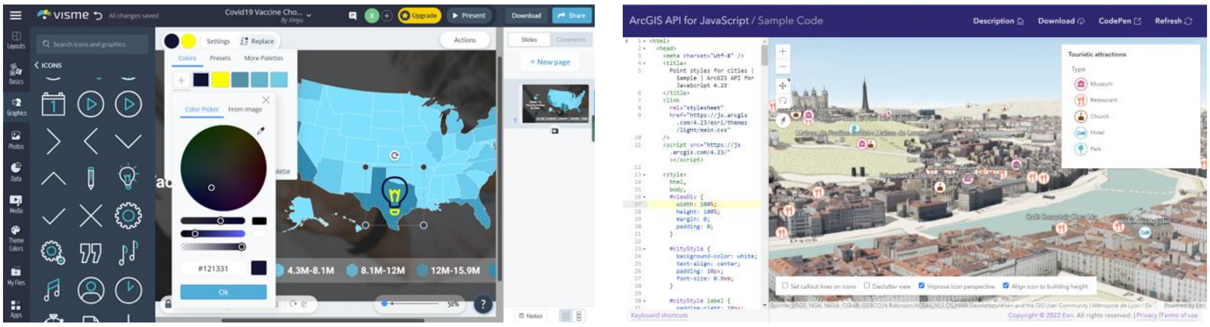


Figure 1.7 The primary six visual variables (Bertin, 1983).

The existing discussion about the theories of elements-based thematic map construction can be divided into two categories (Zhao et al., 2011). One is to consider the visual variables as map construction elements, concerning the user's visual perception and symbol appearance. The other one is to consider the primitive as the map construction element, such as Bertin's distinguishes six construction types (Bertin, 1983).

There has been an increasing demand among the general public for the automated construction of map symbols as a means to further promote personalized mapping. Traditional mapping is conducted by professional cartographers who have been trained over the years to use standardized map symbols to create maps for official or commercial purposes. Recently, general users have tended to create their maps for different purposes. For example, travelers may create their own versions of map symbols with the aim of creating personalized travel maps and sharing them on social media. In this context, the customization of map symbols through automated construction can improve personalized mapping significantly. Some map development platforms provide the function of allowing users to design map symbols independently or select the design style of map symbols. Two examples are illustrated in Figure 1.8.



(a) (b)

Figure 1.8 Some map development platforms (a: Visme Maps generator; b: ArcGIS API).

1.2 The state of the art in the construction of map symbols

The studies for the construction of map symbols can be categorized into three aspects: (1) the usability studies for the design of map symbols; (2) the construction methods of map symbols, and (3) The web-based platforms support map symbol construction.

1.2.1 The usability studies for the design of map symbols

In terms of the design of map symbols, various design rules/ideas have been developed. Bruyas et al. (1998) and Huang et al. (2002) analyzed the factors that affect the design of map symbols and proposed guidelines to develop these symbols. Kostelnick et al. (2008) developed a five-step approach that can be used to develop a symbol set. This approach applies to the design of map symbols suited to digital mapping environments. The major stages of the method include an inventory of existing symbols, development of symbol criteria, development of initial symbol drafts, qualitative evaluation of symbols, and revision of symbols. Robinson et al. (2010) considered symbol standardization to be an evolving objective and proposed that the best way to proceed is to develop a process to formalize, refine, and share mission-specific map-symbol standards. Chi and Dewi (2014) considered that for traffic symbols, word icons had a significantly greater matching accuracy than the other icon formats. McDougald and Wogalter (2014) found that appropriately placed highlighting could aid in determining intended conceptual meanings by emphasizing the pertinent areas and thus enabling the design of complex symbols. Korpi and Ahonen–Rainio (2015) recognized ten qualities (e.g., clarity and esthetic appeal) as constituting the essential set of design goals to help designers implement successful map symbols. Robinson et al. (2011) proposed that the best direction for future work is developing a process to formalize, refine, and share task-specific map symbol standards. Morrison and Forrest (1995) investigated the effects of color and size on the recognition of features. The tutorial provided by Adobe (https://www.adobe.com/hk_en/products/illustrator/ icon-design.html) explains symbol design in four steps: 1. To sketch on paper and scan the rough ideas; 2. To create versatile vector shapes with the Ellipse and Rectangle tools; 3. To create flat icons by stacking and combining vector shapes; and 4. To develop the icon style.

Most abstract, geometric, or graphic symbols have been found to bear little resemblance to the objects they attempt to depict (Clarke, 1989). Leung and Li (2002) came to similar conclusions. In addition, they found that the size of the symbol has a significant impact on the time it takes to recognize and search for the symbol. In addition, except for the symbol itself, the context (e.g. Clarke, 1989; Morrison and Forrest, 1995; Leung and Li, 2002; Lai and Yeh, 2004; Kostelnick et al., 2008; Alhosani, 2009; Halik, 2012; Stevens et al., 2013; Halik and Medynska-Gulij, 2017), users ages (Liu and Ho, 2012) or cultural difference (e.g. Piamonte et al., 2001; Kostelnick et al., 2008; Pappachan and Ziefle, 2008; Korpi and Ahonen-Rainio, 2015) of map symbols were also considered.

1.2.2 The construction methods of map symbols

In the studies about the construction of map symbols, the basic elements and construction methods of map symbols have been discussed. Li (2014) defined the topological structure of a map symbol consists of interior, boundary, and exterior. Stevens et al. (2013) proposed the map symbol box. Similar to the box model specified for cascading style sheets (CSS), the map symbol box model clarifies the foundational elements upon which a symbol is constructed, i.e., icon, padding, border, decoration, frame, and margin. Wu et al. (2017) bifurcated the construction of point symbols into primitive-composing and graphic-description methods. Primitive-composing methods construct map symbols based on basic shapes such as rectangles, stars, and polylines, while graphic-description methods directly describe symbols based on the path-fill-strokes such as the data formats Html, pdf, and SVG (Wu et al., 2017). Some primitive-composing methods of map symbols have been discussed, such as Bertin's distinguishes six construction types (Bertin, 1983). For two-dimensional diagrams, Bertin (1983) distinguishes six construction types: rectilinear construction, orthogonal construction, rectilinear elevation, circular construction, polar construction, and circular elevation. Wilkinson (1999) developed a diagram construction theory based on an object-oriented approach, which is analyzed and characterized by an informal description.

This description consists of seven components of a diagram, i.e., data value variables, transformations, dimensions of the diagram, scale, coordinate system of the diagram, geometric primitives and their style properties, and guidelines and additional information. Schnabel and Hurni (2009) extended their works. They developed six different arrangement principles (i.e., centered, grid, linear, polar, perpendicular, and triangular) for constructing map symbols, such as diagrams. Based on their ideas, Zhang and Zhu (2015) proposed a method based on graphic entities that have three parts including a graphic entity library, symbol synthesizer, and symbols specifications. The synthesizer performs the following tasks: (1) retrieval of graphic entities from the library and locating them in the right place and order; (2) rendering graphic entities with appropriate colors; (3) adjusting the display size of each graphic entity; and (4) adding animation effects to dynamic map symbols.

Some studies have been conducted on the linguistic characteristics of map symbols. The morphological structures of map symbols were discussed. The morphological structure of map symbols can be compared with the structures of natural languages. A morpheme is the smallest meaningful lexical item in natural language (Wiki). Su and Zhou (2008) defined topographic map symbols are also composed of morphemes. A morpheme is a graphic form, and every morpheme is a geometrical cell. They proposed the noun of cartographic language has a complex internal structure, and the basic noun can combine complex noun phrases by spatial relation. For the automatic construction of map symbols, Besides, for the construction of thematic map symbols, Zhao and Zeng (2011) proposed symbols that can be defined using cartographic primitives which are arranged according to their syntactic principles, and they put forward a syntactic construction theory based on a phoneme (thematic map primitive) word (single thematic symbol) sentence (combine symbols or complex symbols) structure model for the automatic construction of thematic symbols. Gong et al. (2022) analyzed the morphological structures of map symbols. It was found that the structures of Chinese are feasible for representing map symbols. The semantics aspects in the construction of map symbols have been considered. Tian et al. (2013) identified, in the traditional symbol design a single symbol was separated from the symbol system easily, and the relationship between symbols did not catch much attention. Therefore, they carried out a concept of Symbol-morpheme in an attempt to unify the graphic and semantic aspects to form a unified map symbols structure model. In a natural language, the form of words is determined by the font (e.g., Times and Times New Roman) and effect (e.g., bold and underline). These are still valid in cartographic symbols if such symbols are comprised of letters and/or numbers. On the other hand, the form of a graphic symbol is defined by visual variables.

In addition, the formal representations of map symbols have been discussed. Bartoněk and Andělová (2022) proposed a formal description of the graphics properties of the symbols, which is based on a general mathematical model. Figma, Pixso, and Sketch are all powerful UI design software. In these softwares, Boolean operators are often used to combine and create complex shapes. The Boolean operations can simplify the works of icon constructions. The Boolean operator is defined as follows.

Union: creates a shape that's the sum of multiple shapes' areas.

Subtract: removes the area of a shape from the one underneath it.

Intersect: creates a shape from the areas where the selected shapes overlap.

Difference: creates a shape from the areas where the original shapes don't overlap. It's the opposite of intersecting.

1.2.3 The web-based platforms support map symbol construction.

Additionally, some researchers pay attention to the available interactive GIS platforms to meet different mapping standards. Firstly, the factors affecting the design of computer icons were discussed. Salman et al. (2012) summarized a graphical interface employing icons provides user-friendly interaction with a computer system. The developed a symbol editor that can provide the ability to select background textures and colors, component

graphics, text, frame shape, symbol size, symbol format, and move components. The guidance provided by IBM pointed out that in the design of the icon, the base grid, padding, key shapes, strokes, corners, and angles will affect the effectiveness of the icon. Microsoft's guidance plan mainly considers the metaphor, grid, rounded corners, detail, silhouette, color and gradients, contrast, shadows, and perspective of symbols. The Apple development team considered symbols' rendering modes (i.e., monochrome, hierarchical, palette, and multicolor), variable color, weights, scales, and design variants (i.e., fill, outline, slash, and enclosed). The designer from Figma publication design identified the basic elements of an icon including size, color, grids, strokes, and fills.

Secondly, various web-based ideas and prototypes have been developed for the construction of map symbols. Schnabel (2005) developed a prototype called "Map Symbol Brewer" to generate map symbols for screen maps with a focus on internet maps. Stevens et al. (2013) developed a visually enabled, web-based interactive tool called "Symbol Store" intended to help mapmakers share point symbols. Robinson et al. (2013) designed and developed the Symbol Store, a visually enabled web-based interactive tool used intended to help mapmakers share point symbols. Liu et al. (2016) proposed an approach that fits symbol recognition and automatic conversation and developed a conversion system based on this approach and ArcGIS Engine. Zhang and Zhu (2015) proposed a method based on the graphic entity for map symbol visualization in vector-based web mapping. This method works with Flash, SVG, and other mapping technologies. Peng et al. (2017) addressed a procedural construction method for interactive map symbols for disasters and emergency response. The design processes for the proposed interactive map symbols include constructing visual graphics and graphic control points, drawing attributes using the graphics editor, performing interactive editing of map graphics, and drawing attributes.

1.3 Scope and objectives of this project

As discussed before, the research studies about the automatic construction of map symbols present three primary themes: (1) the usability studies for the design of map symbols; (2) the construction methods of map symbols; and (3) the web-based platform support map symbol construction. Although many studies on the construction of map symbols have been conducted, the formal representation of map symbols has not been considered deeply, which is believed to be fundamental to the automated construction of map symbols and thus to the mathematization of cartographic theory. The scope of this project is therefore limited to the formal representation of automatic construction of map symbols. Four objectives are therefore proposed for this study:

- To evaluate the feasibility of structures of Chinese characters for the automated construction of map symbols.
- To evaluate the feasibility of additional existing basic operators for the automated construction of map symbols.
- To evaluate the metric and color modifications for the automated construction of map symbols.
- To evaluate the effects of topological properties on map symbol perception.

1.4 The structure of the thesis

There are eight chapters in this thesis. Following the introduction and background in chapter one, the composition of map symbols including the structures and simple mathematical operators for constructing map symbols are described in chapter two. Chapter three describes the feasibility of structures of Chinese characters for representing map symbols. Chapter four describes the improvement of the formal representation of map symbols with additional basic operators. Chapter Five describes the improvement of the formal representation of map symbols with metric and color modifications. Chapter Six introduced the effect of topological properties on the interpretation of map symbols. Chapter Seven describes a prototype system for the automatic construction of map symbols. Chapter Eight introduces a summary of this study, some conclusions, limitations, and future works.

Chapter 2 The composition of map symbols

2.1 The analogy between cartographic language and natural language

2.1.1 The analogy between map symbols and words in natural language

Map is one of the three ancient communication means, including natural language and music (Li et al. 2004), and cartography is "the art, science, and technology of making maps" (Meynen, 1973). In cartography, some researchers consider that maps use a form of language to convey their meaning because map is comparative to natural language (e.g., Kamusella 2001, Kent and Vujakovic 2013). In natural language, information is transmitted by reading, writing, listening, and speaking, and a hierarchy of components in natural language exists (i.e., from alphabetic, words, sentences, and paragraphs to essays). To establish cartographic language, some researchers have studied how spatial information transmits and explained the hierarchy of components in the cartographic language (e.g., Raisz 1948, Keates 1972; Head 1984; Andrews 1990; Ramirez 1993, Robinson, 1995, Guo, 2012, and Tian 2013 and Leppert, 2019). For example, attempts have been made to build cartographic information transmission models (see Figure 2.1) to explain how spatial information is encoded, transmitted, and then received and decoded (Kent, 2007), to construct the components of cartographic language (e.g., Raisz 1948 and Keates 1972), and to investigate the expression stylistic diversity of cartographic words or sentence (e.g., Wood 1972 and Kent 2007).

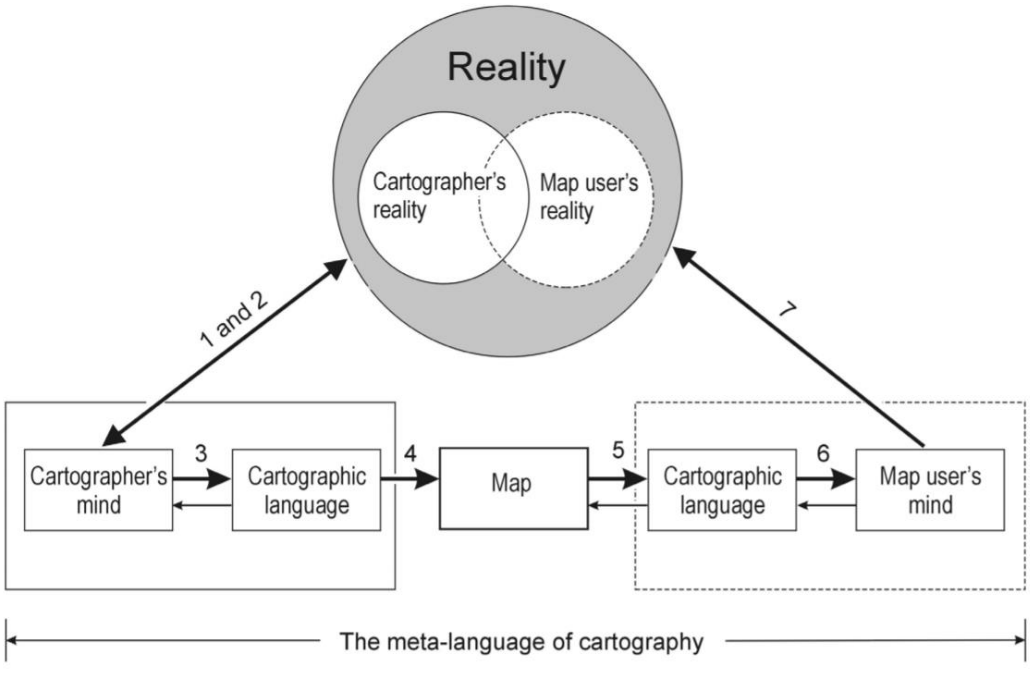


Figure 2.1 Cartographic communication model (Kolacny, 1969).

Many attempts (e.g., Raisz 1948; Keates 1972; Head 1984; Andrews 1990; Ramirez 1993 and Tian 2013) have been made to define cartographic words (see Table 2.1). More specifically, researchers tried to find the corresponding elements of natural language in cartographic language. Raisz (1948) has proposed an analogy that cartography is a kind of language and map symbols can be considered as its words. This view is widely accepted. More specifically, Keates (1972) described that total cartographic words are composed of color, dimension, and form, which are similar to graphic variables proposed by Bertin (1983). According to Ramirez (1993), cartographic language is composed of geometric elements (i.e., point, line, area, and volume marks), alphabets of language (e.g., A, B, C in English), and numerical numbers (e.g., 1,2,3 in Arabic). They are the smallest units (alphabets) of cartographic language. Head (1984) suggested visual variables are equivalent to distinctive features (fundamental elements), and symbols to morphemes, and the range of these symbols constitutes the cartographic words used to describe and represent phenomena on the map.

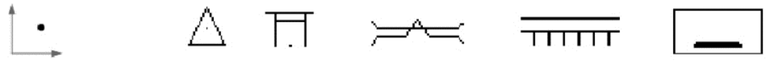
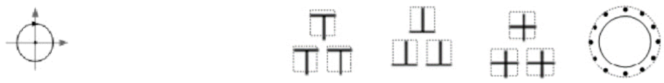
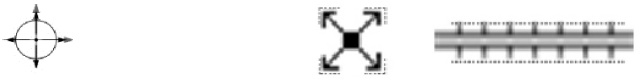
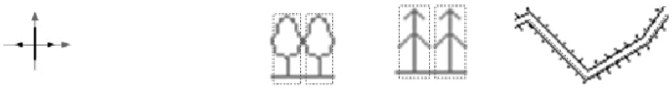
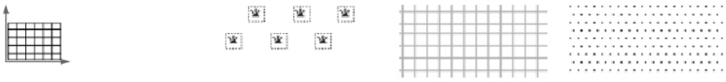
Table 2.1 Correspondence between cartographic words and words in natural language.

Words	Morphemes	Alphabets	Sources
Map symbols	-	-	Raisz, 1948
Map symbols		-	Robinson, 1953
The range of symbols for representing phenomena	Map symbols	-	Head, 1984
-	-	Geometric elements alphabets of language and numerical numbers	Ramirez, 1993
-	-	Graphic variables	Leppert, 2019
Map symbols and labels	Visual variables	-	Guo, 2012
Map symbols	Graphic elements	-	Tian, 2017

Some researchers (such as Robinson, 1995, Head, 1984, Tian, 2013) tried to establish detailed similarities between natural language and cartographic language and use the concept of natural language construction to guide the construction of map symbols. For example, the ethnogenesis and ontogeny of mountain symbols described by Wood (1984), the grammatical rules of nautical chart symbolical language developed by Guo (2012), and syntactic characteristics and smart construction mechanism of thematic map symbols developed by

Tian (2016) and Zhao (2014). To our knowledge, their works are helping to form the theoretical models of cartographic words. However, they did not consider the morphological structure of them.

Table 2.2 Combination operators of topographic map symbols (Tian, 2016)

Categories	Examples
Location	
Rotation	
Polar	
Parallel to the vector	
Symmetry	
Grid	

As cartography develops, people design more diverse symbols (e.g., 3d symbols and dynamic symbols), and people of different cultural backgrounds use different expressions (Wood 1984, Andrews 1990, Kent 2007). Keates pointed cartographic words are composed of color, dimension, and form. Similar to natural language, cartographic language also has an “accent”. Kent (2007) explained that the "accent" of a map needs to be determined by using graphical variables (e.g., size and/or color) that do not affect the basic form. The cartographic accent creates a variety of map symbols’ expression styles.

Figure 2.2 Variations in point symbol form (adapted from Keates, 1989).

We agree with Raisz's opinion, i.e., map symbols are corresponding to the cartographic words. Similar to natural language, a cartographic word also has a morphological structure. In natural language, a morpheme is the smallest meaningful constituent of a linguistic expression. Therefore, we consider the smallest meaningful symbol components to be the morphemes of cartographic language. Li (2014) suggested a morphological structure may be found through the decomposition of a symbol into topological components. From a topological point of view, an object consists of an interior, a boundary, and an exterior. The same goes for a cartographic word. It is more appropriate to call the exterior of the cartographic words frame, and it may be compared to the suffixes here. Except for the frame, the boundary (or shape) of the basic components (i.e., graphics and textual elements) of map symbols, are the roots of cartographic words. The internal color or texture of these components can be compared to prefixes here.

For the line symbols and area symbols, we consider the basic components of a line symbol to be the same as that of point symbols, i.e., geometric elements (i.e., point, line, area, and volume marks), alphabets of language (e.g., A, B, C in English), and numerical numbers (e.g., 1,2,3 in Arabic). Symbol components are combined into line symbols according to a special collection structure. Compared with point symbols, line symbols may have more symbol components and their internal structures are more complex. The complex line symbols or area symbols can be considered as the symbol set. With proper arrangements of simple symbols, complex line symbols could be structured.

2.1.2 The analogy between symbol sets and sentences in natural language

Cartographers using linguistic or semiotic paradigms have little agreement on the conceptual and syntax details of the cartographic language (Head 1991). The strongest objection to the map language analogy was Robinson and Petchenik (1976), who argued that map languages lacked syntax because map reading did not use the necessary structures. The order in which maps are read: Maps are not generated or read in a specific linear order like natural languages. Kent (2007) argues that the effect of scale makes it difficult to establish cartographic grammar. However, while most maps lack the syntax of a structured reading order in the narrow sense, they still exhibit a structured syntax in terms of the interrelationships between the symbols that compose them (Kent 2007). Lyutyy (1984) described cartographic syntax as “combinations of symbols in the sense of grammatical categories, or the forms of correct expression in the language”. Head (1984) considered the syntax of a map language to be the mathematical order of items in the map space, or the adopted style of map representation, such as choropleth or point maps. Schlichtmann (1988) discussed the syntax of macro symbols and their composition beyond texts. He identified two kinds of syntax: local syntax refers to syntax that governs the relationship between the components of local signs, and a second syntax, called supralocal, governs the relationship of local symbols within a text involving spatial arrangements. Frank and Mark (1996) have identified the function of syntax as building words and sentences, respectively. Du (2003) and Tian (2016) considered the syntax aspects to describe the spatial relation of each symbol.

Let us go back to the basic definition of the syntax for an answer. The syntactic rules defined by Cruse (2011) are essentially rules that combine simpler meanings in a systematic way to form more complex meanings. If cartographic semiotics in the context of semiotics is considered, it is easy to distinguish the whole range of symbols’ relations -- syntax, semantics, and pragmatics, which is very similar to the structure of the symbols in the natural language system (lyutyy, 1984). Therefore, it is believed that the cartographic language has syntax. A cartographic sentence consists of a series of symbols, and the syntactic aspect describes the mutual relationships of the symbols (cartographic words). Cartographic grammars act like the rules to combine map symbols.

According to the hierarchical and recursive features of the cartographic language, the syntactic structure of the cartographic sentence can be refined into the simplest form of "cartographic words + syntactic rules". The cartographic sentence can be regarded as a set of symbols like the natural language sentence is composed of words. In sentence structure, vocabulary not only participates in the composition of the drawing statement, but also has many different functions, such as representing a certain spatial relationship, expressing distance and direction, connecting drawing statements, and so on.

According to the part of speech, English words can be divided into nouns, verbs, pronouns, numerals, adjectives, adverbs, and so on. But not every vocabulary can be reflected on the map. According to the role of words in sentences, cartographic vocabulary can be divided into nouns, adjectives, verbs, and adverbs (Andrews 1990). The symbol itself can be regarded as a noun, the color of the symbol, the texture and other characteristics as adjectives, the spatial relationship between morphemes and morphemes as a verb, and the adverbs reflect the time and place of the symbol. Tian (2016) has a similar idea, according to the words' functions, he classified the cartographic words (Table 2.3) into five types: subject, predicate, object, adjectives, time, and place adverb.

Table 2.3 Different components of cartographic sentences (Tian et al. 2016).

Syntactic component	Word types	Examples
Subject	Topographic symbols	Primary highway, trail, perennial river
	Thematic symbols	Army symbol, travel thematic symbol
Predicate	Spatial relation	Topographic relation, metric relation…
Object	Same as subject	Same as subject
Adverb (Time and space)	Describe time	30th Dec 2018
	Describe location	(30°N, 120°E)
Adjectives	Symbolic property	HSV (180, 100, 100)

Tian (2016) divided spatial relations into four aspects (Table 2.4): position, direction, distance, and topographic relation. Each predicate corresponds to a predicate function.

Table 2.4 Spatial relation predicates system (Tian et al. 2016).

Predicate lexicon		Examples
Position relation	Name of place	Hong Kong, Chengdu
	Coordinate system	(30°N, 120°E)
Direction relation	Relative reference	Front, back, left, right
	Absolute reference	East, west, south, north
Distance relation	Qualitative	Far, close
	Quantitative	50m, 100m….
Topographic relation	Separated	Nearby, around, along, parallel…
	Adjacent	Broder, flow, pass…
	intersect	Intersect, cross, inflow…
	contain	On, contain, inner, inside….

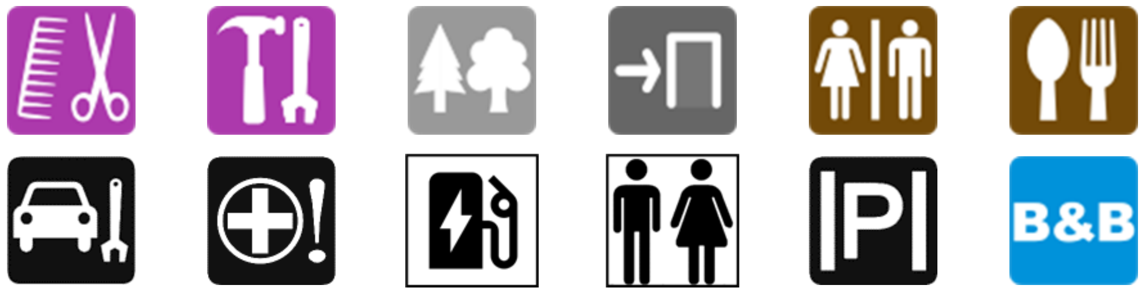
2.2 The structures of map symbols: Comparison between the structures of natural languages and map symbols

There are more than 6000 languages in the world, and English and Chinese are two of the most widely spoken ones among them. This study uses map symbols to present a comparison of the characteristics of English and Chinese.

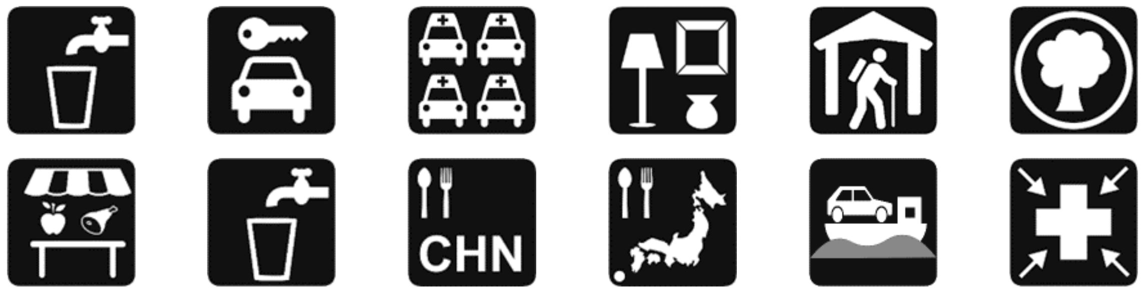
2.2.1 Comparison between the structures of English words and map symbols

In the written forms of most Western languages, the arrangement of letters and morphemes follows a one-dimensional, linear structure. In English, an alphabet is used in writing, in left-to-right order (Taylor and Taylor 2013). Alphabets first form morphemes, the smallest meaning-bearing units of natural language, and these morphemes, in turn, form words. Morphemes can be classified as either free or bound (Bergman et al. 1988). Free morphemes such as “work” and “house” can be considered individual words, while bound morphemes (e.g., “-er” and “pre-”) should be used with free morphemes to form words (Bauer, 1983). Words formed from single free morphemes are called simple words, whereas those formed from two or more morphemes are called complex words. Compound words are complex words comprising two or more roots. A word typically constitutes a root and affixes. The affixes entail prefixes and suffixes. For example, the word “map” has neither a prefix nor a suffix; “cartography” has the prefix “carto-”; and “photogrammetry” has the prefix “photo-” and the suffix “-metry.” “Mailbox” and “layman” are examples of compound words.

This system is applicable to map symbols. In cartographic symbols, a graphic element is the smallest component of a symbol, and one or more graphic elements compose a cartographic symbol. Such smallest units of cartographic symbols include geometric elements (i.e., point, line, area, and volume marks), alphabets of languages (e.g., A, B, C, … and a, b, c … in English), and numerical numbers (e.g., 1, 2, 3, … in Arabic). In Figure 2.3a, compound map symbols with a one-dimensional linear structure are presented. However, some map symbols are composed of two-dimensional structures (see Figure 2.3b). English word structures are not suitable for guiding their construction.



(a) Map symbols with a one-dimensional left-right structure



(b) Map symbols with a two-dimensional structure

Figure 2.3 Compound map symbols.

2.2.2 Comparison between structures of Chinese characters and map symbols

Unlike word symbols for Western languages (e.g., English), Chinese characters feature a two-dimensional pattern (Huang and Wang 1992). Li (1995) used an analogy between maps and language to suggest that the visual ideographic language constituted by map symbols appears to be closer in nature to written Chinese than it is to alphabetic languages. However, the structures of map symbols do not seem to exactly match either English or Chinese writing; rather, they appear to be a combination of the two (Figure 2.4).

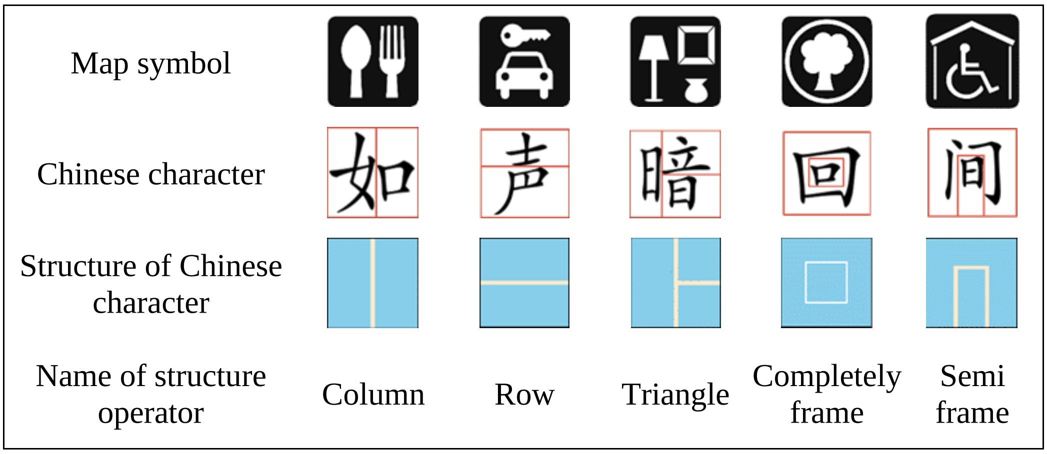
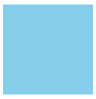
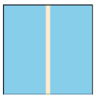
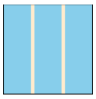
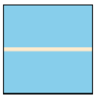
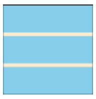
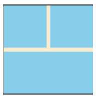
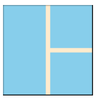
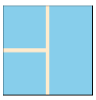
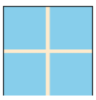
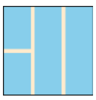
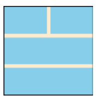
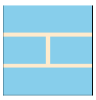
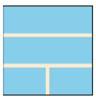
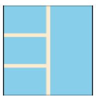
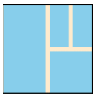
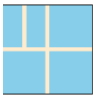
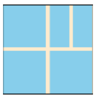
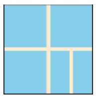
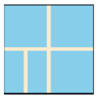
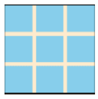
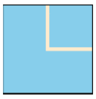
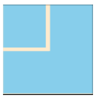
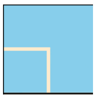
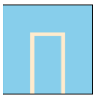
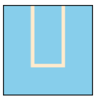
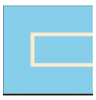
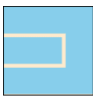
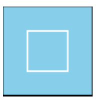


Figure 2.4 Comparison between the structures of map symbols and Chinese characters**.**

Chinese characters contain a finite number of morphemes that form tens of thousands of characters in different structures. Their structures are grouped into several categories (Table 2.5) (Chen and Lee 1996; Huang and Wang 1992; Lin and Fan 1994; Liu et al. 2004; Liu 2011; Tan and Perfetti 1998; Wang 2002; Wang and Fan 2001). These basic structures can be combined into more complex structures. Row, column, triangle, and frame (i.e., partially framed, semi-framed, and completely framed structures) structures are recognized by most linguists in Chinese characters (Chen and Lee 1996; Huang and Wang 1992; Lin and Fan 1994; Liu 2011; Wang 2002; Wang and Fan 2001). However, Wang (2002) noted that the structural generalization of the Chinese characters in international standards is incomplete and that some complex structures can be added. This study, thus, suggests two additional compound structures, i.e., four-part and multi-part structures. Structures with no more than three components or directions, including a single body, a column structure, a row structure, and a triangle structure, are simple structures. Those with more than three components or a combination of multiple directions, including a four-part structure, a multi-part structure, and a frame structure, are complex.

Table 2.5 Classifications of Chinese character structures.

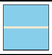
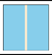
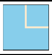
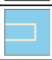
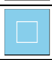
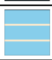
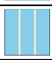
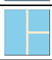
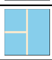
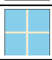
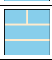
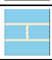
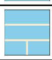
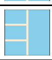
Classification		**Structures**	**Sources**
Simple combination	Single body		Wen (1984); Huang and Wang (1992); Liu (1993); Xing (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan (2001), Wang (2002); Chen (2004); Liu (2011)
	Column		Wen (1984); Huang and Wang (1992); Liu (1993); Xing (1993); Zhang (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan, (2001); Wang (2002); Chen (2004); Liu (2011)
			Huang and Wang (1992); Liu (1993); Chen and Lee (1996); Wang (2002); Chen (2004); Liu (2011)
	Row		Wen (1984); Huang and Wang (1992); Liu (1993); Xing (1993); Zhang (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Chen (2004); Liu (2011)
			Liu (1993); Zhang (1993); Chen and Lee (1996); Wang (2002); Chen (2004); Liu (2011)
	Triangle		Huang and Wang (1992); Chen and Lee (1996); Wang (2002)
			Huang and Wang (1992); Chen and Lee (1996)
			Chen and Lee (1996)
			Chen and Lee (1996)
Complex combination	4 parts		   
			   

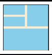
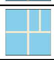
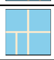
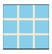
				   
	Multi-parts			   
	Frame	Partial frame		Liu (1993); Xing (1993); Zhang (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Liu (2011)
				Xing (1993); Zhang (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Liu (2011)
				Chen and Lee (1996)
				Liu (1993); Xing (1993); Zhang (1993); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Liu (2011)
		Semi-frame		Wen (1984); Liu (1993); Xing (1993); Zhang (1993); Lin and Fan (1994); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Chen (2004); Liu (2011)
				Liu (1993); Xing (1993); Zhang (1993); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Chen (2004); Liu (2011)
				Liu (1993); Xing (1993); Zhang (1993); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Chen (2004); Liu (2011)
				Chen and Lee (1996)
		Complete frame		Wen (1984); Liu (1993); Xing (1993); Zhang (1993); Chen and Lee (1996); Wang and Fan (2001); Wang (2002); Chen (2004); Liu (2011)

Chinese characters are combined by radicals (e.g., “口”, “又”, “土”) under different structures. For example, the character “林” is combined by two radicals (i.e., “木” and “木”)

under the left-right structure mentioned before. According to the number of radicals, the structures of Chinese characters can be classified into the following categories: single structure, two-radical structure, three-radical structure, four-radical structure, and multi-radical structure. The formal representations of Chinese characters' structures (see Table 2.6).

Table 2.6 Formal representation of constructing structures of Chinese characters.

Classification	Structures	Formal representation of structures	Examples
One component		$S_1 = f_1(X) = X$	口
Two components		$S_{2,1} = f_{2,1}(X_1, X_2) = X_1 \downarrow X_2$	节
		$S_{2,2} = f_{2,2}(X_1, X_2) = X_1 \rightarrow X_2$	时
		$S_{2,3} = f_{2,3}(X_1, X_2) = X_1 \Gamma X_2$	庄
		$S_{2,4} = f_{2,4}(X_1, X_2) = X_1 \llcorner X_2$	返
		$S_{2,5} = f_{2,5}(X_1, X_2) = X_1 \lrcorner X_2$	-
		$S_{2,6} = f_{2,6}(X_1, X_2) = X_1 \urcorner X_2$	-
		$S_{2,7} = f_{2,7}(X_1, X_2) = X_1 \sqcap X_2$	问
		$S_{2,8} = f_{2,8}(X_1, X_2) = X_1 \sqcup X_2$	凶
		$S_{2,9} = f_{2,9}(X_1, X_2) = X_1 \sqsubset X_2$	区
		$S_{2,10} = f_{2,10}(X_1, X_2) = X_1 \sqsupset X_2$	-
		$S_{2,11} = f_{2,11}(X_1, X_2) = X_1 \odot X_2$	国
Three components		$S_{3,1} = f_{3,1}(X_1, X_2, X_3) = X_1 \Downarrow X_2 \Downarrow X_3$	竟
		$S_{3,2} = f_{3,2}(X_1, X_2, X_3) = X_1 \Rightarrow X_2 \Rightarrow X_3$	啊
		$S_{3,3} = f_{3,3}(X_1, X_2, X_3) = X_1 \Delta X_2 \Delta X_3$	霖
		$S_{3,4} = f_{3,4}(X_1, X_2, X_3) = X_1 \nabla X_2 \nabla X_3$	想
		$S_{3,5} = f_{3,5}(X_1, X_2, X_3) = X_1 \lhd X_2 \lhd X_3$	程
		$S_{3,6} = f_{3,6}(X_1, X_2, X_3) = X_1 \rhd X_2 \rhd X_3$	部
Four components		$S_{4,1} = f_{4,1}(X_1, X_2, X_3, X_4) = (X_1 \downarrow X_2) \rightarrow (X_3 \downarrow X_4)$	韩
		$S_{4,2} = f_{4,2}(X_1, X_2, X_3, X_4) = X_1 \downarrow (X_2 \Rightarrow X_3 \Rightarrow X_4)$	蘅
		$S_{4,3} = f_{4,3}(X_1, X_2, X_3, X_4) = (X_1 \Rightarrow X_2 \Rightarrow X_3) \downarrow X_4$	燮
		$S_{4,4} = f_{4,4}(X_1, X_2, X_3, X_4) = (X_1 \rightarrow X_2) \Downarrow X_3 \Downarrow X_4$	翼
		$S_{4,5} = f_{4,5}(X_1, X_2, X_3, X_4) = X_1 \Downarrow (X_2 \rightarrow X_3) \Downarrow X_4$	彝
		$S_{4,6} = f_{4,6}(X_1, X_2, X_3, X_4) = X_1 \Downarrow X_2 \Downarrow (X_3 \rightarrow X_4)$	蕊
		$S_{4,7} = f_{4,7}(X_1, X_2, X_3, X_4) = X_1 \rightarrow (X_2 \Downarrow X_3 \Downarrow X_4)$	境
		$S_{4,8} = f_{4,8}(X_1, X_2, X_3, X_4) = (X_1 \Downarrow X_2 \Downarrow X_3) \rightarrow X_4$	颤

		$S_{4,9} = f_{4,9}(X_1, X_2, X_3, X_4) = (X_1 \downarrow X_2) \Rightarrow X_3 \Rightarrow X_4$	翻
		$S_{4,10} = f_{4,10}(X_1, X_2, X_3, X_4) = X_1 \Rightarrow (X_2 \downarrow X_3) \Rightarrow X_4$	撷
		$S_{4,11} = f_{4,11}(X_1, X_2, X_3, X_4) = X_1 \Rightarrow X_2 \Rightarrow (X_3 / X_4)$	搬
		$S_{4,12} = f_{4,12}(X_1, X_2, X_3, X_4) = X_1 \rightarrow (X_2 \nabla X_3 \nabla X_4)$	潜
		$S_{4,13} = f_{4,13}(X_1, X_2, X_3, X_4) = (X_1 \nabla X_2 \nabla X_3) \rightarrow X_4$	戳
		$S_{4,14} = f_{4,14}(X_1, X_2, X_3, X_4) = (X_1 \Delta X_2 \Delta X_3)) \rightarrow X_4$	鸓
		$S_{4,15} = f_{4,15}(X_1, X_2, X_3, X_4) = X_1 \rightarrow (X_2 \Delta X_3 \Delta X_4)$	驦
		$S_{4,16} = f_{4,16}(X_1, X_2, X_3, X_4) = (X_1 \lhd X_2 \lhd X_3) \downarrow X_4$	璧
		$S_{4,17} = f_{4,17}(X_1, X_2, X_3, X_4) = (X_1 \rhd X_2 \rhd X_3) \downarrow X_4$	驡
Multi components		$S_{5,1} = f_{5,1}(X_1, X_2, X_3, X_4, X_5) = (X_1 \nabla X_2 \nabla X_3) \rightarrow (X_4 \downarrow X_5)$	-
		$S_{5,2} = f_{5,2}(X_1, X_2, X_3, X_4, X_5) = (X_1 \downarrow X_2) \rightarrow (X_3 \nabla X_4 \nabla X_5)$	-
		$S_{5,3} = f_{5,3}(X_1, X_2, X_3, X_4, X_5) = (X_1 \downarrow X_2) \rightarrow (X_3 \Delta X_4 \Delta X_5)$	-
		$S_{5,4} = f_{5,4}(X_1, X_2, X_3, X_4, X_5) = (X_1 \Delta X_2 \Delta X_3) \rightarrow (X_4 \downarrow X_5)$	-
		$S_{9,1} = f_{5,5}(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9) = (X_1 \Downarrow X_2 \Downarrow X_3) \Rightarrow (X_4 \Downarrow X_5 \Downarrow X_6) \Rightarrow (X_7 \Downarrow X_8 \Downarrow X_9)$	-
	……		

Notes: $S_{i,j}$ is a specific structure, $f_{i,j}$ is the function for constructing structure of Chinese characters ($S_{i,j}$); i denotes the classifications of structure and j denotes the serial number of functions. The operators $\rightarrow, \downarrow, \Rightarrow, \Downarrow, \Delta, \nabla, \lhd, \rhd, \Gamma, \llcorner, \lrcorner, \urcorner, \sqcap, \sqcup, \sqsubset, \sqsupset$ *and* $\odot$ are the structure operators for constructing Chinese characters.

2.3 The four simple mathematical operators for representing map symbols

Li (2014) proposed four operators (i.e., blend, union, overlay, and frame) for representing the structures of map symbols. As these four operators only consider simple operations, they are called basic operators. In the following part of this section, the details of these operators will be illustrated.

- **Blend operators**

A blend operator is a binary operator designed to fuse two or more components from any direction into a new complex component, as some map symbols have complicated graphics. For example, the compound symbol of the toilet in the following symbol is horizontally formed by fusing the two components of "male" and "female" (see Figure 2.5a). The compound symbol of “horse riding” is vertically formed by the components of “human” and “horse”.

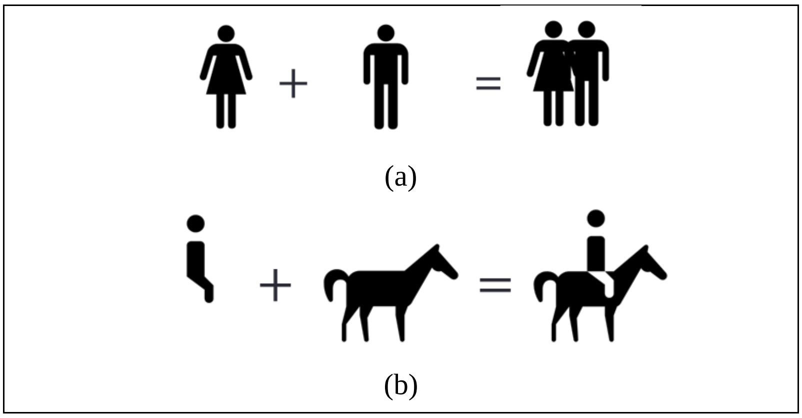


Figure 2.5 Examples of blend operators: (a) the construction of compound symbol “toilet”; (b) the construction of compound symbol “horse riding”.

- **Union operators**

A union operator is an operator designed to combine two or more components from any direction into a new complex component. For example, the compound symbol of the “traveler” in the following symbol is formed by fusing the three components of “human”, “backpack”, and “walking stick”. (See Figure 2.6).

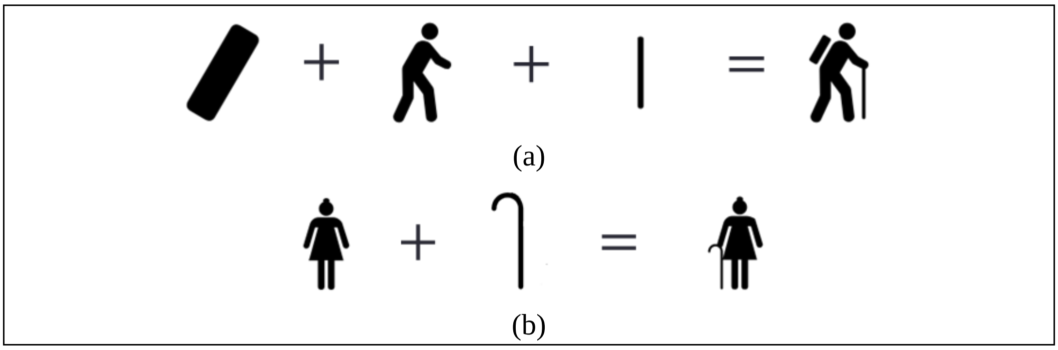


Figure 2.6 Examples of union operators: (a) the construction of compound symbol “traveler”; (b) the construction of map symbol “”.

- **Overlay operators**

After testing, most map symbols can be expressed in Chinese character structures. However, there are some topological problems in the structural operators, such as partial overlap and full overlap problems (Gong et al., 2022). The overlay operator is a binary operator used to move one component to the location of another (see Figure 2.7) and solve the problems of full overlap.

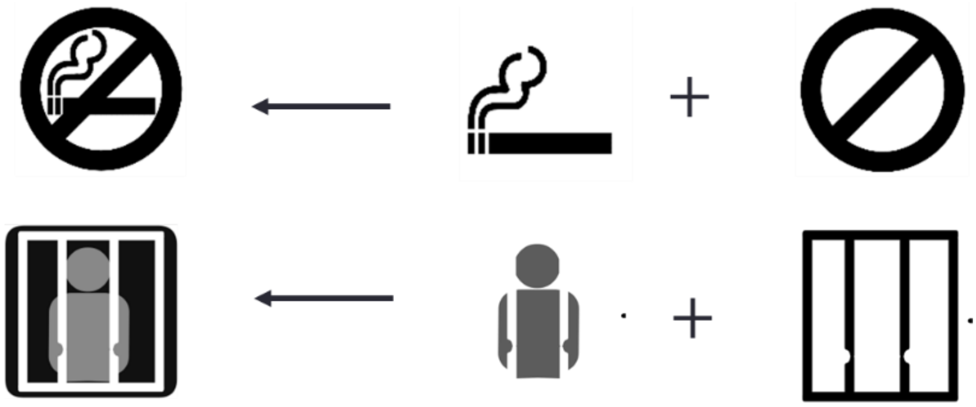


Figure 2.7 The examples of overlay operators.

- **Frame operators**

Li (2014) defined a map symbol can be topologically decomposed into three components, i.e., interior, symbol components, and frame. The boundary of a symbol component can be closed (with boundary) or open (without boundary). The frame of a map symbol can be non-empty (framed) or empty (open). The filling of the frame can be unfilled or filled, and the shape of the frame can be regular or irregular, the irregular shapes are used in most cases.

Some cartographers noticed that the shape of the frame affects the user's understanding of the semantics of the symbol and used different shapes of frames to express different phenomena when designing symbols. For example, the NATO Joint Military Symbology devised by the US Army Corps of Engineers (Opach, and Rød, 2022) and a standard set of symbols for use in the emergency management and first responder communities developed by the Federal Geographic Data Committee (FGDC) Homeland Security Working Group (Akella, 2009). With the popularity of symbols for commercial purposes, it has been found that subjective preference may affect the success or failure of symbol design (Huang et al., 2002; Robinson et al., 2010). People do prefer different frames for different symbols, but the circle and square are most preferred. Frame operators are primarily used to generate frames. It can be assumed that the symbol is placed in the geometric center of the frame. There are three types of frame operators, i.e., circle, rectangle, and triangle (see Figure 2.8).

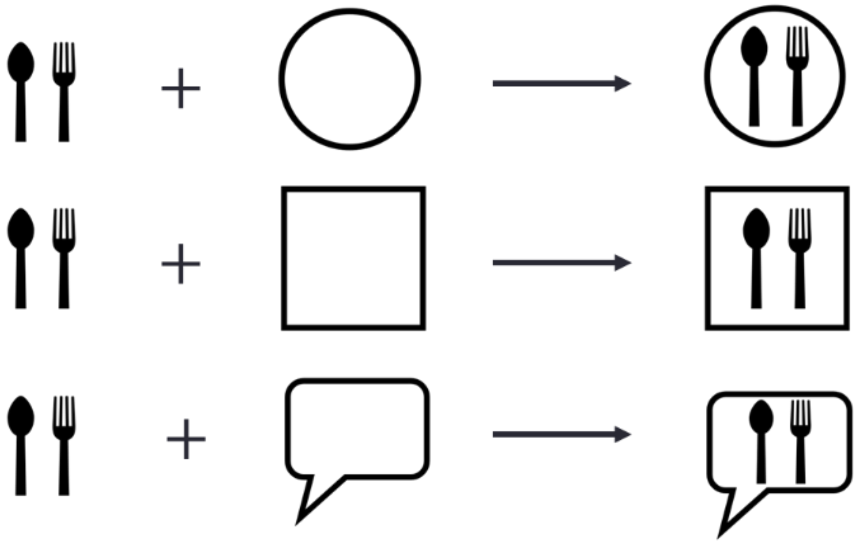


Figure 2.8 The examples of frame operators.

Chapter 3 The feasibility of structures of Chinese characters for representing map symbols.

3.1 A strategy for constructing map symbols based on the structures of Chinese characters

After carefully checking the related literature, it is found that although some scholars suggested that they can use Chinese as a second language to facilitate map-reading education, there is little research about designing or constructing map symbols using the knowledge of Chinese characters. It is believed that the analogy between maps and Chinese is helpful for the construction of map symbols.

Chinese is one of the oldest written languages in the world, with a history of more than thousands of years. Chinese characters mainly originate from the pictures of memorizing events, and hieroglyphs are the basis for the formation and development of the Chinese character system. Chinese is also one of the most widely spoken languages. At present, more than 25% of people from all over the world use Chinese. Chinese characters are square characters. Compared with other pictograms, Chinese characters have clear geometric structures, such as the up and down structures, and left and right structures. In addition, the relationship between the form and the meaning of Chinese characters is very close, and it has obvious intuitiveness. Each radical of a Chinese character has a corresponding semantic meaning, which is very similar to the symbols' component.

In our understanding, a map symbol can be treated as a character (morpheme) in Chinese. The morpheme of written Chinese is usually a character that is a component of a word (Li, 1995), and a Chinese character may include one, two, or more radicals to form each individual character. The radicals have different properties, such as shapes, sizes, and orientations. Such formal units (i.e., symbol components) can also be identified in map symbols. Considering the syntax of maps, Schlichtmann (1985) claimed that ordinary maps have a definite set of ordering rules which are syntactically similar to the syntax of written language. Li (1995) put forward that the scale transformation and the projection transformation are the basic syntactic rules for all maps. It is noted that he emphasized the evolution of human language, i.e., a simplifying and stylizing process indicates the direction of the evolution of map language. We agree with his points and believe the structures of Chinese characters can guide the formal representation of the automatic construction of map symbols.

It is believed that constructing formal representations of map symbols is a complex process, and the first step in this process is to formally represent their structures. Therefore, an approach to constructing map symbols using Chinese characters' structures was proposed. The strategy for evaluating the feasibility of this approach is as follows:

- The structures of map symbols from representative datasets are determined.
- Through descriptive statistics and questionnaire-based analysis, the determined structures of map symbols are compared with those of Chinese characters.

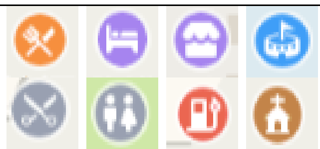
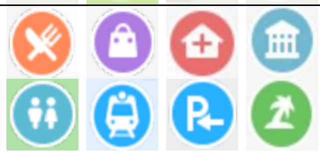
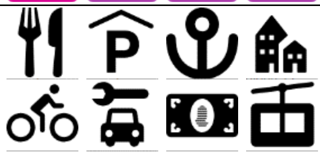
3.2 Data and Method

3.2 1 Experimental data

Map symbols from eight widely used datasets were selected as the experimental data (see Table 3.1). The map symbols in each dataset feature different categories. This study reorganizes these symbols and classifies them into five types. The first type includes amenity-related symbols of restaurants, libraries, police departments, post offices, etc.; the second collects shopping-related symbols such as those of estate agents, hairdressers, and department stores; the third presents tourist-related symbols such as those of museums, theaters, theme parks, and viewpoints; the fourth comprises transportation-related symbols, including symbols of airport, bus stop, car share, and petrol stations; and the fifth refers to emergency facilities, such as hospitals, the fire department, and fire watch towers. The sources of these datasets are given in Table 3.1, and these datasets can be downloaded from here for free.

Table 3.1 Selected map-symbol sets.

Data set (number)	Categories	Examples	Sources
SOSM (163)	Amenity, barrier, highway, historic, leisure, man-made, natural religion, shop, tourism		https://github.com/gravitystorm/openstreetmap-carto (accessed on 4 August 2023)
GM (52)	Catering, activities, shopping, services		https://github.com/scottdejonge/map-icons (accessed on 4 August 2023)
GI (104)	General, toilets, food, stores, activities, transport, health, entertainment, services, business, government, religious,		https://www.w3schools.com/icons/google_icons_maps.asp (accessed on 4 August

	accessibility		2023)
COSM (402)	Aerial-way, aero-way, amenity, barrier, club, craft, emergency, highway, historic, information, leisure, man-made, military, natural, office, power, public transport, railway, shipping, shop, tourism, waterway		http://osmicons.org/wiki/Main_Page (accessed on 4 August 2023)
GD (47)	Eating, accommodation, transport, tourism, bank, shopping, amenity		https://ditu.amap.com/ (accessed on 4 August 2023)
BD (60)	Catering, accommodation, transportation, bank, amusement, amenity, shops, attractions		https://map.baidu.com/ (accessed on 4 August 2023)
SJJB (282)	Accommodation, amenity, barrier, education, example, food, health, land-use, money, place of worship, poi, power, shopping, sport, tourist, transport, water		http://www.sjjb.co.uk/mapicons/ (accessed on 4 August 2023)
MIKI (174)	No categories		https://labs.mapbox.com/maki-icons/ (accessed on 4 August 2023)

Notes: Number refers to the number of map symbols extracted from each symbol set. Some symbols that do not belong to map symbols are not extracted. SOSM refers to the standard open street map icons; GM, Google Maps data; GI, Google Icons data; COSM, the complete OSM icons; GD, the GAODE map icons (Chinese); BD, Baidu map icons (Chinese); SJJB, SJJB map icons; MIKI, MIKI map icons. Tables 3–6 use the same symbols as Table 3.1.

3.2.2 Experimental design: Task and procedure

This study evaluated the feasibility of Chinese character structures for representing map symbols. The experimental process is delineated in the following.

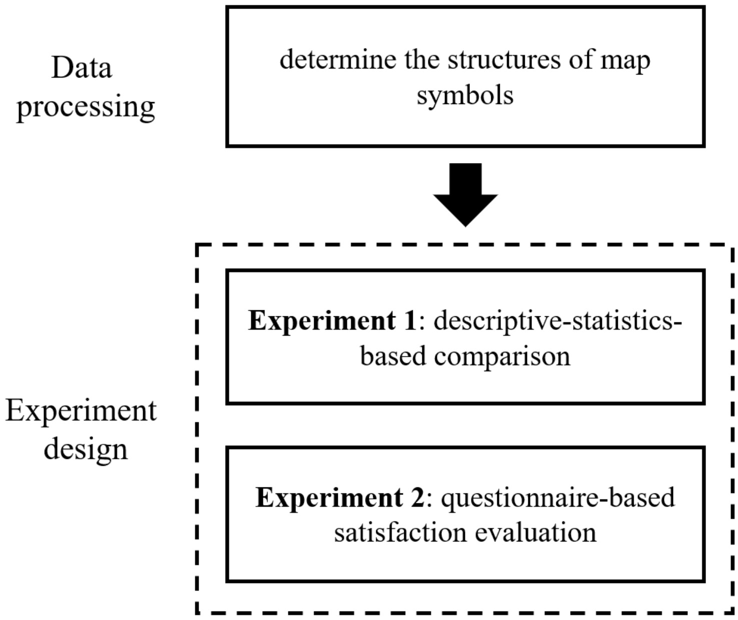


Figure 3.1 Experimental processes.

In the course of data processing, the structures of map symbols must be determined. This is achieved by recognizing the positions of the basic components in map symbols. These components are perhaps the smallest meaningful graphics or text elements or an amalgamation of both. For example, in Figure 3.2, the structures of three map symbols—namely, "Chinese restaurant," "video games," and "beach resort"—are determined in this way. It should be noted that the first two symbols have clear structures, while the last one does not.

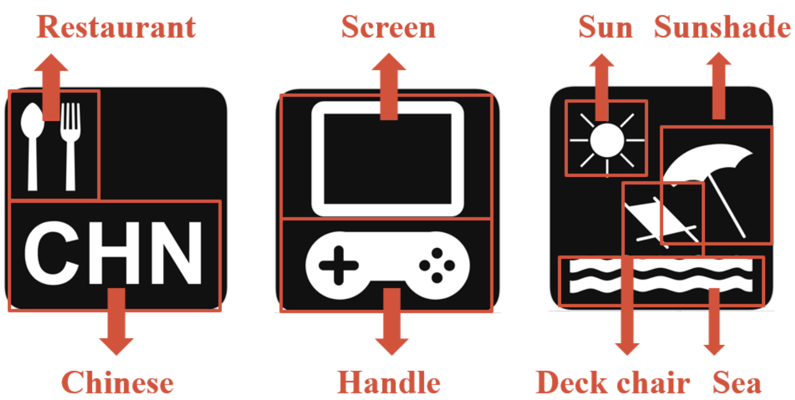


Figure 3.2 The structures of three map symbols by recognizing the positions of basic components.

Experiment 1 entails a comparison of the determined structures of map symbols with those of Chinese characters. Map symbols with clear structures are bifurcated as Group A—in which the structure of each symbol corresponds to certain structures of Chinese characters—and Group B, to which this correspondence does not apply. For symbols in

Group A, the frequencies of the corresponding structures of the Chinese characters are counted. Specifically, this study analyzes each symbol set separately to identify whether the structural distribution of each symbol set is similar to each other. The formula to calculate the Pearson correlation coefficient (r) is as follows:

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{n}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{n}\right)}} \tag{1}$$

Where $X = (x_1, x_2, \dots, x_n)$ and $Y = (y_1, y_2, \dots, y_n)$ are the proportions of the structures of Chinese characters in two individual symbol sets, and n is the number of the structures of Chinese characters. For symbols in Group B, the study analyzed the reasons for the dissimilarities. In addition, an analysis of the internal topological relationships of symbols in Groups A and B was also conducted.

Experiment 2, a questionnaire-based test, was conducted on the online platform Wenjuanxing. Based on this platform, 138 completed questionnaires from 138 participants aged 18–60 were obtained. Only 18% of the participants had ever learned cartography or attended cartography sessions. This experiment acquired subjective satisfaction levels with regard to the feasibility of using the structures of Chinese characters to represent map symbols. The datasets of the map symbols are divided into several groups. The symbols in each group and the structures of Chinese characters were shown to participants. A 5-point Likert scale was used (from 5, very satisfied, to 1, very unsatisfied) to identify the subjective opinions of the participants. For example, a “completely satisfied” response indicates that the respondent considers that the structures of Chinese characters can represent those of map symbols adequately. Participants who felt that the structures of Chinese characters cannot express the structure of map symbols were prompted to provide a reason for the same.

3.3 Experimental Results and Analysis

3.3.1 Results and Analysis of Experiment 1

- **Percentage of map symbols fitting into the Chinese character structure**

It was found that some map symbols can be represented by Chinese characters, but others cannot. For example, Figure 3.3 below is a symbol of an “alcohol shop” map. This symbol contains three components, i.e., the graphic of a bottle, the text of percentage, and the graphic of a wine glass. It was found that there is no overlap between each component, and the spatial relationships between components are similar to that between radicals in the Chinese character with a triangle structure. This symbol can be constructed by the triangle-structure operator.

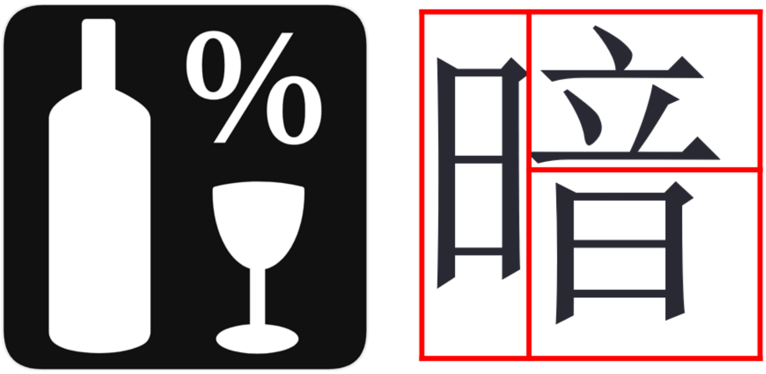


Figure 3.3 An example of map symbols perfectly represented by the triangle-structure.

The statistical results are presented in Table 3.2. Respondents indicated that 77.5% of map symbols could perfectly fit the structures of Chinese characters. Google Icons (GIs) have the highest percentage of perfect symbols (99%). It can be noted that the structures of most compound GIs are relatively simple. Some examples of symbols rated perfect are demonstrated in Figure 3.4 below.

Table 3.2 Proportions of map symbols that fit perfectly and imperfectly into the structures of Chinese characters.

Symbol set	**Perfectly fit (%)**	**Imperfectly fit (%)**
BD	75.0	25.0
COSM	66.2	33.8
GD	85.1	14.9
GM	86.5	13.5
GI	99.0	1.0
MIKI	86.7	13.3

SOSM	83.4	16.6
SJJB	74.1	25.9
sum	77.5	22.5

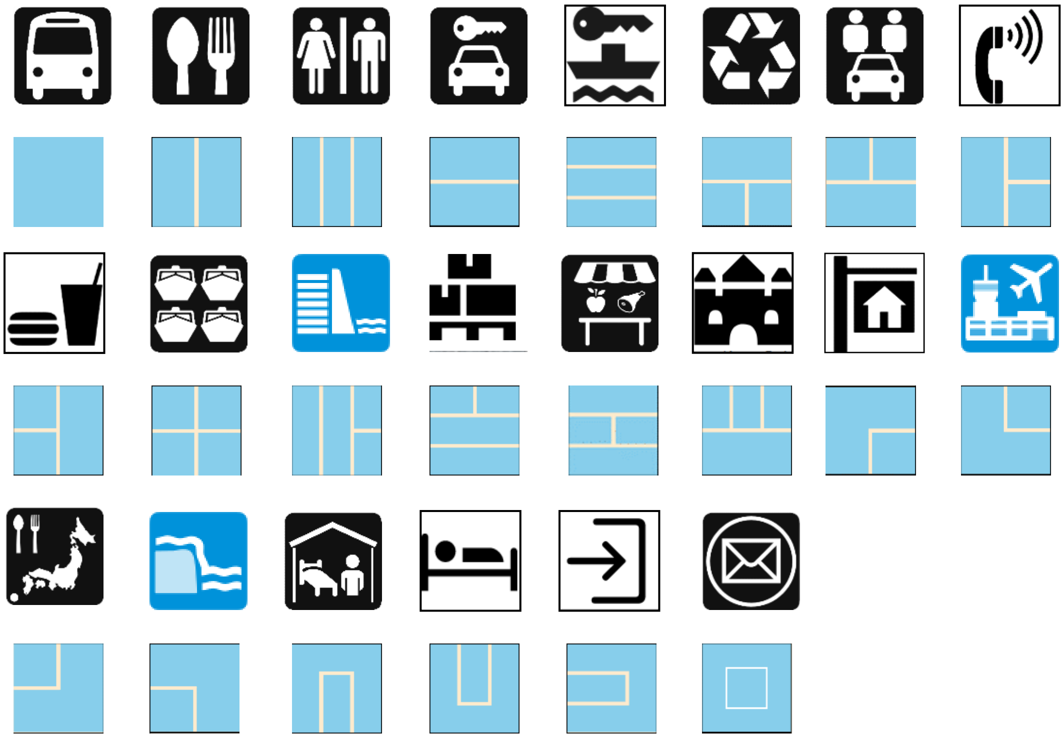


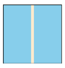
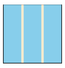
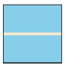
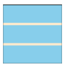
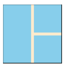
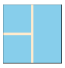
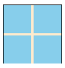
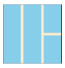
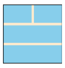
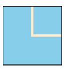
Figure 3.4 Some examples of map symbols perfectly represented by Chinese character structures.

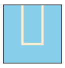
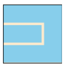
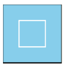
- **Frequency of different structures applied**

The proportion in each structure of perfect symbols was calculated (see Table 3.3). Map symbols with a singular structure account for the largest proportion of each symbol set. In addition, where each symbol in a set has multiple components, designers prefer simpler structures, such as a two-row structure or a two-column structure. Some possible complex structures are not seen in symbol design, possibly because such structures are too complex to be identified or integrated by users.

Table 3.3 Symbol proportions that perfectly fit structures of Chinese characters.

	BD	COSM	GD	GM	GI	MIKI	SOSM	SJJB	sum

	72.1	34.4	65.8	46.7	52.0	57.2	46.9	50.0	48.1
	2.3	5.8	5.3	8.9	11.8	4.1	6.9	6.2	6.4
	2.3	0.8	2.6	0.0	0.0	0.7	0.8	1.4	0.9
	14.0	12.7	7.9	17.8	13.7	22.1	20.0	16.7	16.2
	2.3	0.8	0.0	4.4	1.0	2.1	3.8	0.5	1.5
	0.0	1.5	0.0	0.0	1.0	0.7	1.5	1.0	1.0
	0.0	16.2	0.0	0.0	0.0	0.7	4.6	3.3	5.8
	0.0	3.5	5.3	0.0	2.0	1.4	1.5	2.4	2.3
	0.0	3.9	0.0	0.0	0.0	0.7	1.5	0.5	1.4
	0.0	3.5	0.0	0.0	0.0	0.0	0.0	1.0	1.1
	0.0	0.4	0.0	0.0	0.0	0.0	0.0	1.0	0.3
	0.0	0.4	0.0	0.0	1.0	0.0	0.8	0.0	0.3
	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.5	0.2
	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.1
	0.0	0.4	2.6	0.0	1.0	1.4	0.0	0.0	0.5
	2.3	0.0	2.6	2.2	1.0	2.1	0.0	0.5	0.8
	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3

	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.2
	0.0	2.7	0.0	0.0	2.0	0.0	0.8	1.4	1.3
	0.0	0.8	0.0	0.0	0.0	0.0	0.8	0.0	0.3
	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.1
	4.7	10.8	7.9	20.0	13.7	6.2	9.2	12.9	10.7
sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Notes: The abbreviations are the same as those in the first column of Table 3.1.

Table 3.4 presents the calculated correlation coefficients for the structural distributions of each symbol set. The correlation coefficient between each symbol set was found to be higher than 0.8, indicating that the structural distributions of these symbol sets are very similar. Thus, map-symbol designers with different cultural backgrounds display similar preferences for symbolic structures in the process of symbol construction. In other words, all of them prefer simpler structures, including left–right structures, up–down structures, and completely framed structures. The reason may be that symbols with simple structures are easier to recognize.

Table 3.4 Correlation coefficients between the structural distributions for each symbol set.

	BD	COSM	GD	GM	GI	MIKI	SOSM	SJJB
BD	1	0.87	0.99	0.93	0.97	0.98	0.96	0.97
COSM	0.87	1	0.86	0.88	0.89	0.88	0.92	0.92
GD	0.99	0.86	1	0.92	0.97	0.97	0.94	0.97
GM	0.93	0.88	0.92	1	0.98	0.95	0.97	0.98
GI	0.97	0.89	0.97	0.98	1	0.97	0.97	0.99
MIKI	0.98	0.88	0.97	0.95	0.97	1	0.99	0.98

SOSM	0.96	0.92	0.94	0.97	0.97	0.99	1	0.99
SJJB	0.97	0.92	0.97	0.98	0.99	0.98	0.99	1

3.3.2 Results and Analysis of Experiment 2

The average satisfaction level with using structures of Chinese characters to represent structures of map symbols (all sets combined) was found to be 3.89. Furthermore, over half of the participants (i.e., 89) responded with "satisfied" or "very satisfied." These results indicate that public attitudes toward using the structures of Chinese characters to represent the structures of map symbols are generally positive.

The participants also raised some queries on this subject. These can be broadly summarized into three aspects: (1) the identification of the basic components of the symbol, i.e., the smallest meaningful combination of graphics; (2) the identification of symbol structures when the sizes of two components differ significantly; and (3) a judgment of whether asymmetric symbolic structures are similar to the structures of Chinese characters.

3.4 Discussion and Conclusion

3.4.1 Structures of map symbols that do not fit well into Chinese character structures

Further analysis was conducted to identify why some map symbols' structures do not fit into the structures of Chinese characters. It was found that two main types of problems, namely, topological and geometric.

- **Topological problems**

Topological problems relate to the overlap between the components of a map symbol. Some symbols have overlapping components (Table 3.5), in two types of overlap: partial and full. A partial overlap means that two components have no more than 50% overlap with each other (see Figure 3.5a), while a full overlap suggests that one component is entirely overlapped by the other (see Figure 3.5b). In the eight datasets employed, few map symbols with partial and full overlap issues were identified. Among the Chinese characters, only disjoint or meet relations exist with corresponding components (i.e., radicals). Because of this, the structures of Chinese characters can only represent map symbols whose internal topological relations are disjoint or meet.

Table 3.5 Proportions of topological relationships of map symbols.

	BD	COSM	GD	GM	GI	MIKI	SOSM	SJJB	sum
Disjoint	36.4	74.8	41.7	34.4	66.7	70.8	72.2	53.4	64.8
Overlap	27.3	8.7	20.8	9.4	0.0	3.4	12.4	23.0	12.2
Meet	30.3	6.5	25.0	28.1	5.9	14.6	3.1	8.4	9.7
Contain	6.1	10.0	12.5	28.1	27.5	11.2	12.4	15.2	13.2
sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

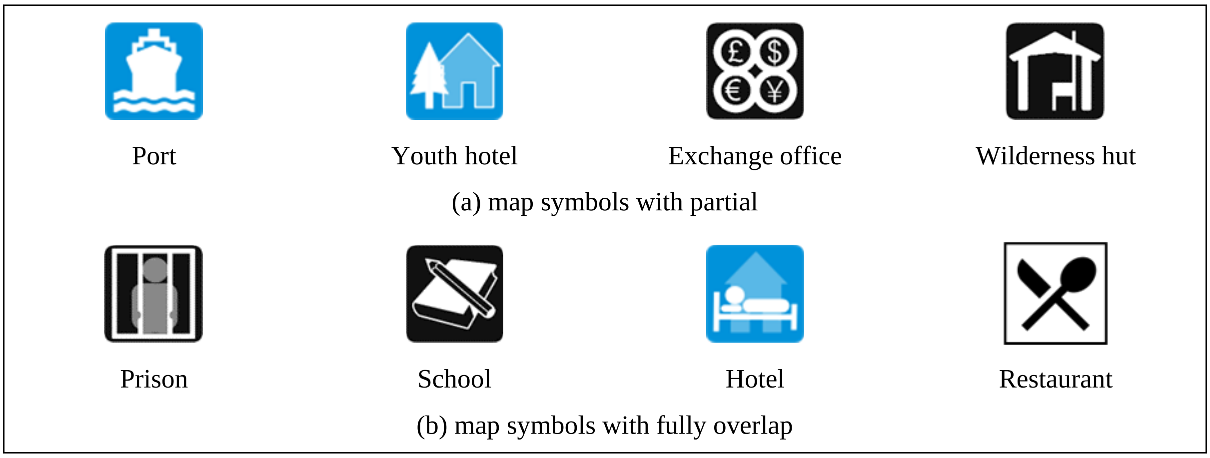


Figure 3.5 Map symbols with two types of overlap.

- **Geometric problems**

The geometric problems identified include scaling, direction, and distance problems. Scaling problems may appear in cases where some components are enlarged or reduced in the design of a map symbol. Directional problems are related to rotation. Distance problems resemble topological problems. Some examples of map symbols that feature these types of geometric problems are shown in Table 3.6.

Table 3.6 The symbols with geometric problems.

Geometric problem	Examples of map symbols			
Scaling				
Direction 1				
Direction 2				
Distance				
Mixed				

- **Combined topological and geometric problems**

Both topological and geometric problems may appear in a complex map symbol. Some examples are given in Fig. 3.6. For example, the area of the component "human" in Figure 3.6a is much larger than the area of the component "baseball bat," which makes it difficult to recognize the directional relationship between these two components. In addition, there is an overlap between them.

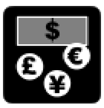
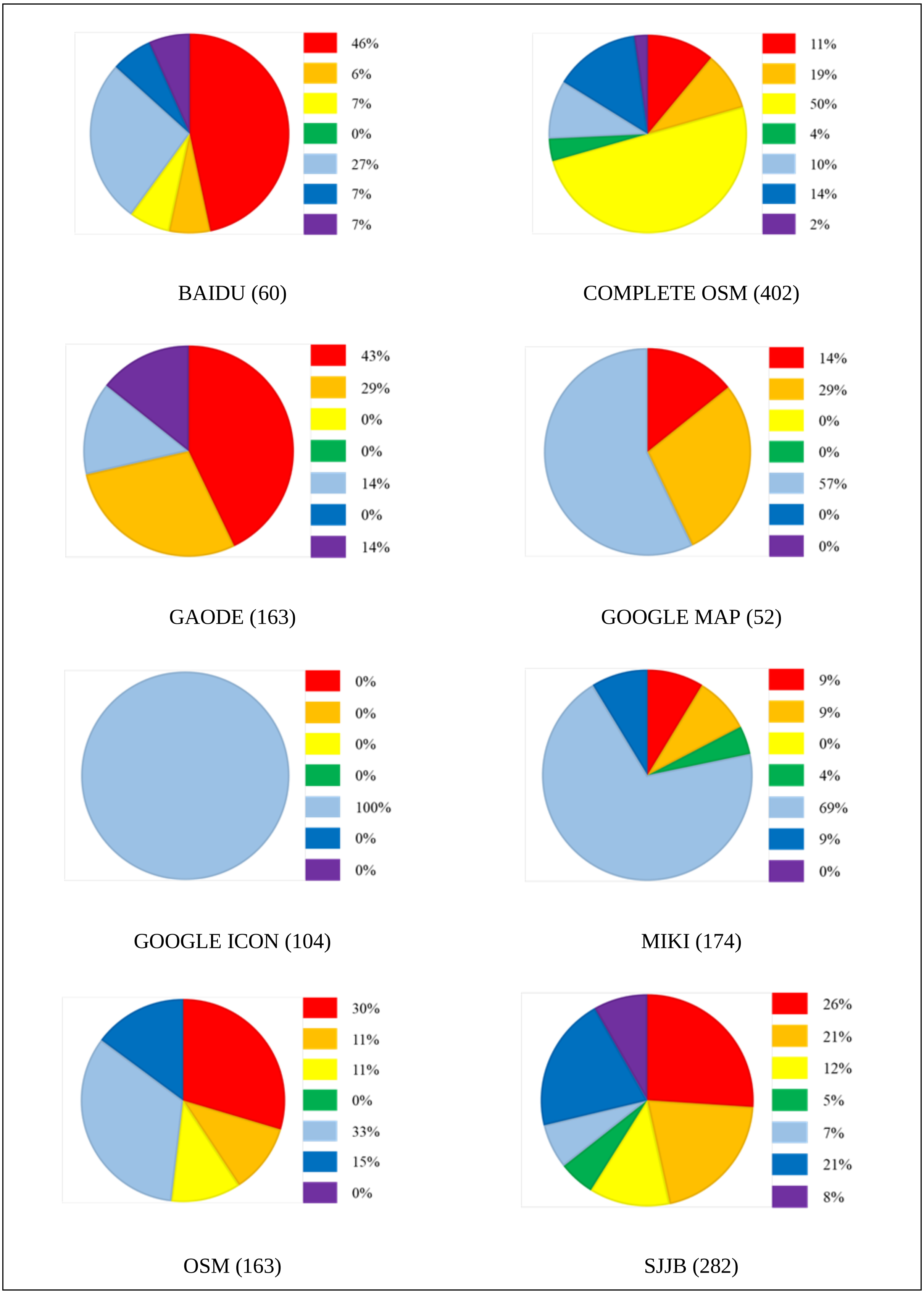
    

Figure 3.6 Map symbols with both topological and geometric problems.

These map symbols with imperfect fit can be classified into the following types: partial overlap, full overlap problems, scale problems, direction problems, distance problems, mixed geometric problems, and mixed topological and geometric problems. As indicated in Figure

3.7, 14.4% of symbols have geometric problems, 7.2% have topological problems, and 0.9% have both topological and geometric problems.



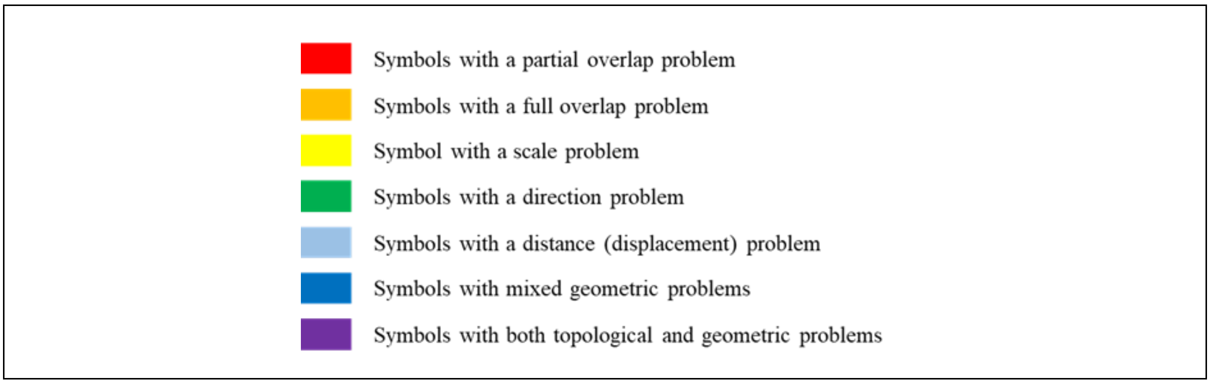
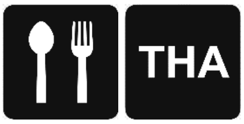


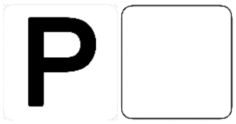
Figure 3.7 Proportions of imperfect symbols of different types.

3.4.2 Need for additional operators for compound map symbols

The above analysis indicates that owing to geometric and topological problems, the structures of Chinese characters cannot be used in isolation to construct all types of map symbols. To resolve the geometric problems, basic metric operators such as translation, rotation, and scaling operators are required. A translation operator entails moving the symbol components in different directions (Li and Su, 1995). Rotation and scaling operators can scale and rotate the component. An overlay operator overlays one component on another. To construct symbols with complex structures, blend operators are useful. Such operators can combine two components into a larger one. In addition, solutions such as adding a frame and interior to the symbols (i.e., frame and contrast operators) are possible. Some examples of the introduced operations/operators are given in Table 3.7.

Table 3.7 Examples of some operators for constructing map symbols.

Morphological operators	Original symbols	After operation
Structure		
Overlay		
Translate		

Rotate		
Scale		
Frame		
Color		

3.5 Summary

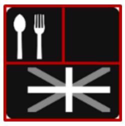
This study evaluated the feasibility of using structures drawn from Chinese characters to represent the structures of map symbols. Eight widely used map-symbol datasets were selected for testing, and two experiments were designed to evaluate the feasibility. The first experiment was based on descriptive statistics, while the other was a questionnaire-based evaluation. Before the two experiments were conducted, the structures of map symbols from eight datasets were determined. The descriptive statistics experiment compared the determined structures of map symbols with the structures of Chinese characters. It was found that 77.5% of map symbols perfectly fit into the structures of Chinese characters. The questionnaire-based evaluation acquired subjective opinions (i.e., satisfaction level) of the feasibility of using structures of Chinese characters to represent the structures of map symbols. On a 5-point scale from very unsatisfied to satisfied, more than half of the participants responded that they were satisfied or very satisfied, with an overall score of 3.89. These results indicate that the structures of Chinese characters are suitable to represent the structures of map symbols. This work could benefit ubiquitous mapping and enrich cartographic theory.

Chapter 4 Improvement of formal representation of map symbols with additional basic operators

4.1 The need for additional basic operators for representing map symbols

It has been suggested by the previous study that the structural operators of Chinese characters can be used for such a purpose with a success rate of 77.5% although with imperfection in some cases (Table 4.1). It means that (1) the other 22.5% of symbols should be formally represented by other mathematical solutions and (2) those imperfect cases should be made perfect through modification or refinement. For example, a compound map symbol may be composed of two symbols with overlaps (e.g., the non-smoking symbol in Figure 2.5). Still, the structural operators cannot represent such a composition.

Table 4.1 Imperfect fit with map symbols represented by structural operators of Chinese characters.

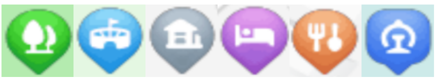
Perfectly fit			
Imperfectly fit: position problem			
Imperfectly fit: Orientation			

For this issue, the feasibility of Chinese character structures was reanalyzed. To solve the representation problems of the map symbol that didn't perfectly fit Chinese characters, some logical operators such as union, and difference, and simple mathematical operators such as overlap, and blend proposed by Li (2014) may be helpful.

4.2 Design experiment for improvement evaluation

In this experiment, the feasibility of basic operators, i.e., blend, union, structure, and frame operators for constructing all the map symbols in eight symbol sets were evaluated. Specifically, it was to check whether each symbol in the symbol sets can be constructed by the existing operators by way of human eye observation. Map symbols from eight widely used datasets were selected as the experimental data (see Table 4.2). These map symbols consist of 837 compound symbols and 445 simple symbols. This study reorganizes these symbols and classifies them into five categories, i.e., amenity, shopping, tourist, transportation, and emergency. The sources of these datasets are given in Table 4.2, and these datasets can be downloaded for free.

Table 4.2 Selected map-symbol sets.

Data set (number)	**Examples**	**Sources**
OSM (163)		https://github.com/gravitystorm/openstreetmap-carto (accessed on 4 August 2023)
GM (53)		https://github.com/scottdejonge/map-icons (accessed on 4 August 2023)
GI (104)		https://www.w3schools.com/icons/google_icons_maps.asp (accessed on 4 August 2023)
COSM (401)		http://osm-icons.org/wiki/Main_Page (accessed on 4 August 2023)
GD (47)		https://ditu.amap.com/ (accessed on 4 August 2023)
BD (60)		https://map.baidu.com/ (accessed on 4 August 2023)
SJJB (281)		http://www.sjjb.co.uk/mapicons/ (accessed on 4 August 2023)
MIKI (173)		https://labs.mapbox.com/maki-icons/ (accessed on 4 August 2023)

Notes: Number refers to the number of map symbols extracted from each symbol set. Some symbols that do not belong to map symbols are not extracted. OSM refers to the standard open street map icons; GM, Google Maps data; GI, Google Icons data; COSM, the complete OSM icons; GD, the GAODE map icons (Chinese); BD, Baidu map icons (Chinese); SJJB, SJJB map icons; MIKI, MIKI map icons.

We invited 52 Ph.D. students and staff aged 22–36. In total, 38% of the participants had learned cartography or attended cartography sessions. In the first step, the basic elements, including graphics and texts, or the combination of them, and the structures of map symbols must be determined. Secondly, participants were asked whether each symbol can be constructed using structures of Chinese characters in isolation. The map symbol with a single structure is considered to be constructed with a single structural operator. When the analysis results from participants are different, the analysis results accepted by more people were taken. For map symbols that did not perfectly fit the structures of Chinese characters, additional basic operators were adopted to express them. The experimental process is delineated in Figure 4.1.

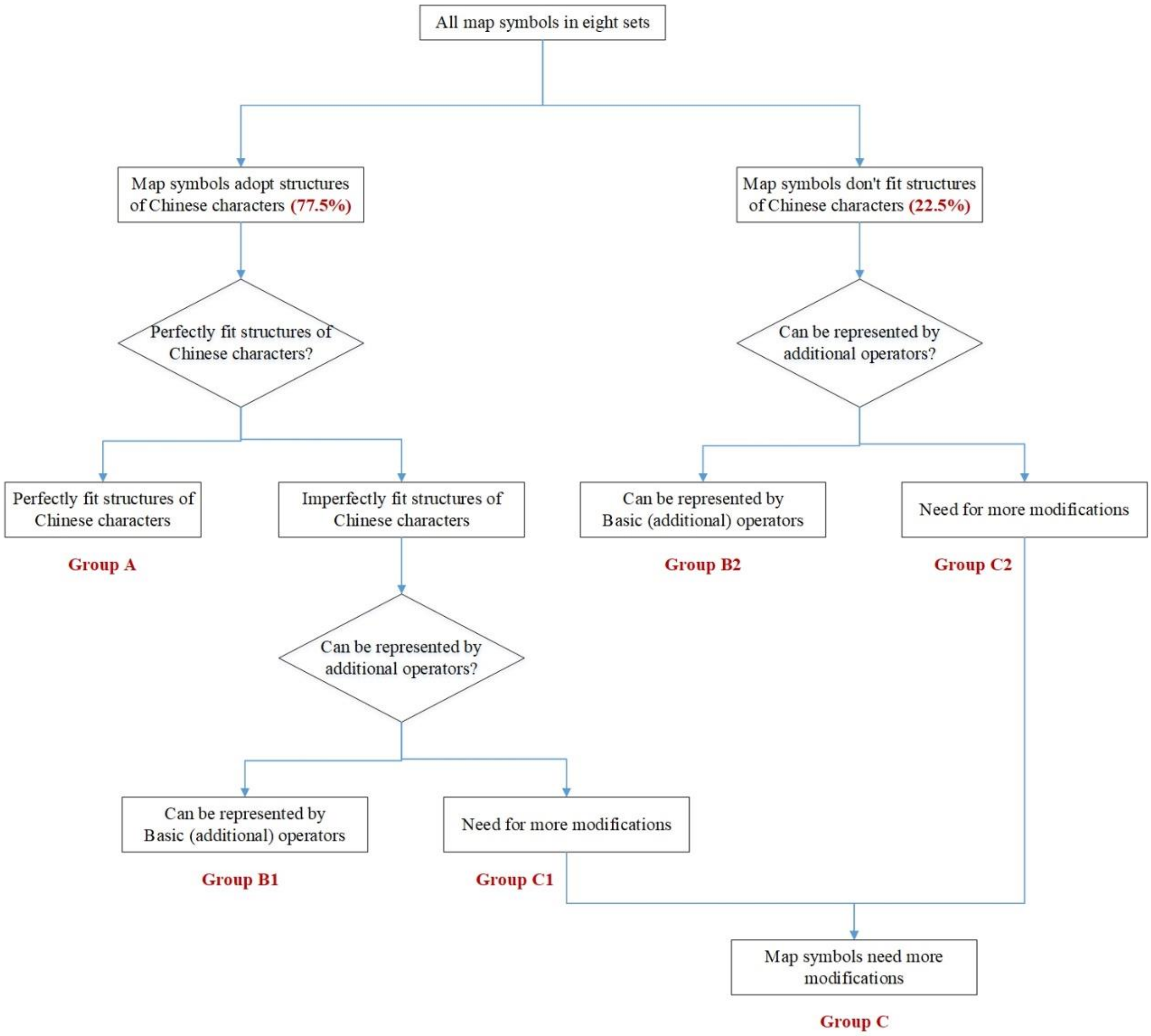


Figure 4.1 Experimental process.

All map symbols in these eight sets were bifurcated into group A, in which each symbol perfectly fits the structural operators of Chinese characters, and group B, in which the map symbols fit structural operators with an imperfection, or the structural operators do not apply. For the symbols in group B, the additional basic operators were employed to express them. The symbols in group B were divided into two groups, group B1 is map symbols that can be expressed by additional operators, and group B2 cannot. The last step is to count the map symbols in each symbol set that can be represented by additional basic operators.

4.3 Results of experiments: improvement with additional basic operators

The statistical results indicated that map symbols in group A account for 60.6% of the total (see Figure 4.2). It means that 60.6% of map symbols perfectly fit the structures of Chinese characters. 8.7% of map symbols (i.e., group B1) can be expressed by Chinese character structures, but more operators, such as union and blend, were needed to construct complex components. There are also some map symbols that require metric or colour modification, which cannot be done by additional operators. There are some examples illustrated in Table 4.3.

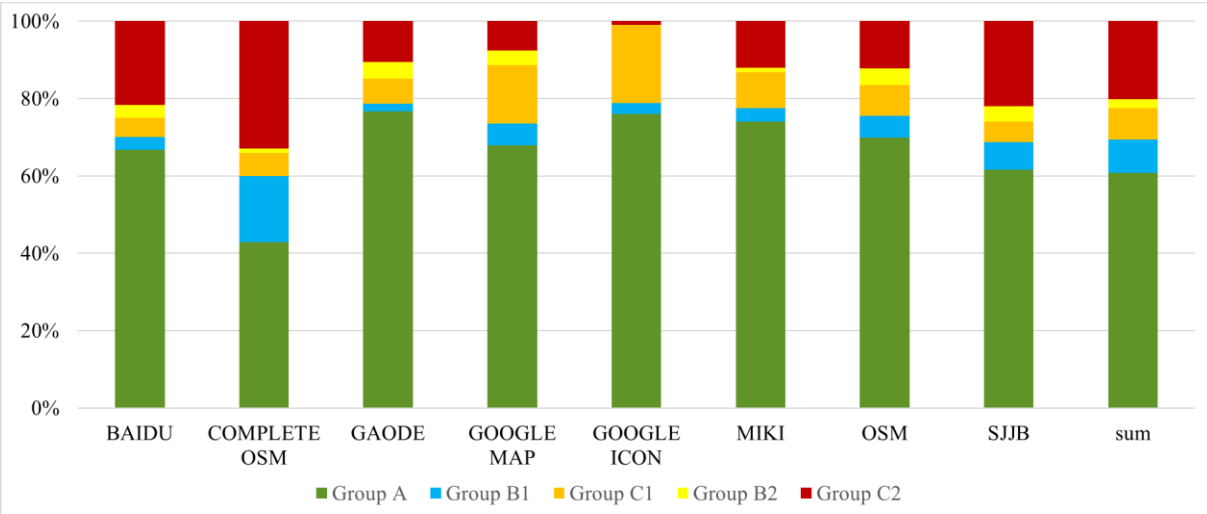


Figure 4.2 The proportions of map symbols that can be solved by additional operators.

Table 4.3 The map symbols imperfect fit with structural operators of Chinese characters.

Need union operators. (From Group B1)			
Need blend operators. (From Group B1)			
Need both additional operators and modifications. (From Group C1)			

Among the symbols that imperfectly fit structures of Chinese characters, 10.7% of map symbols need union operators, while the proportion of map symbols need blend operators or both union and overlay are only 0.2% and 0.1%, respectively. Among the remaining 22.5% of map symbols that cannot be expressed by the Chinese character structure (see Table 4.4), such as some map symbols with overlapping components, it was found that 8.7% of map symbols were expressed after adding additional operators. The remaining map symbols require more modifications.

Table 4.4 The map symbols didn't fit with the structural operators of Chinese characters.

Need additional operators. (From Group B2)			
Need modifications. (From Group C2)			
Need both additional operators and modifications. (From Group C2)			

The usage of each operator is illustrated in Figure 4.3. It was found that the usage rate of the union operator is the highest, followed by the overlay operator. It is worth noting tha the construction of a map symbol may require more than one operator. For example, the union operator is used to build complex components, the structural operator combines components into a composite symbol according to a certain spatial structure, and the frame operator adds a frame, etc. The experimental results suggested that the additional operators can improve the formal representation of map symbols, but quite a few map symbols require modifications.

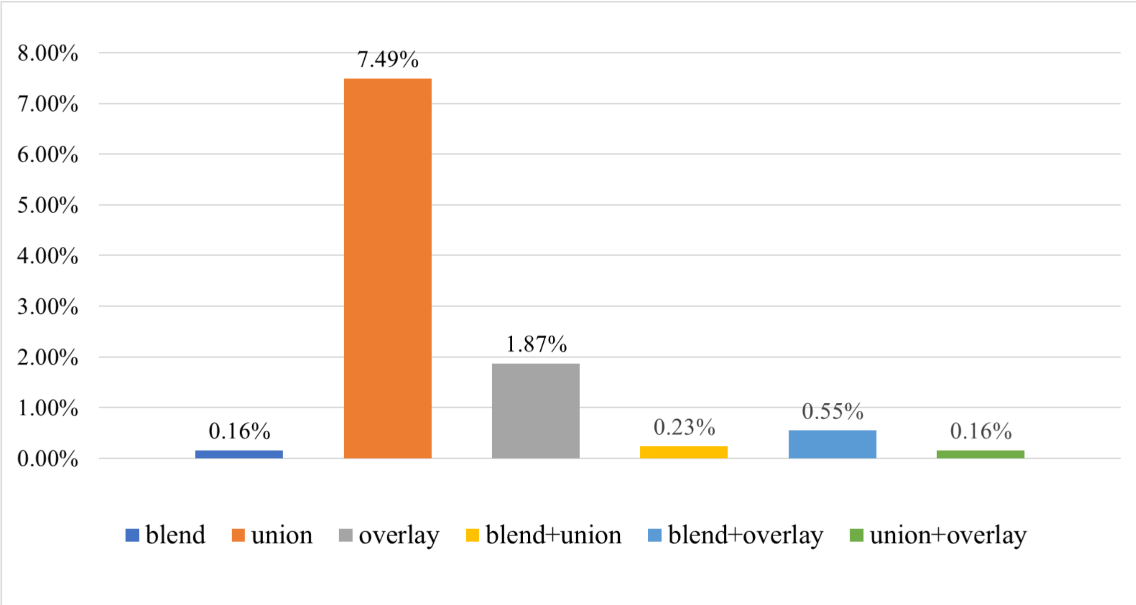


Figure 4.3 The usage of additional operators in map symbols that didn't fit the structures of Chinese characters.

In addition, the frames of map symbols were counted and analyzed. Generally speaking, the design of all symbols in a symbol set is consistent, such as the same frame shape for each symbol, the same background color for symbols, and so on. In these eight symbol sets, the symbols from BD, COSM, GD, and SJJB adopted frame operators. The BU and BD symbol sets and the GD symbols adopted the circular frames and the other two adopted square frames.

Chapter 5 Improvement of formal representation of map symbols with metric and colour modifications

5.1 Need for metric and colour modifications

Some examples are illustrated in Figure 5.1. There is no overlap between each component, but the graphic of one component is not complete. This component is cut from a complete graphic element. It looks like an incomplete graphic where one component's graphic is overlapped by the buffer of another component's graphics.

Figure 5.1 The incomplete shape of some components.

By observation, it was found that when two components overlap, the color of a component or part of a component may change. In general, every symbol in a symbol set, including the frame, has a consistent color. But it was found that when two components overlap, the two components may have different colors. Sometimes part of the component changes color, sometimes the whole component changes color. For example, the following symbols are formed by adjusting the color of the symbol components (see Figure 5.2).

Figure 5.2 The examples of symbols are formed by adjusting the color.

The map symbols whose center of gravity of the symbol components coincides with the center of gravity of the radicals of Chinese characters, and whose component size ratio fits the structural unit ratio of Chinese characters are considered as perfectly fitting the structures of Chinese characters.

5.2 Metric modifications

Metric modifications play an important role in the construction of map symbols to reposition the components and change their size or orientation. It is worth noting that metric details occasionally overwrite topological properties, particularly in situations where small metric modifications imply topological changes (Egenhofer and Shariff, 1998). For example, after the translation in Figure 5.4, the topological relationship between the two components changes from disjoint to overlap. Five modifications can be applied to a symbol component: buffer, translation, rotation, scaling, and color (some spatial models are described in Appendix A).

- **Buffer modifications**

The buffer is defined by Esri (https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/buffer.htm) as follows: Creates buffer polygons around input features to a specified distance. For the problem of incomplete component shape, buffer modifications were adopted to solve it.

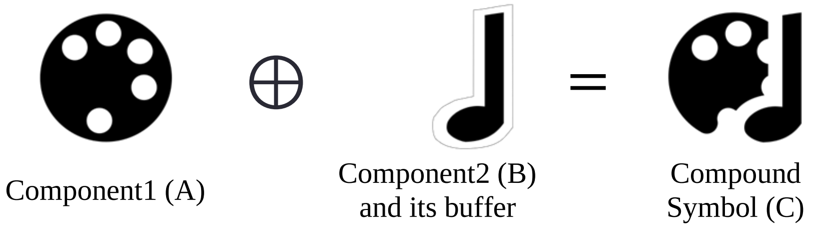


Figure 5.3 An example of buffer modifications.

For example, in the symbol of "art center" (See Figure 5.3), the buffer of the note component is on the right of the palette. After the buffer is built, the component on the left overlaps. The incomplete graphics that have been overlapped and the graphics that do not build buffers were taken and combined into new compound symbols. The formal representations of buffer modifications are as follows:

$$\text{A union with } \mathrm{B}^{\text{buffer(2mm)}} = \mathrm{C} \quad (2)$$

- **Translation modifications**

After the compound symbol is built, the component's position relative to the canvas is determined. The translation modifications move all the geometry objects of the symbol component to a new position relative to the canvas. There are four kinds of direction modifications, namely north (TN), east (TE), south (TS), and west (TW).

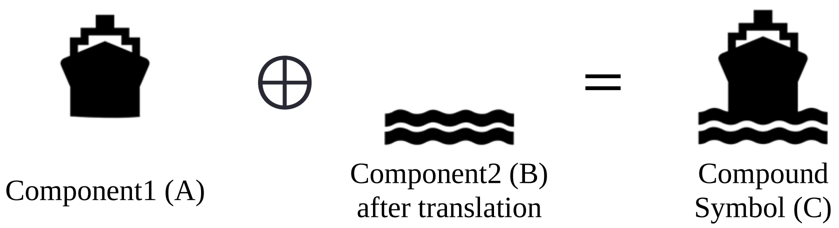


Figure 5.4 An example of translation modification.

For example, the symbol of “Port” is constructed by the union of a graphic of a river and a graphic of a boat with a down translation of 10 mm. (see Figure 5.4). The formal representations of translation modifications are as follows:

$$A^{ts(2mm)} \text{ union with } B = C \quad (3)$$

- **Rotation modifications**

Rotation modification rotates all the geometric objects of a component to a new direction relative to the canvas. There are two kinds of rotation modifications. One is to rotate a single component (see Figure 5.5).

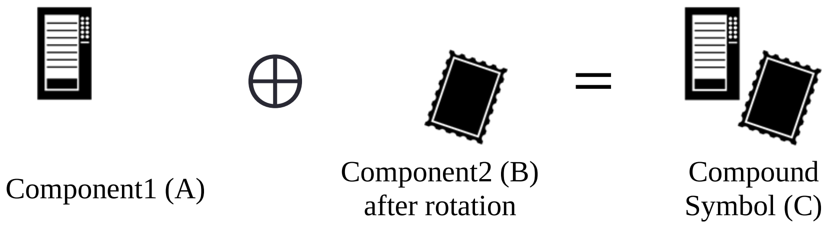


Figure 5.5 An example of rotations modifications.

For example, the symbol of “stereo equipment” is constructed by the union of the graphic of radio and the graphic of a film with a 30-degree rotation. The formal representations of this rotation modification are as follows:

$$A \text{ union with } (B^{rotate(30)}) = C \quad (4)$$

The other one is to combine the components into a compound component and then rotate the compound component (see Figure 5.6).

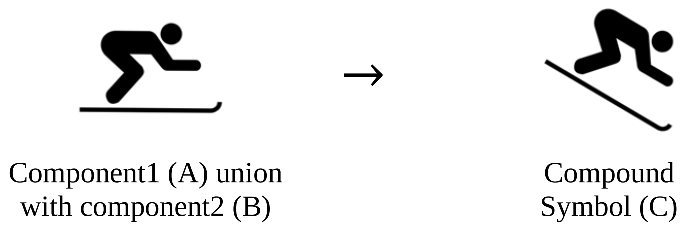


Figure 5.6 An example of rotations modifications.

For example, the symbol of “Skiing” is the graphic of skiing is translated with a 45-degree rotation. The formal representations of this rotation modification are as follows:

$$(A \text{ union with } B)^{rotate(30)} = C \quad (5)$$

- **Scale modifications**

All the geometric objects of the symbol component are transformed to a new size (see Figure 5.7).

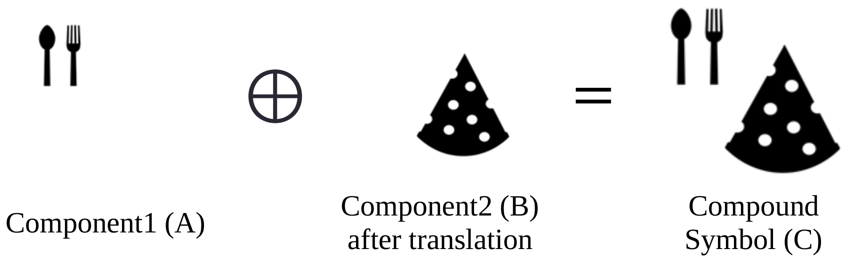


Figure 5.7 An example of a scaling modification.

For example, the symbol of "Pizza restaurant" is the union of a graphic of the canteen and a graphic of cheese enlarged by 150%. The formal representations of scale modifications are as follows:

$$\text{A union with } \text{B}^{\text{enlarge}(1.5)} = \text{C} \tag{6}$$

5.3 Colour modifications

By observation, it was found that when two components overlap, the color of a component or part of a component may change. Color modification is used to adjust the color of the overlapped part of a symbol component, to make the shape of components look clearer. In general, the symbol components of a symbol set are uniforms in color, such as all black or all white. But when one component fully overlaps another component, if there is no border, the shape of the component will be invisible. So, the color of the components is adjusted to better identify their shape just like Figure 5.8.

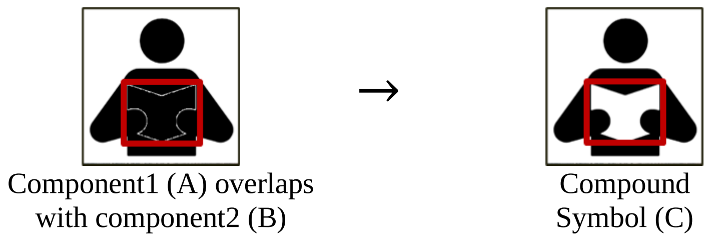


Figure 5.8 An example of color modification: one component partially overlaps another component.

For example, in the symbol of "library", the color of overlap between the component of human and the component of book was adjusted to white. There is another case where the color is adjusted only on a part of the component. As the analysis in the previous chapter when two components partially overlap, the overlapping area of the two components will change color, such as the same color as the background just like in Figure 5.9.

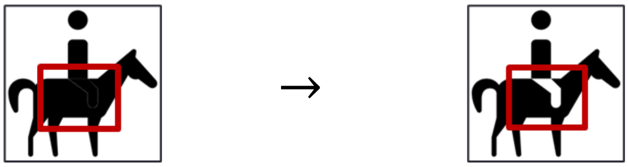


Figure 5.9 An example of color modification: one component partially overlaps another component.

For example, in the symbol of "riding", the color of overlap between the component of human and the component of a horse was adjusted to white. The formal representations of color modifications are as follows:

$$(\text{A overlap with B})^{\text{color(white)}} = \text{C} \tag{7}$$

5.4 Evaluation of proposed metric modifications for map symbol construction

According to the analysis in the last section, another experiment was conducted. This experiment evaluated whether the metric and color modifications can improve the formal representations of map symbols. The map symbols in groups C1 and C2 were used for evaluation. Participants were asked to identify whether these map symbols can formally be represented by the metric and color modifications.

After statistics, it was found that, in group C1, 6.01% of the map symbols only need metric modifications or color modifications to complete the formal representations, and the remaining 2.03% need both additional operators and modifications to complete them. The usage of each modification is illustrated in Figure 5.10.

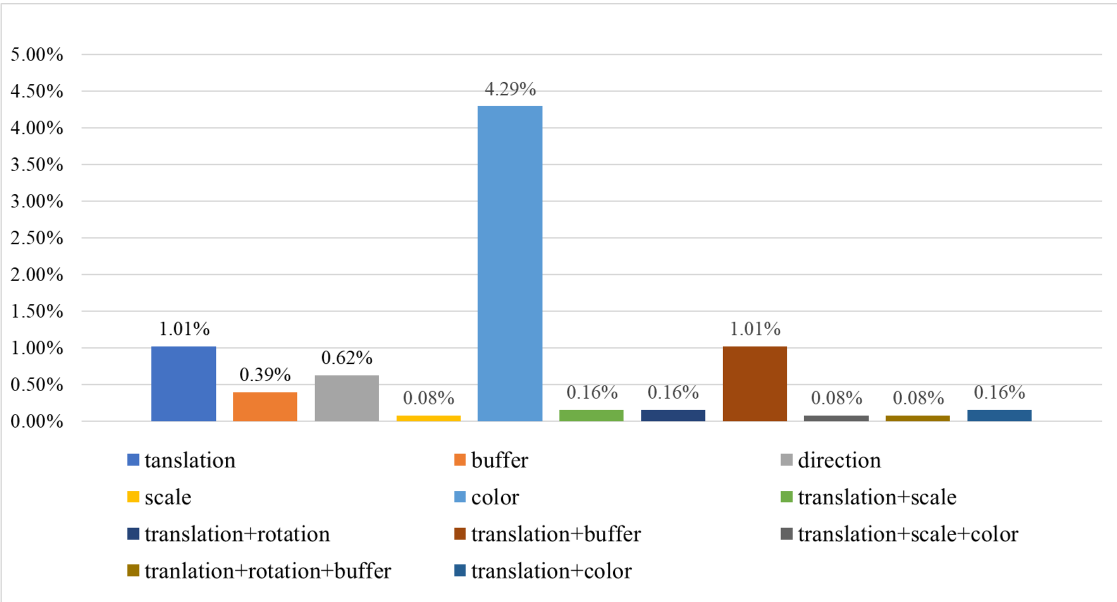


Figure 5.10 The usage of metric and color modifications in Group C1.

In group C2, 11.5% of the map symbols only need metric modifications or color modifications to complete the formal representations, and the remaining 8.6% need both additional operators and modifications to complete them. The usage of each modification is illustrated in Figure 5.11.

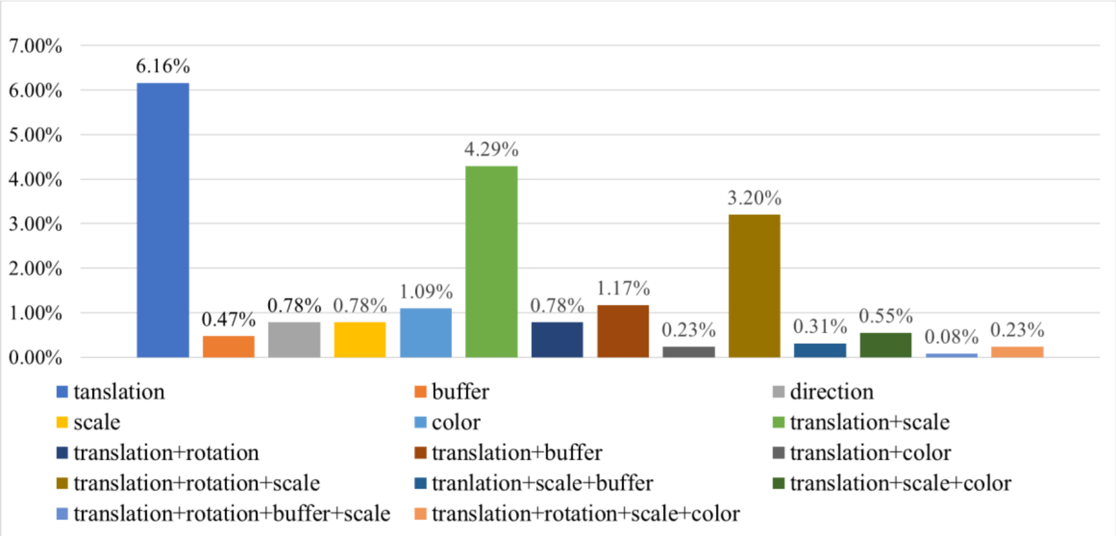


Figure 5.11 The usage of metric and color modifications in Group C2.

The translation modifications had a high usage rate, as 6.16% of the map symbols that didn't fit the structure of Chinese characters (i.e., group C2) need translation refinements to complete the formal expressions, and 1.01% of the map symbols only need translation modifications to fit the structures of Chinese characters. Second, 4.29% of map symbols that do not perfectly fit the structure of Chinese characters need color modifications. The experimental results indicated that the construction of some map symbols required more than one kind of modification as 12.4% of the map symbols that require two or three kinds of modification can complete the construction of compound symbols. A few symbols even require four kinds of modifications to complete them. Moreover, it was found that the translation modifications were often used in conjunction with other modifications to construct compound symbols, as 15.3% of the symbols require both translation modifications and scale modifications, and 11.2% of the symbols require all metric modifications. Moreover, it was found that the translation modifications were often used in conjunction with other modifications to construct compound symbols, as 4.45% of the symbols require both translation modifications and scale modifications. The experimental results suggested the metric and color modifications improved the formal representations.

5.5 Summary: symbol construction with basic operators and modifications

In summary, the primitives, including text primitives and graphics primitives, are generated according to the semantics first. Then, some primitives will be blended or union into complex components. The next step is structure operation or overlay operation. Once the structure is determined, the location of each unit in the structure is determined. Frame operator adds frames of different shapes or colors to symbols. The metric modifications reposition the components or change their size or orientation. In addition, the color modifications adjust the colors of components and frames. The process of symbol construction is demonstrated in Figure 5.12.

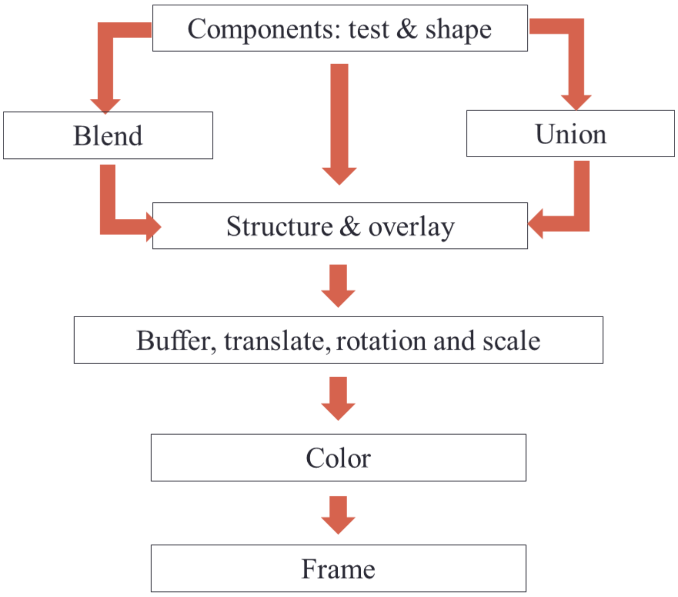


Figure 5.12 The process of symbol construction.

To demonstrate the operators discussed in the previous sections, an example was presented for evaluation. The SJJB symbol set has become a complete symbol system after long-term development, it contains symbols for eight themes. This set of symbols has been widely used. Taking the symbol "surface parking" of this symbol set as an example, the symbol construction process was analyzed.

According to semantics, the extracted symbolic elements are the graphics of "boat", "wrench", and "nut". In the second step,a three-unit structure was adopted, such as a triangle structure, to construct symbols. Figure 5.13 shows the structure operation of the compound symbol.

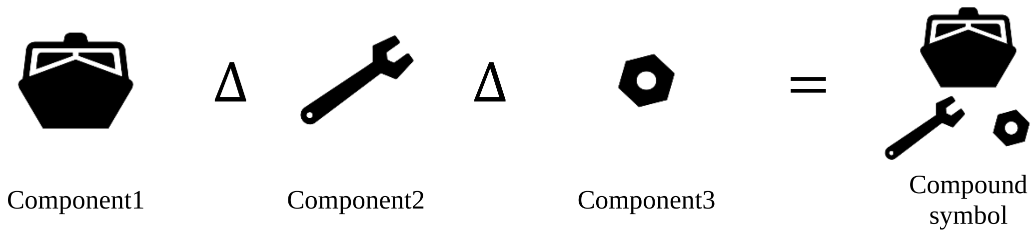


Figure 5.13 The structure operation of the compound symbol.

After combining the symbol components into a compound map symbol according to structure, the size, color, position, and orientation of the components may be adjusted. Figure 5.14 shows the metric and color modifications of symbol components. Finally, the square was selected as the frame of the symbol.

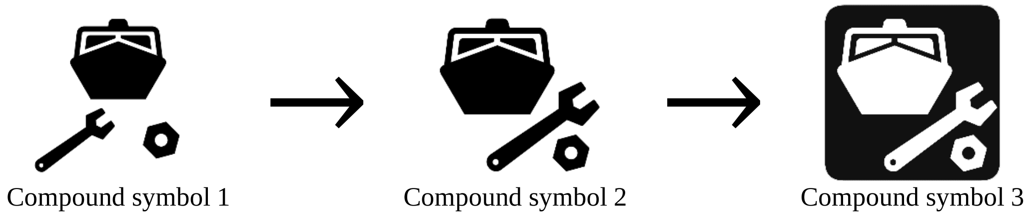


Figure 5.14 The process of adjusting color and metric modifications.

Chapter 6 Effect of topological properties on interpretation of map symbols

6.1 The effect of complexity on symbols interpretation

Two types of complexity, i.e., visual complexity (VC) and intellectual complexity (IC) were identified by Brophy (1980) and MacEachren (1982). Li (2019) identified symbols can be classified into four types, i.e., low VC and IC, low VC but high IC, high VC but low IC, and high VC and IC (see examples in Figure 6.1) based on the complexity.

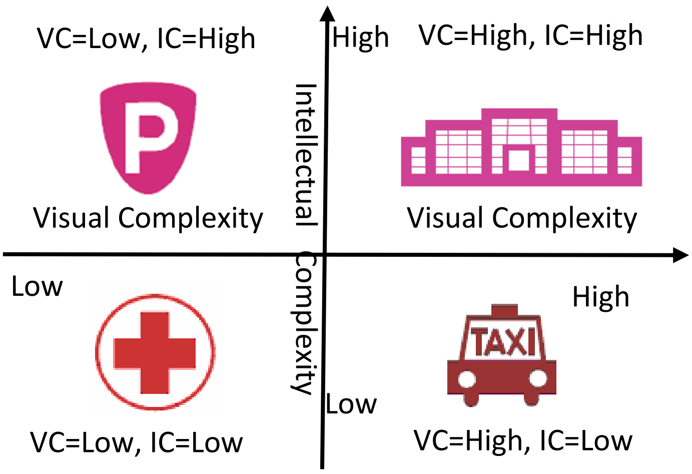
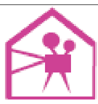


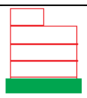
Figure 6.1 Four kinds of map symbols based on the complexity of map symbols (Li, 2019).

To evaluate the effects of two kinds of complexities on symbol interpretation, an empirical study was conducted. Over 140 symbols have been downloaded from the Internet and extracted from Hong Kong maps, and 40 students have participated in the evaluation. They were asked to provide these map symbols' meanings. All map symbols were categorized into four groups, i.e., one with high IC but low VC, one with high IC and VC, one with low IC but high VC, and one with low IC and VC. All the symbols are of the same size. The statistical results are presented in Table 6.1. The experimental results indicated that the effectiveness of symbols is strongly related to the IC while not significantly related to VC. The differences between the correct percentages for the four types of symbols are significant. Groups 1 and 3 had a response rate of just around 100%, while groups 2 and 4 had a response rate of around 10%.

Table 6.1 Testing effects of complexity on point symbol interpretation.

Symbol	Meaning	Correct response	Details

Group 1: graphically simple and intellectually simple symbols (low VC and IC)			
	Information Center	100%	A few said: reception center
	Hospital/Clinic	90%	A few said: first aid, emergency room
	Smoking area	100%	
	Theatre/Music Hall	90%	
	Coffee shop	100%	
Group 2: graphically simple but intellectually complex symbols (low VC but high IC)			
	Television station	0%	Power station, lighthouse, wireless station
	Park	0%	Unknown, Canada, country park
	Police station	20%	Park, car park, post office
	Grave	20%	Mostly church
	Telecom building	10%	80% unknown, a few said: typhoon signal
Group 3: graphically complex but intellectually simple symbols (high VC but low IC)			
	Ice rink	100%	
	BBQ Site	90%	
	Cinema	100%	
	Taxi stand	100%	

	Petrol station	100%	
Group 4: graphically complex and intellectually complex symbols (high VC and IC)			
	Museum	5%	Unknown, historical site, theatre, hospital
	Hotel	0%	Warehouse, sports ground, shopping mall
	Hotel	5%	left luggage, unknown, airport
	Stadium	0%	Unknown, industrial estate, resort, shopping mall
	Museum	20%	Legislative council, unknown, historical site, court, Rome

Some symbols were found to have complex graphical properties, but they bore only a poor resemblance to the objects they were trying to describe. Bruyas et al. (1998) pointed out that the basic elements of an object, i.e., the typical properties of objects held in memory as mental representations, are always recognized fastest, while additional elements may interfere with the rapid comprehension of symbols. On the other hand, oversimplified symbols lack the typical elements of expressing objects. Graphical complexity does not affect the interpretation of a symbol, provided the graphic character of the symbol is sufficiently clear. Although some symbols have complex graphic properties, they are difficult to recognize.

6.2 The effect of topological properties on the interpretation of map symbols.

6.2.1 The topological structure of map symbols

We considered the morphological structure of map symbols to be an important factor in symbol complexity. Therefore, a component-based approach was proposed to make an analysis of the structure of a symbol. More precisely, the analysis of the topological components of a symbol has been conducted.

In natural language, a word typically consists of a root (or stem) and affixes, which include prefixes and suffixes. In cartography, a symbol can be treated as a word in the cartographic language. In analogy with words in natural language, a map symbol should have a basic structure, which may be found by decomposing a symbol into topological components. As Figure 6.2 shows, the symbols can be decomposed into three basic components: interior, boundary, and exterior (Li, 2014). The boundary of a map symbol can be closed (with boundary) or open (without boundary). The exterior is an essential element of the symbol and can be called a frame here. The exterior of a map symbol can be non-empty (framed) or empty (open). The filling of a frame can be unfilled or filled, and the shape of a frame can be regular or irregular, the irregular shapes are used in most cases.

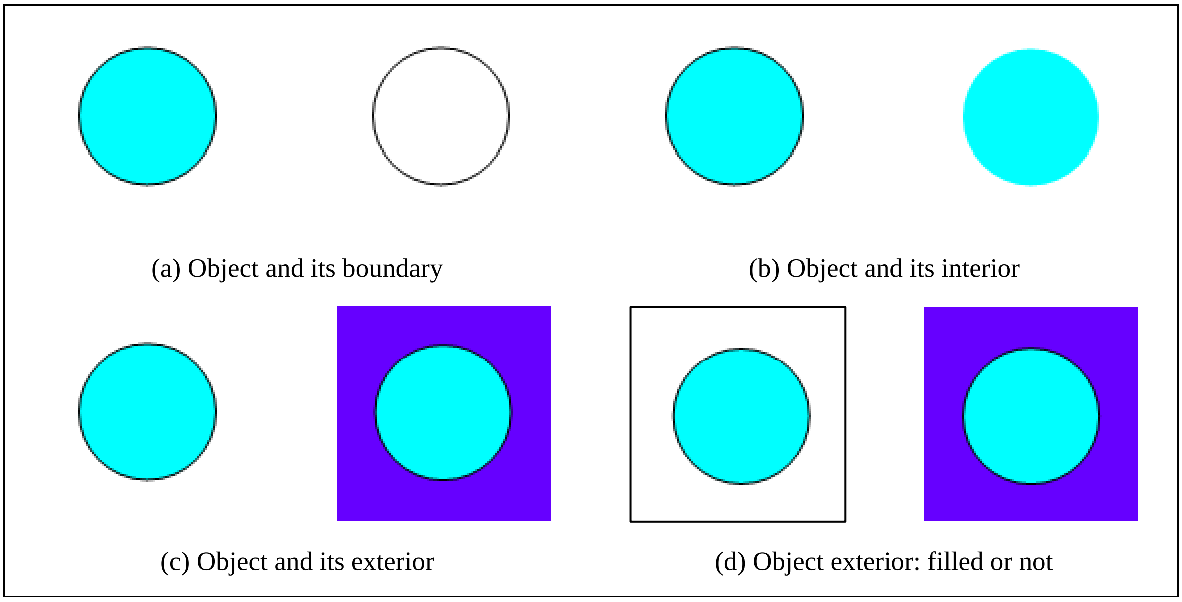
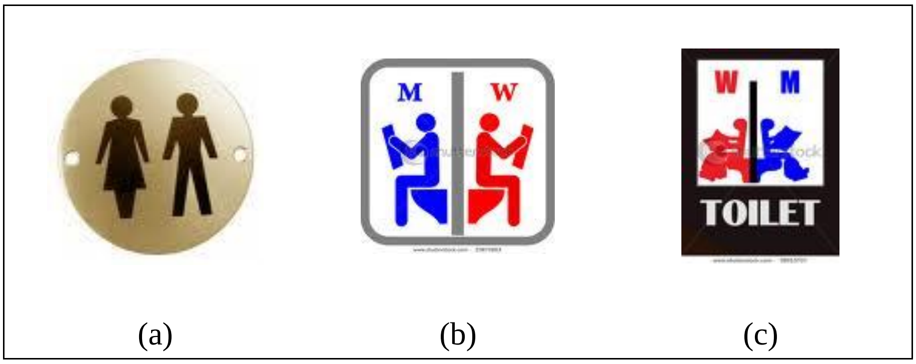


Figure 6.2 The topological structure of point symbols.

Some people noticed the effect of topological properties on the interpretation of map symbols. Huang et al. (2002) identified boundary as one of seven design elements, the other six elements are color, layout, order, figure/ground, symbolic, and typography. Forrest and Caster (1985) identified, in general, the framed symbols performed significantly better than unframed symbols in visual search. The frame shape can stimulate imagination, which may affect the interpretation of map symbols. There are some examples demonstrated in Figure 6.3, i.e., the variations in the frame shape of toilet symbols. Inappropriate symbol frames can confuse users about their true meaning.



(d) (e) (f)

Figure 6.3 Variations in frame shape of toilet symbols.

Some cartographers noticed that the shape of frames affect the user's understanding of the semantics of the symbol and used different shapes of frames to express different situations, such as emergencies, when designing symbols (Robinson et al., 2010; Opach, and Rød, 2022). For example, the NATO joint military symbology developed by the US Army Corps of Engineers (North Atlantic Treaty Organization, 2017) and the standard set of symbols for use in the emergency management and first responder communities developed by the Federal Geographic Data Committee (FGDC) Homeland Security Working Group (Akella, 2009). With the popularity of symbols for commercial purposes, it has been found that subjective preference may affect the success or failure of symbol design (Huang et al., 2002; Robinson et al., 2010). Forrest and Catster (1985) suggested that circles and squares are the most readily perceived frames since their shapes are the simplest and most regular.

In image enhancement, adjusting contrast helps to make it easier for visual interpretation and understanding of imagery. Some people discussed the color and contrast of the interior of map symbols. Forrest and Caster (1985) found that using variable internal size and color appears to facilitate different visual searches. Also, darker, or more solid symbols are recognized faster. Stevens et al. (2013) pointed out that how users interpret symbols is influenced by figure-background relations or contrast gradients. Huang et al. (2002) suggest that the contrast between symbols and frames should be sufficiently distinct. There are some examples of variations in the contrast between the interior and frame in Figure 6.4.

Contrast between symbol components

Interior/frame

Figure 6.4 The contrast relation in compound symbols (refer to Li, 2014)

6.2.2 The effect of topological properties on the interpretation of map symbols

We considered the topological properties of map symbols to have effects on their interpretation. Therefore, an experimental evaluation was conducted for evaluating the effect of topological properties on the interpretation of map symbols. The experimental evaluation included four main sections: the effect of frame shape, the effect of interior, the effect of contrast between frame and interior, and user preference of frame shape.

- **Effect of frame shape**

In the first section, participants were requested to read four sets of symbols, which represented the hospital, car park, toilet, and supermarket. Each set of symbols contains symbols from three different frames, and they represent the same semantics. These different symbols with different frames and their correct responses in the percentage of symbol interpretation are shown in Table 6.2.

Table 6.2 Test of effect of frame on point symbol interpretation.

Symbol	Frame shape	Correct response	Details
Three hospital symbols as examples			
	Circle	Almost 100%	Hospital=50%, clinic=30%, first aid=10%, emergency service=10%

	irregular shape	95%	Hospital=50%, first aid=15%, clinic=15%, red cross=15%
	Circle	95%	Hospital=50%, 15, first aid=10%, clinic=15%, red cross=5%
Three car park symbols as examples			
	irregular shape	55%	unknown=40%, park=5%
	Pentagon	45%	Police station=35%, unknown=20%
	Square	50%	Parks' Supermarket=35%, Police station=15%
Three toilet symbols as examples			
	Circle	95%	5% washing room
	Square	90%	Misunderstanding is elevator
	irregular shape	90%	Misunderstanding is campsite
	irregular shape	50%	Misunderstanding is changing room, bathroom
Two supermarket symbols as examples			
	No frame	Almost 95%	5% market
	Pentagon	30%	30% unknown, shopping mall

The results indicated that the frame shapes do affect the symbol interpretation. From the examples of hospital symbols, it was found the frame shape slightly affects the effectiveness of symbols with low intellectual complexity. However, some intellectual complex map symbols are difficult to interpret, regardless of the shape of the frames The examples of toilet and supermarket symbols indicated the frame shapes can stimulate imagination, which may affect the symbol interpretation. Furthermore, if the frame is too emphasized, it will increase intellectual complexity.

- **Effect of interior**

In the second section, participants were requested to read one set of "hospital" symbols. These are different symbols with different interiors and their correct responses in symbol interpretation are shown in Table 6.3.

Table 6.3 Test of effect of the interior on point symbol interpretation.

Symbol	Interior	Correct response	Details
Three hospital symbols as examples			
	Full red color	100%	Hospital=50%, clinic=30%, first aid=10%, emergency service=10%
	No color	95%	Hospital=50%, first aid=15%, clinic=15%, red cross=15%
	No color	95%	Hospital=50%, 15, first aid=10%, clinic=15%, red cross=5%

It was found that all three symbols received almost 100% correct responses. The experimental result indicated that the interior does not affect symbol interpretation if the symbol has a well-understood interior.

- **Effect of contrast between frame and interior**

In the third section, subjects were requested to read two sets of symbols, i.e., the map symbols of hospital and school. In each set, the symbols with different contrasts between the interior and frame represent the same meaning. The percentage of correct responses in symbol interpretation was shown in Table 6.4. It was found that the symbol with a well-understood interior is slightly affected by the contrast, while is largely affected when the meaning of the interior is vague.

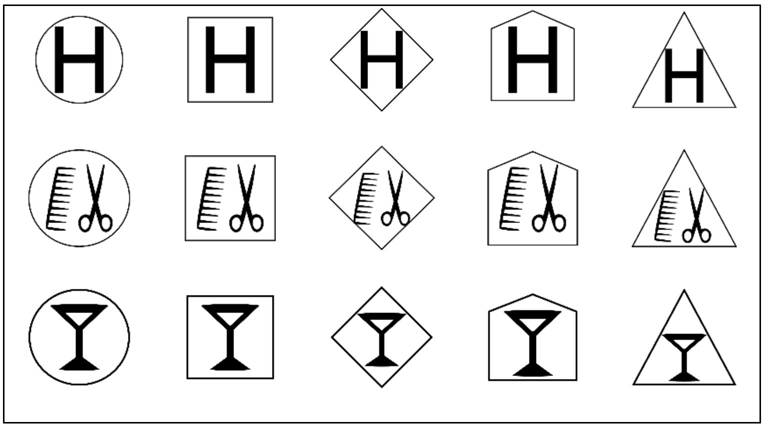
Table 6.4 Test of effect of contrast between interior and exterior on symbol interpretation.

Symbol	Contrast	Correct response	Details
Two hospital symbols as examples			

	Full color interior/ no-color exterior	Almost 100%	Hospital=50%, clinic=30%, first aid=10%, emergency service=10%
	No-color interior/ full color exterior	95%	Hospital=50%, 15, first aid=10%, clinic=15%, red cross=5%
Three school symbols as examples			
	No-color interior/ full color exterior	Almost 100%	School/kinder garden
	Full color interior/ no-color exterior	30%	Library=25%, Heritage Museum=25%, unknown=20%
	Full color interior/ no-color exterior	45%	Unknown=30%, library=25%

6.2.3 The user preference of frame shape

The subjective preference may affect the success or failure of symbol design (Huang et al., 2002; Robinson et al., 2010). A new question arose, which kind of frame do people prefer to use? Thus, another experimental evaluation was performed to assess the user preference on the symbol frame shape. All the symbols (over 140) used previously and5 different types of frames for each symbol, i.e., circle, square, rhombus, pentagon, and triangle were adopted. Given symbols, subjects (map readers) were asked to choose the most satisfying frame for each symbol. There are some examples of symbols with different frames are illustrated in Figure 6.5. Table. 6.5 summarizes people's preferences in terms of percentages.



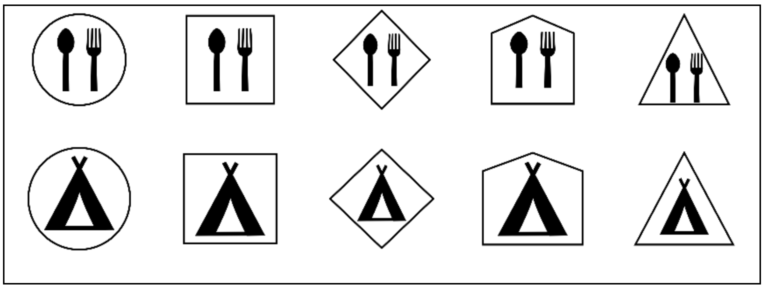


Figure 6.5 Examples of symbols with different frames.

The results indicated that people do have different preferences for different symbols, but circles and squares are the most popular, i.e., 20% of each of them two. It means safer to use them two types.

Table 6.5 The user preference of frame shape (%).

	○	□	◇	⬠	△		○	□	◇	⬠	△
	15	45	5	30	5		20	30	25	25	0
	20	30	35	10	5		45	20	20	10	5
	25	40	10	15	10		15	10	55	10	10
	60	10	25	5	0		35	25	20	10	10
	30	25	20	10	15		10	15	25	10	40
ATM	30	40	10	15	5		25	25	30	5	15
	35	25	25	5	0		35	30	5	20	10
	30	50	5	5	10		35	30	15	20	0
	30	30	15	25	0		65	10	15	5	5
	45	20	30	5	0		45	20	15	10	10
	25	30	20	15	10		55	15	10	0	20

	10	10	35	15	30		45	10	20	15	10

6.3 Summary

The aim of the investigation is to measure the effect of topological properties on symbol interpretation, and a series of experimental evaluations on the effect of topological properties of map symbols have been conducted. The following conclusions can be drawn from the experimental results:

- The intellectual complexity of the interior is the key to the success of a symbol.
- Frame does have an effect on symbol interpretation and people prefer circles and squares in most cases.
- Contrast between the interior and frame does have an effect on efficiency, especially in the case when the intellectual complexity of the interior is high.

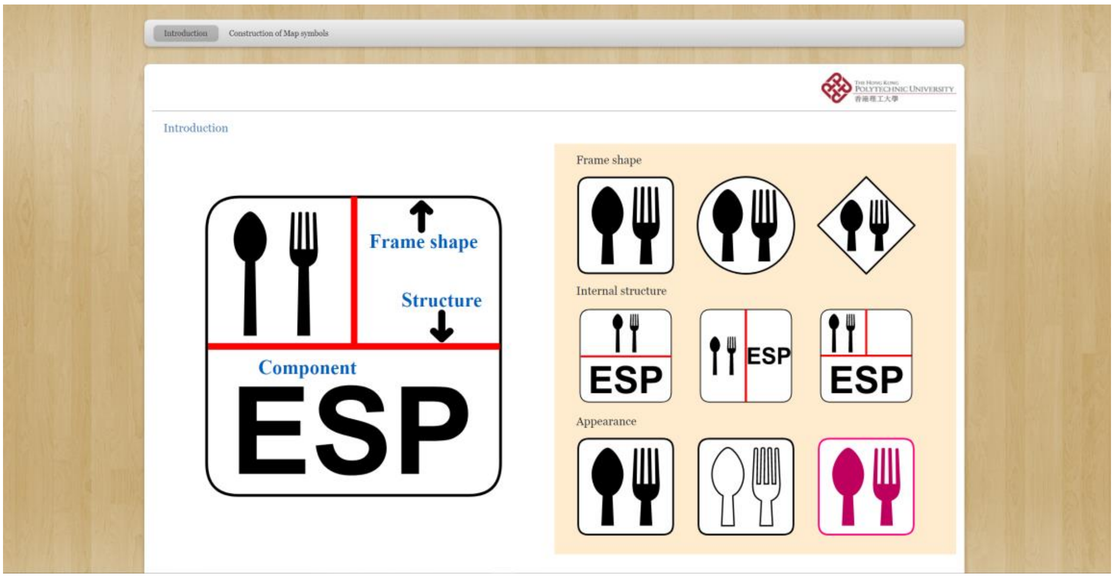
Chapter 7 A prototype system for automatic construction of map symbols

With the development of graphical Interfaces, automatic symbol visual editing tools have become an increasingly indispensable part of map symbology. Its direct benefit is to give users a convenient and easy-to-use interface, which can make software applications draw map symbols more intuitively, and better display map symbols to users. To support the automatic construction of map symbols, a web-based prototyping tool called *CartoWord* was developed. The following sections describe the core design objectives of *CartoWord*'s, and system functions of this prototype.

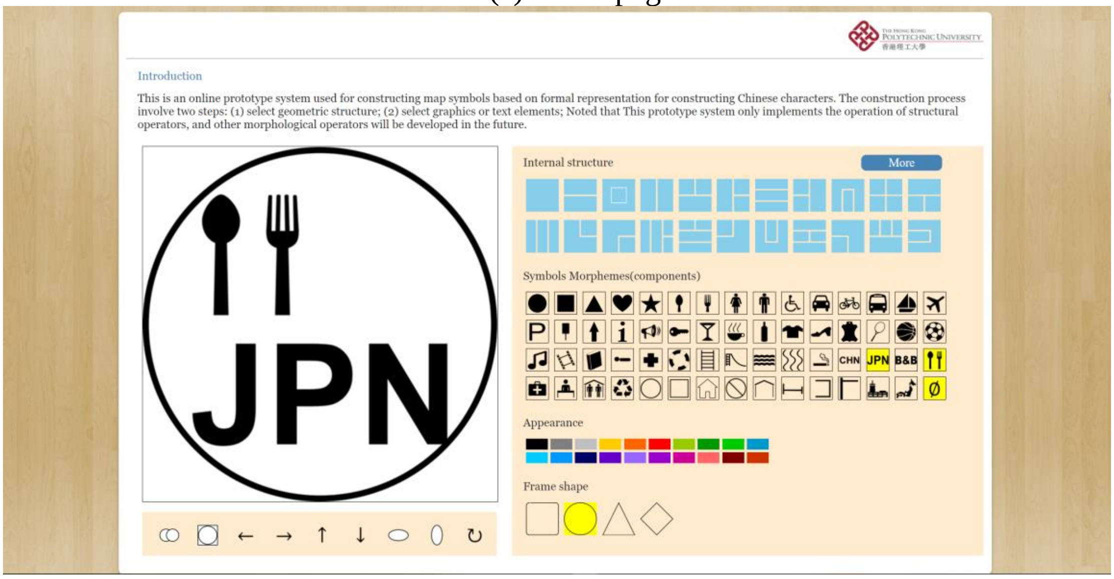
7.1 Developed technology and user interface

Given the widespread use of Graphics Device Interface (GDI) in symbols editors, a prototype system has been implemented based on GDI to construct the map symbols based on structure operators, metric modifications and color modifications. GDI provides several functions for drawing 2D graphs. The web-based user interface and core algorithm of this prototype system were implemented with Asp.Net. Some of the codes relevant to this prototype system are shown in Appendix.

CartoWords has a primary interface that includes an introduction panel, a construction operators' panel, and a map symbol display (see Figure 7.1(b)). The symbol display is the main visualization element, while the construction operators' panel provides tools for constructing symbols. The construction operators' panel consists of six components, i.e., structural operators, graphic & text elements, colors, frame shape, and other topological and geometric operators.



(a) Homepage



(b) Symbol construction page

Figure 7.1 The user interface of the symbol construction page.

7.2 Working flow of CartoWords

According to the sequence of symbol construction, the prototype process was designed in the following four stages:

(1) Selecting internal structure of symbols: according to previous research, there are at least 22 structures (such as column structure or row structure) in Chinese characters that can be used to construct symbols, and some map symbols need to be adjusted. These 22 structures were provided in the user interface for users to choose from. To select the structure operator:

To select the structure operator:

- Click the structure icon to be selected. The content in the left drawing panel will be cleared, and the new corresponding structure frame will be displayed on the left panel (see Figure 7.2). In other words, the symbol will be reconstructed.

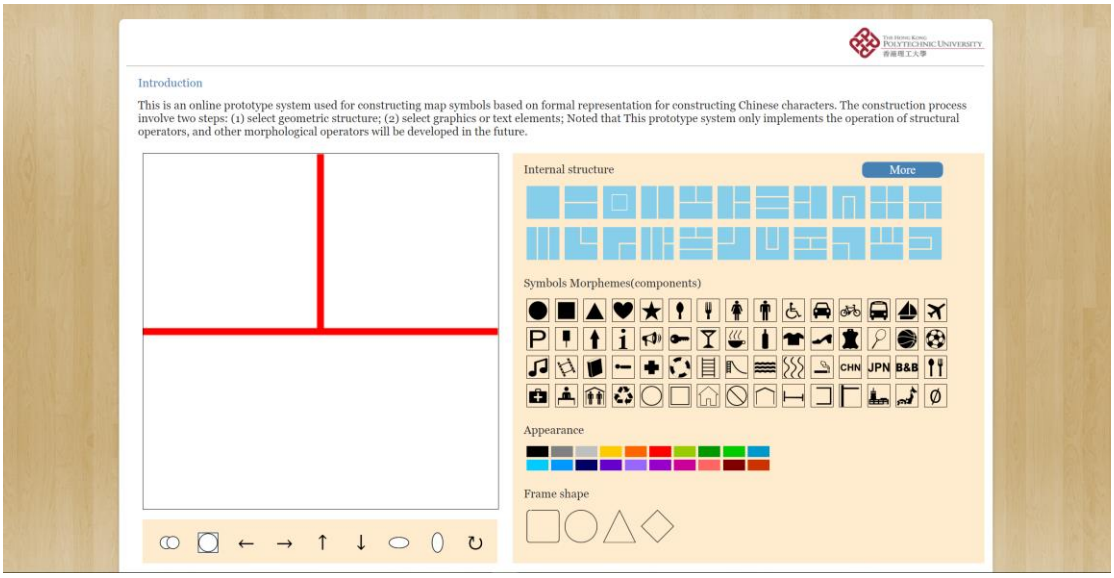


Figure 7.2 Click the structure icon.

- Click the **More** button. This opens or closes the **Not commonly used structures** dialogue box (see Figure 7.3).

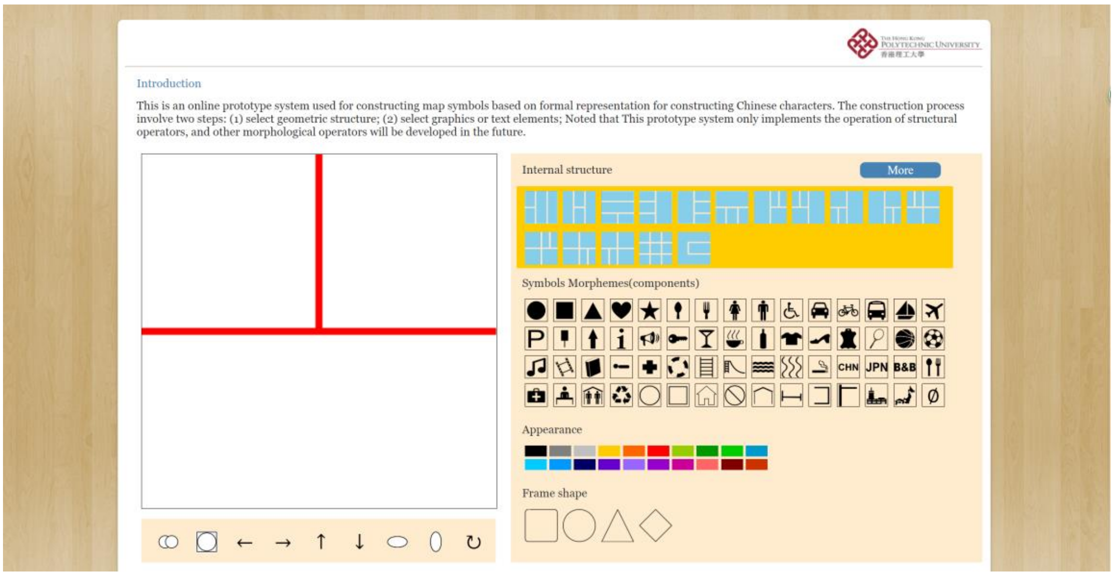


Figure 7.3 The Not commonly used structures dialog box.

(2) Selecting symbol components: some commonly used morphemes were extracted from the existing symbol set and placed them in the interface for users to select.

To fill the symbol elements in the structural frame:

- Click on the symbol elements icons to be selected. The background colour of the icon will turn yellow and the corresponding elements will be inlaid into the structure in the order in which they are clicked (see Figure 7.4).

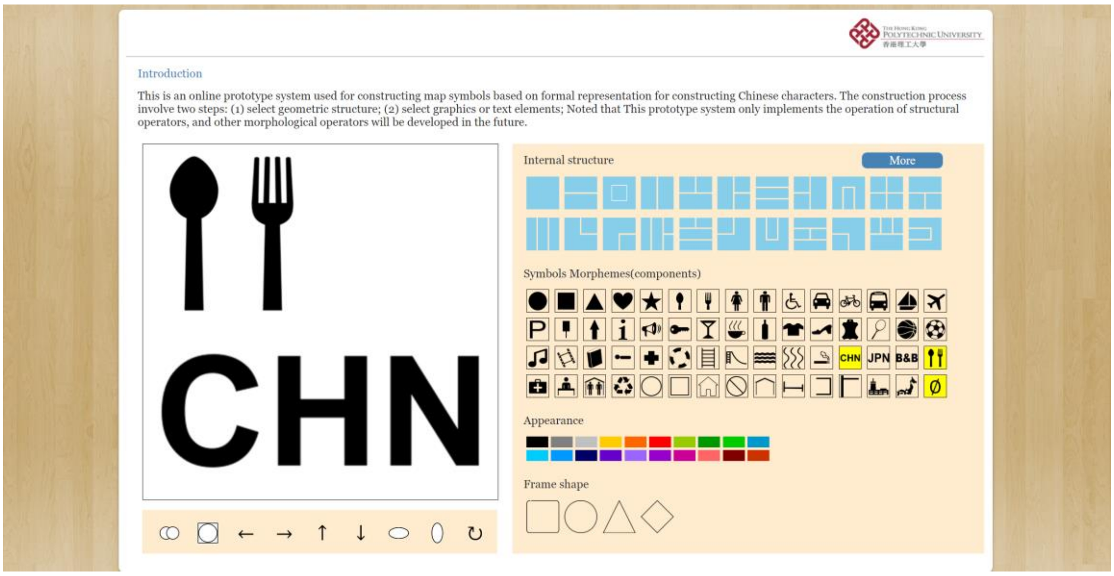


Figure 7.4 The symbols constructed by only the structure operator.

- When the number of filled elements equals the number of components required by the structure, no other buttons can be clicked.

- If the icon is already highlighted, by clicking this icon, the background colour of the icon will change back to transparent and the corresponding elements in the left drawing board will be cleared (see Figure 7.5).

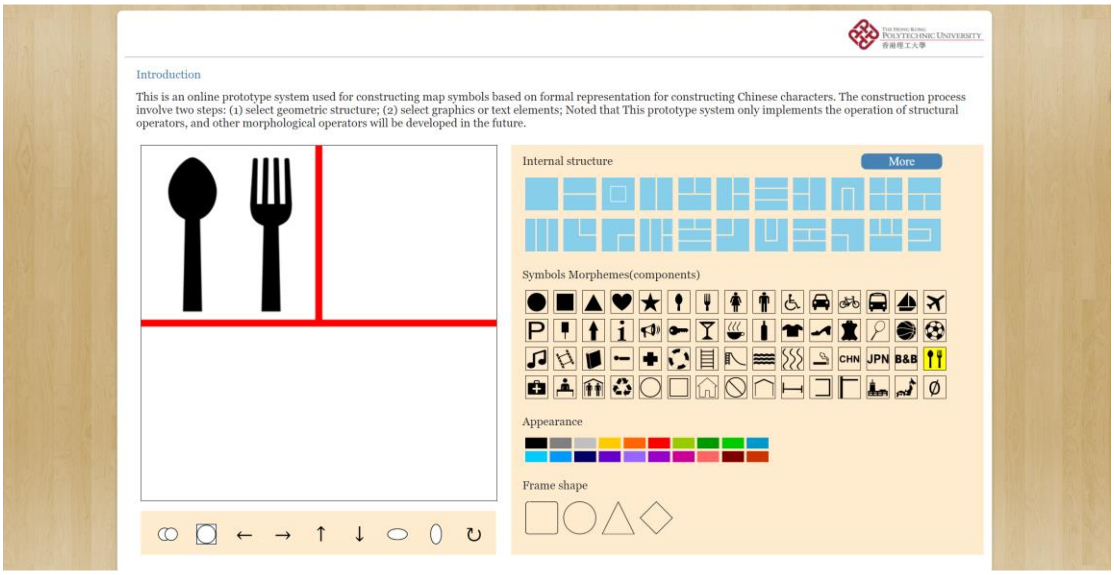
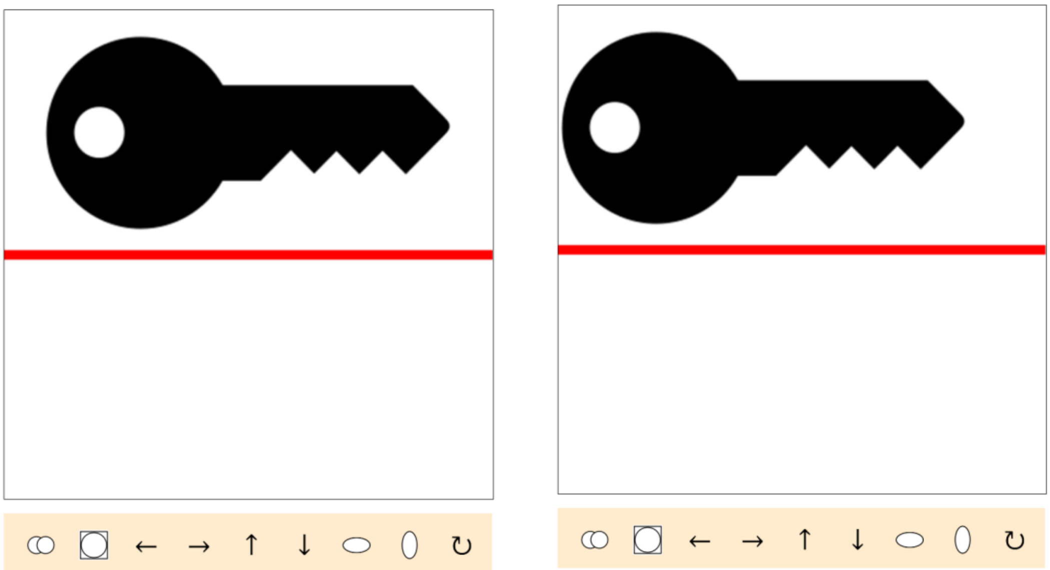


Figure 7.5 Click the icon already highlighted, and the corresponding elements on the left drawing board will be clear.

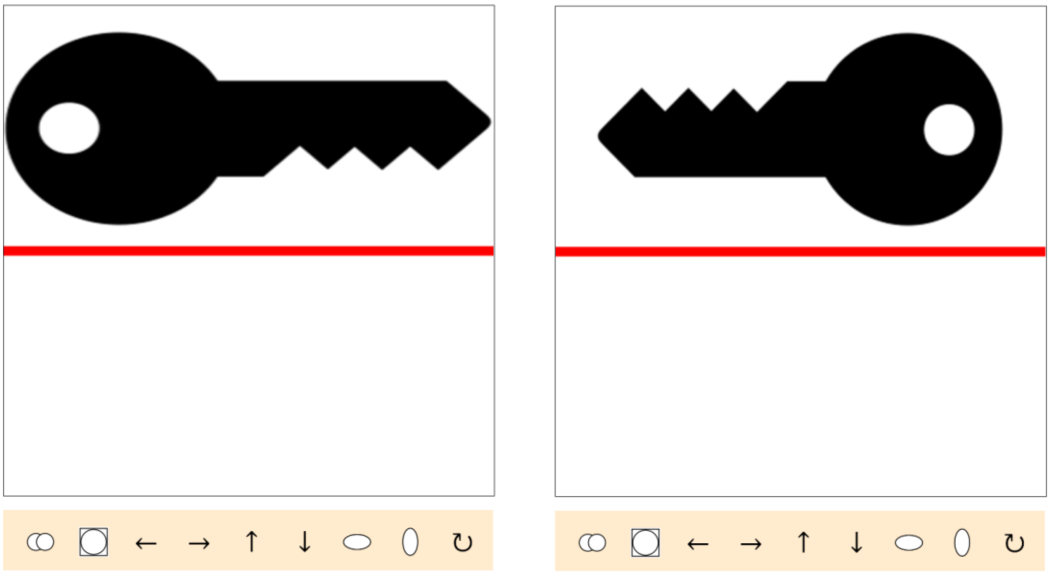
(3) Adjust the shape, size, and position of elements based on metric operators.

To adjust the metric relation between elements:

- The default shape, size, and position of elements are determined according to the structure operator (see Figure 7.6).
- Click the button in the lower-left corner to adjust the direction, size, and position of the element. You can only adjust the newly selected element.



(a) Original element (b) After translation



(c) After scaling (d) After rotation

Figure 7.6 After metric refinements.

- There is also a special metric operator, the overlay operator (see Figure 7.7).

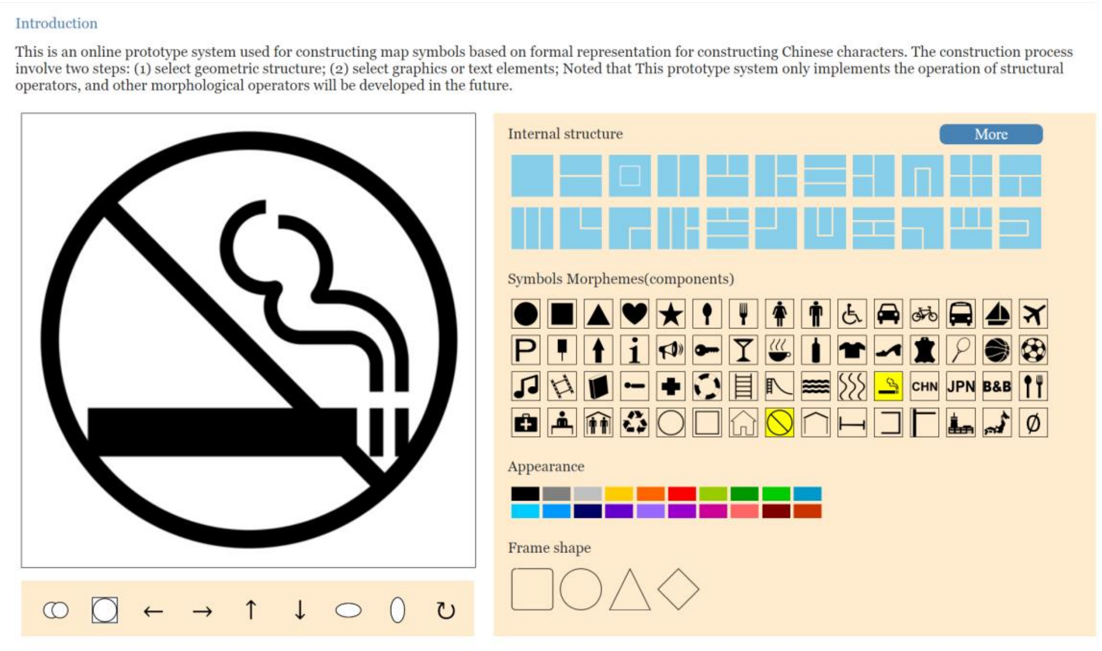


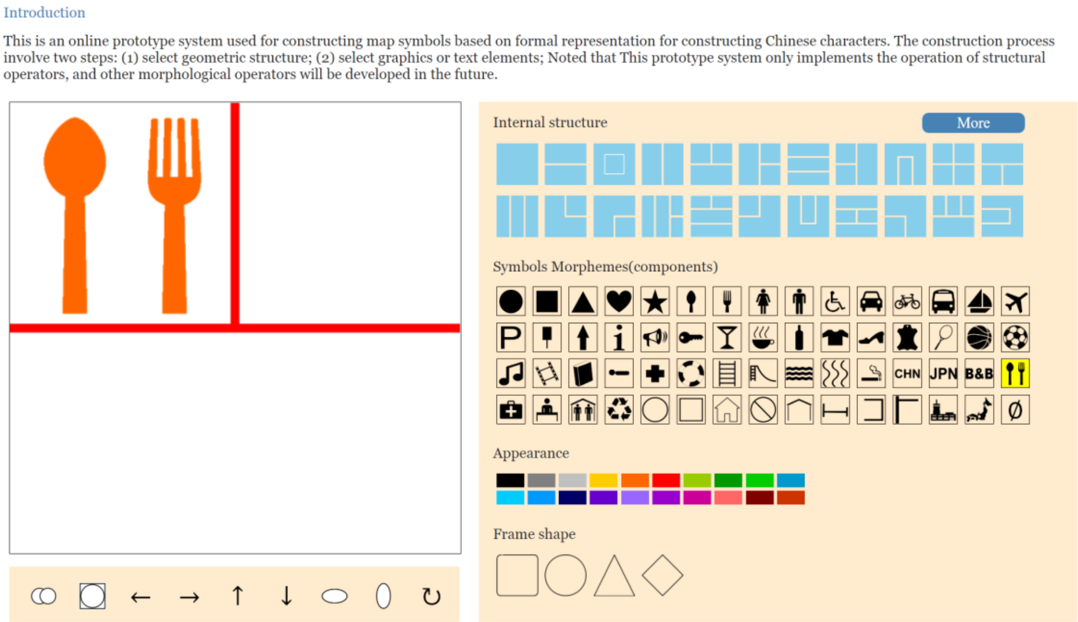
Figure 7.7 The symbols with an overlay structure.

(4) Selecting the color of symbol components: users can modify the color of each component (morpheme), but not the outline.

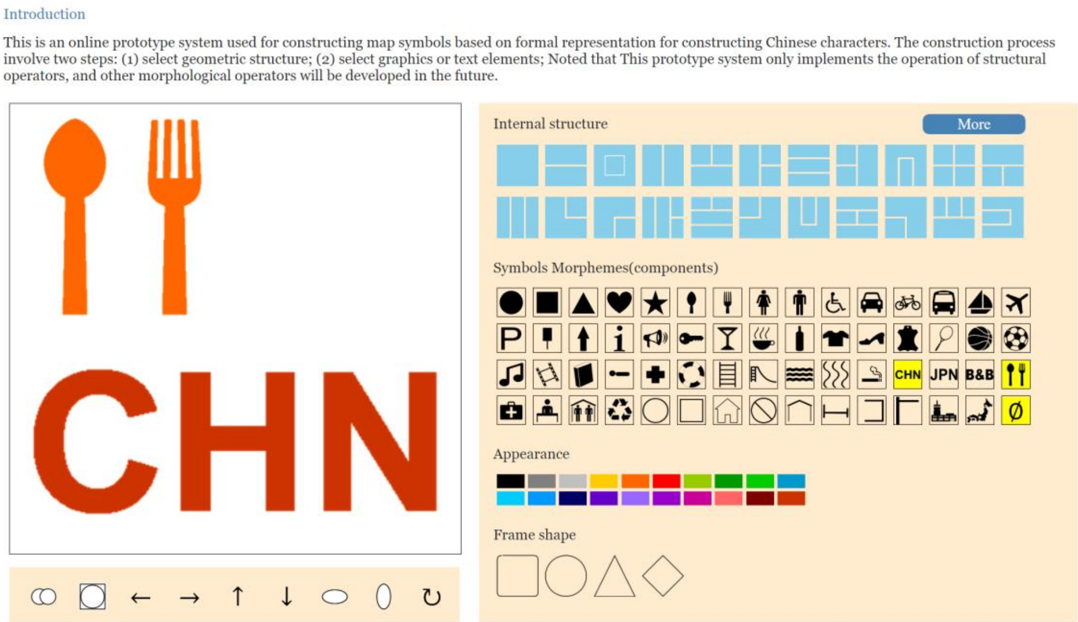
To modify the fill color of components:

- All components are black by default.

- Click the color you want to modify from 20 preset colors. Each time you select the color, you can only modify the newly selected element (see Figure 7.8). But when you click on the structure operator, all the components will turn back to black.



(a) Modify the color of the first element



(b) Modify the color of the select element

Figure 7.8 Modify the color of the symbol.

(5) Frame shape of symbols: users can choose different frame shapes, and the size of the

components will also change as the frame shape changes, but the aspect ratio of the component will not change (see Figure 7.9).

To modify the frame shape of symbols:

- Click the frame icon you want to select, and the background color of the icon will turn yellow.

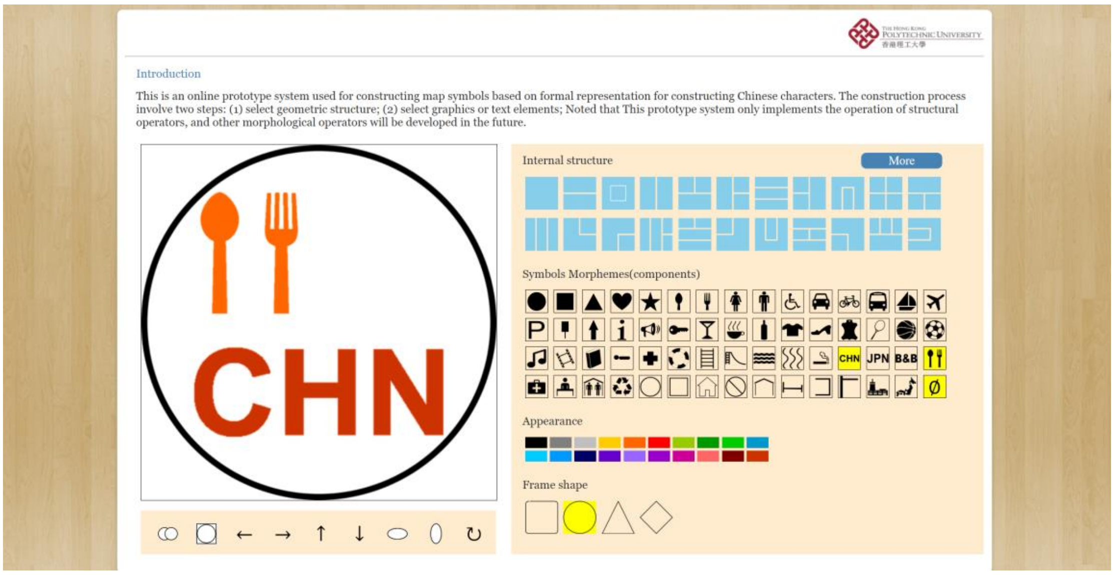


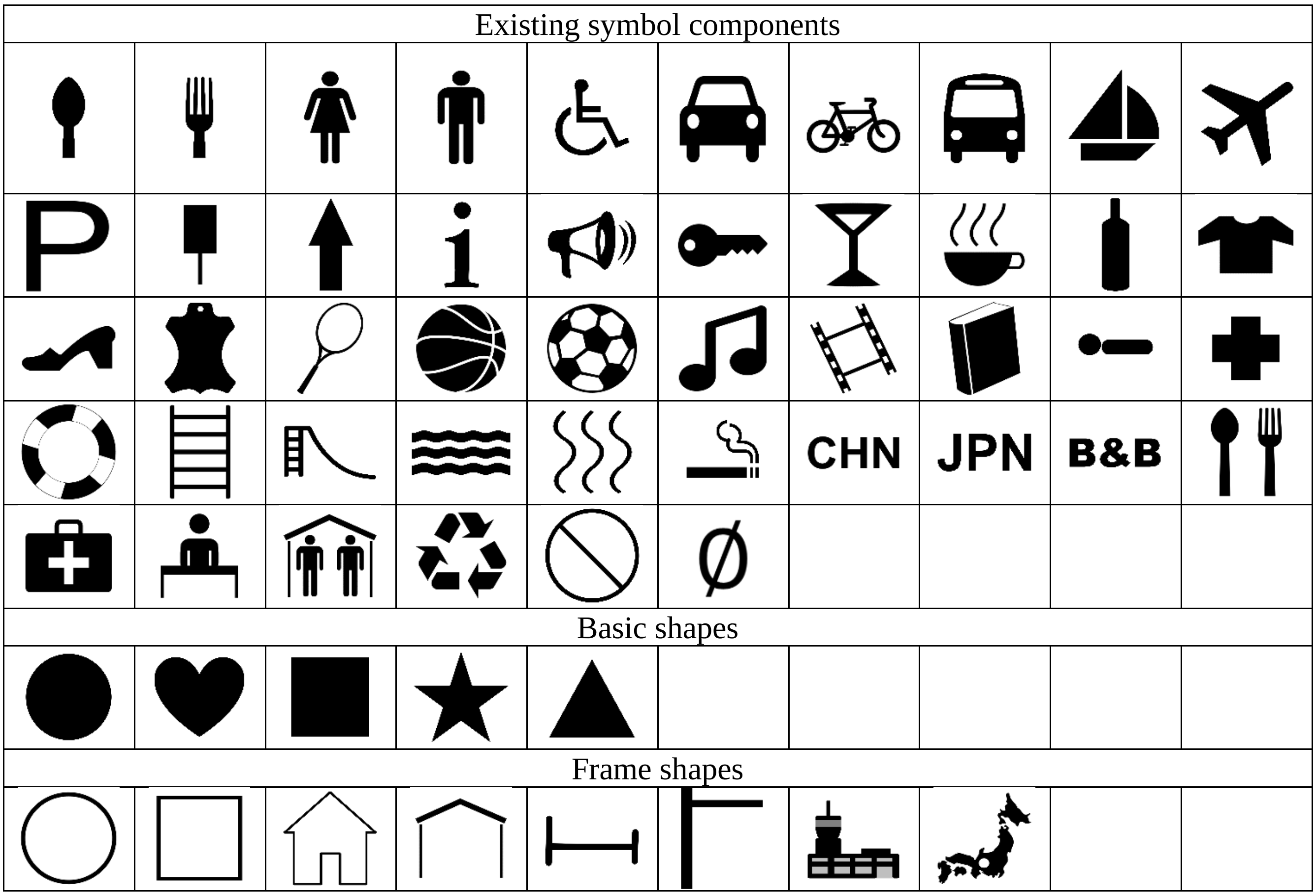
Figure 7.9 Add frame to symbol.

- When clicking other components, the shape of the outer frame and the size of the symbol will be re-adjusted.

7.3 Construction of morphemes library

Making compound symbols is time-consuming. The morphemes (i.e., graphic elements or text elements) library provides a mechanism for sharing morphemes. The compound symbols are constructed by a combination of morphemes retrieved from the library. The morphemes in the library can be reused. Different compound symbols can use the same morphemes. All symbol morphemes are commonly used graphic or text elements that have been extracted from existing symbol sets (see Table 7.1), such as the shape of a restaurant, a house, the Red Cross, etc. Eight widely used map symbol sets provided by Google Maps symbols, GAODE Maps symbols, and Baidu Maps symbols were adopted for extracting the morphemes.

Table 7.1 Part of the extracted components.



Chapter 8 Summary and Conclusion

8.1 Summary

These studies mainly aim to develop formal representations of map symbols. The formal representation of map symbols is fundamental to their automated construction and, thus, to the mathematization of the cartographic theory. The objective of this study is to develop the formal representation of map symbols.

The first project evaluated the feasibility of using structures drawn from Chinese characters to represent the structures of map symbols. Eight widely used map-symbol datasets were selected for testing, and two experiments were designed to evaluate the feasibility. The first experiment was based on descriptive statistics, while the other was a questionnaire-based evaluation. Before the two experiments were conducted, the structures of map symbols from eight datasets were determined. The descriptive statistics experiment compared the determined structures of map symbols with the structures of Chinese characters. It was proven to be appropriate to represent most of the map symbols.

The second project solved the representation problems of these two types of map symbols (i.e., the map symbol didn't or imperfectly fit the structures of Chinese characters) by employing additional basic operators and proposed some metric and color modifications. To validate these proposed solutions, experiments have been carried out by using eight sets of symbols that were used in the first project. All map symbols in these eight sets were bifurcated into group A, in which each symbol perfectly fits the structural operators of Chinese characters, and group B, in which the map symbols fit structural operators with imperfection, or the structural operators do not apply. For the symbol in group B, additional basic operators were employed to express them. The symbols in group B were divided into two groups, group B1 is map symbols that can be expressed by additional operators, and group B2 cannot. The proportions of map symbols in each symbol set were counted.

The third project first explores which complexity has a greater impact on map interpretation. Then, a component-based approach is employed to analyze the effects of the topological properties of map symbols on the interpretation. A series of experimental evaluations on the frame shape, interior, and contrast between the frame and interior were conducted, respectively.

8.2 Conclusion

It is believed that this work could benefit ubiquitous mapping and enrich cartographic theory. Based on evaluating the feasibility of using structures drawn from Chinese characters to represent the structures of map symbols. It was found that 77.5% of map symbols perfectly fit into the structures of Chinese characters. The questionnaire-based evaluation acquired subjective opinions (i.e., satisfaction level) of the feasibility of using structures of Chinese characters to represent the structures of map symbols. On a 5-point scale from very unsatisfied to satisfied, more than half of the participants responded that they were satisfied or very satisfied, with an overall score of 3.89. These results indicate that the structures of Chinese characters are suitable to represent the structures of map symbols.

Based on evaluating the feasibility of addition operators and modifications for representing the map symbol that didn't or imperfectly fit the structures of Chinese characters, it was found almost all the map symbols can be formally represented with additional operators and metric and color modifications. The percentages of map symbols that did not fit the structures of Chinese characters solved by additional operators and modifications are 2.4% and 20.1%, respectively. The percentages of map symbols that imperfectly fit them solved by these operators and modifications are 8.7% and 8%, respectively. Based on these results, it can be concluded that: (1) the additional basic operators can improve the formal representation of map symbols. The experimental results proved that the additional operators proposed by Li (2014) are beneficial for developing the systematic map symbol algebra system to support the automatic construction of map symbols. Specifically, the union and blend operators are beneficial for constructing complex components or symbols. The overlap operators are beneficial for constructing complex symbols with one component fully overlapping another component, and (2) The proposed modifications can improve the formal representation of map symbols. These modifications are made at the component level of the map symbol, adjusting the structure of the symbol. They are used to modify the position, direction, or size of symbol components.

Based on evaluating the effect of topological properties on symbols interpretation, it was found that (1) the intellectual complexity of the interior is the key to the success of a symbol, (2) the frame does have an effect on symbol interpretation and people prefer circle and square in most cases, and (3) contrast between interior and frame does have an effect on efficiency, especially in the case when intellectual complexity of interior is high.

8.3 Limitations and Future Work

This work could not only enrich cartographic theory but also prompt the mathematization of map symbol construction. However, some limitations still exist in the formal representations of map symbols and interactive platforms in this study. Although the proposed modifications offer feasibility, further investigation is required to enable the automatic construction of map symbols. For example, the automatic construction of map symbols in several scenarios has not been well considered. Secondly, an interactive and automated map symbol construction platform based on these operators is still lacking.

In the era of artificial intelligence, large language models also need the special language of maps to join the AI family. An in-depth exploration of the linguistic features of map representation is an important step in providing basic theory to promote the development of map LLM. On the other hand, as mentioned in the background description of the paper, personal map development requires automatic map design. The formal map symbol representation plays an important role in automatic cartography.

In the aspects of the design and construction of map symbols, more effective and friendly mapping platforms are needed to be developed in the future. More efforts will be made to develop the functions to help users construct the map symbols easily and quickly in different scenarios. In addition, a symbol-sharing system will be created that allows users to refer to map symbols created by other users in the same scenario or other scenarios.

Reference

AlHosani, N. M. (2009). The perceptual interaction of simple and complex point symbol shapes and background textures in visual search on tourist maps (Doctoral dissertation), University of Kansas.

Akella, M. K. (2009). First responders and crisis map symbols: Clarifying communication. *Cartography and Geographic Information Science*, 36(1), 19-28. https://doi.org/10.1559/152304009787340179

Andrews, J. H. (1990). Map and Language/A metaphor extended. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 27(1), 1-19. https://doi.org/10.3138/M085-88H8-1343-4758

Ariza, E., Morales-Jones, C., Yahya, N., & Zainuddin, H. (2010). Why TESOL? Theories and issues in teaching English as a second language for K-12 teachers (4th ed.). Dubuque, IA: Kendall/Hunt Publishing Company.

Ballatore, A., & Bertolotto, M. (2015). Personalizing maps. *Communications of the ACM*, 58(12), 68-74.

Bartoněk, D., & Andělová, P. (2022). Method for cartographic symbols creation in connection with map series digitization. *ISPRS International Journal of Geo-Information*, 11(2), 105. https://doi.org/10.3390/ijgi11020105

Bauer, L. (1983). English word-formation. Cambridge university press. https://doi.org/10.1017/CBO9781139165846

Bergman, M. W., Hudson, P. T., & Eling, P. A. (1988). How simple complex words can be: Morphological processing and word representations. *The Quarterly Journal of Experimental Psychology Section A*, 40(1), 41-72. https://doi.org/10.1080/14640748808402282

Bertin, J. (1983). Semiology of graphics: diagrams, networks, maps.

Billen, R., & Clementini, E. (2004, March). A model for ternary projective relations between regions. In *International Conference on Extending Database Technology* (pp. 310-328). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-

24741-8_19

Blaut, J. M., & Blaut, J. (1987). Notes toward a theory of mapping behavior. *Children's Environments Quarterly*, 27-34.

Blok, C. A. (1987). Testing symbols on a Dutch tourist map, scale 1: 50.000. *ITC journal*, 1, 67-71.

Brophy, D. M. (1980). Some reflections on the complexity of maps. *In Technical papers of ACSM 40th Annual Meeting* (pp. 343-352). American Congress on Surveying and Mapping.

Bruyas, M. P., Le Breton, B., & Pauzié, A. (1998). Ergonomic guidelines for the design of pictorial information. International Journal of Industrial Ergonomics, 21(5), 407-413. https://doi.org/10.1016/S0169-8141(96)00081-9

Byrne, M. D. (1993, May). Using icons to find documents: Simplicity is critical. In *Proceedings of the INTERACT'93 and CHI'93 conference on Human factors in computing systems* (pp. 446-453), Amsterdam, Netherlands. https://doi.org/10.1145/169059.169369

Chen, J. W., & Lee, S. Y. (1996). A hierarchical representation for the reference database of on-line Chinese character recognition. In *International workshop on structural and syntactic pattern recognition* (pp.351–360), Berlin Heidelberg: Springer.

Chen, J. (1999). A raster-based method for computing Voronoi diagrams of spatial objects using dynamic distance transformation. *International Journal of Geographical Information Science*, 13(3), 209-225. https://doi.org/10.1080/136588199241328

Chen, J., Li, C., Li, Z., & Gold, C. (2001). A Voronoi-based 9-intersection model for spatial relations. *International Journal of Geographical Information Science*, 15(3), 201-220. https://doi.org/10.1080/13658810151072831

Chen L. (2004). Modern Chinese Ocean. University of China Press. (in Chinese)

Chi, C. F., & Dewi, R. S. (2014). Matching performance of vehicle icons in graphical and textual formats. *Applied ergonomics*, 45(4), 904-916. https://doi.org/10.1016/j.apergo.2013.11.009

Clarke, L. M. (1989). An experimental investigation of the communicative efficiency of point symbols on tourist maps. *The Cartographic Journal*, 26(2), 105-110. https://doi.org/10.1179/caj.1989.26.2.105

Cruse, A. (2011). Meaning in language: An introduction to semantics and pragmatics. Oxford University Press, New York. https://doi.org/10.1016/j.pragma.2011.03.014

Deng, M., Cheng, T., Chen, X., & Li, Z. (2007). Multi-level topological relations between spatial regions based upon topological invariants. *GeoInformatica*, 11, 239-267.

Deng, M., & Li, Z. (2008). A statistical model for directional relations between spatial objects. Geoinformatica, 12(2), 193-217. https://doi.org/10.1007/s10707-006-0004-x

Du, Q. (August 2003). A carto-linguistic paradigm taking a methodological perspective. In Proceedings of 21st International Cartographic Conference (pp. 1520-1528), Durban, South Africa.

Dewar, R. (1988). Criteria for the design and evaluation of traffic sign symbols. *Transportation Research Record*, 1160(1), 1-6.

DiBiase, D., MacEachren, A. M., Krygier, J. B., & Reeves, C. (1992). Animation and the role of map design in scientific visualization. *Cartography and geographic information systems*, 19(4), 201-214. https://doi.org/10.1559/152304092783721295

Egenhofer, M. J. (1989, June). A formal definition of binary topological relationships. In *International conference on foundations of data organization and algorithms* (pp. 457-472). Springer, Berlin, Heidelberg.

Egenhofer, M. J., & Franzosa, R. D. (1991). Point-set topological spatial relations. *International Journal of Geographical Information System*, 5(2), 161-174. https://doi.org/10.1080/02693799108927841

Egenhofer, M.J., Herring, J.R. (1991). Categorizing Binary Topological Relations Between Regions, Lines, and Points in Geographic Databases (Technical Report), Department of Surveying Engineering. University of Maine.

Egenhofer, M. J., & Shariff, A. R. B. (1998). Metric details for natural-language spatial relations. *ACM Transactions on Information Systems (TOIS)*, 16(4), 295-321.

https://doi.org/10.1145/291128.291129

Freeman, H., & Ahn, J. (1987). On the problem of placing names in a geographic map. *International Journal of Pattern Recognition and Artificial Intelligence*, 1(01), 121-140. https://doi.org/10.1016/j.jvlc.2007.08.006

Forrest, D., & Castner, H. W. (1985). The design and perception of point symbols for tourist maps. *The cartographic journal*, 22(1), 11-19. https://doi.org/10.1179/caj.1985.22.1.11

Forsythe, A., Sheehy, N., & Sawey, M. (2003). Measuring icon complexity: An automated analysis. *Behavior Research Methods, Instruments, & Computers*, 35, 334-342.

https://doi.org/10.3758/BF03202562

Forsythe, A. (July 2009). Visual complexity: is that all there is?. In Engineering Psychology and Cognitive Ergonomics: 8th International Conference, LNCS (pp. 158-166). Springer Berlin Heidelberg.

Frank, A. U. (1996). Qualitative spatial reasoning: Cardinal directions as an example. *International journal of geographical information science*, 10(3), 269-290. https://doi.org/10.1080/02693799608902079

Frutiger, A. (1989). Signs and symbols: Their design and meaning. New York: Van Nostrand.

Garlandini, S. and Fabrikant, S.I. (2009). Evaluating the effectiveness and efficiency of visual variables for geographic information visualization. *In International Conference on Spatial Information Theory* (pp. 195–211). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-03832-7_12

Goguen, J., & Harrell, D. F. (2004). Information visualization and semiotic morphisms. In G. Malcolm (Ed.), Multidisciplinary Study of Visual Representation and Interpretations. Oxford, U.K. Elsevier.

Gong, X., Li, Z., & Liu, X. (2022). Structures of Compound Map Symbols Represented with Chinese Characters. Journal of Geovisualization and Spatial Analysis, 6(1), 6. https://doi.org/10.1007/s41651-022-00099-w

Goyal, R. K. (2000). Similarity assessment for cardinal directions between extended spatial objects (Doctoral dissertation), Spatial Information Science and Engineering, University of Maine.

Guo, L. (2012). The constructing and realizing techniques for grammatical rules of the nautical chart symbolical language (Doctoral dissertation), Information Engineering University. (In Chinese)

Haar, R. (1976). Computational Models of Spatial Relations. Technical Report: TR-478, MSC-72-03610, Computer Science, University of Maryland, College Park, MD.

Halik, Ł. (2012). The analysis of visual variables for use in the cartographic design of point symbols for mobile Augmented Reality applications. *Geodesy and Cartography*, 61(1), 19-30. https://doi.org/10.2478/v10277-012-0019-4

Halik, Ł., & Medyńska-Gulij, B. (2017). The differentiation of point symbols using selected visual variables in the mobile augmented reality system. *The Cartographic Journal*, 54(2), 147-156. https://doi.org/10.1080/00087041.2016.1253144

Head, C. G. (1984). The map as natural language: a paradigm for understanding. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 21(1), 1-32. https://doi.org/10.3138/E816-M074-8791-4506

Head, C.G. (1991). Mapping as Language or Semiotic System: Review and Comment. In: Mark, D.M., Frank, A.U. (eds) Cognitive and Linguistic Aspects of Geographic Space. NATO ASI Series, vol 63. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-2606-9_14

Huang, J. T., & Wang, M. Y. (1992). From unit to gestalt: Perceptual dynamics in recognizing Chinese characters. In *Advances in psychology* (Vol. 90, pp. 3-35). North-Holland. https://doi.org/10.1016/S0166-4115(08)61885-3

Huang, S. M., Shieh, K. K., & Chi, C. F. (2002). Factors affecting the design of computer icons. *International journal of industrial ergonomics*, 29(4), 211-218. https://doi.org/10.1016/S0169-8141(01)00064-6

International Cartographic Association. (2003). A Strategic Plan for the International Cartographic Association 2003–2011: As Adopted by the ICA General Assembly 2003-

08-16.

Jancewicz, K., & Borowicz, D. (2017). Tourist maps-definition, types and contents. *Polish Cartographical Review*, 49. https://doi.org/10.1515/pcr-2017-0003

Kamusella, T. D. (2001). Language as an instrument of nationalism in Central Europe. *Nations and Nationalism*, 7(2), 235-251. https://doi.org/10.1111/1469-8219.00014

Keates, J. S. (1972). Symbols and meaning in topographic maps. *International Yearbook of Cartography*, 12, 168-181.

Kent, A. J. (2007). An analysis of the cartographic language of European state topographic maps: aesthetics, style, and identity (Doctoral dissertation), University of Kent/Canterbury Christ Church University. https://doi.org/10.13140/RG.2.1.4620.3363/2

Kent, A. J., & Vujakovic, P. (2011). Cartographic language: Towards a new paradigm for understanding stylistic diversity in topographic maps. *The Cartographic Journal*, 48(1), 21-40. https://doi.org/10.1179/1743277411Y.0000000004

Kent, A. J., & Vujakovic, P. (2011). Cartographic language: Towards a new paradigm for understanding stylistic diversity in topographic maps. *The Cartographic Journal*, 48(1), 21-40. https://doi.org/10.1179/1743277411Y.0000000004

King, R. (1990). Visions of the World and the Language of Maps. Department of Geography, Trinity College, Dublin.

Kolacny, A. (1969). Cartographic information – a fundamental term in Modern Cartography. *The Cartographic Journal*, 6, 47-49.

Kostelnick, J. C., Dobson, J. E., Egbert, S. L., & Dunbar, M. D. (2008). Cartographic symbols for humanitarian demining. *The Cartographic Journal*, 45(1), 18-31. https://doi.org/10.1179/000870408X276585

Korpi, J., & Ahonen-Rainio, P. (2015, November). Design guidelines for pictographic symbols: evidence from symbols designed by students. In *Proceedings of the 1st ICA European Symposium on Cartography* (pp. 10-12).

Lai, P. C., & Yeh, A. G. O. (2004). Assessing the effectiveness of dynamic symbols in cartographic communication. *The Cartographic Journal*, 41(3), 229-244. https://doi.org/10.1179/000870404X13300

Lan, T., Li, Z., & Ti, P. (2019). Integrating general principles into mixed-integer programming to optimize schematic network maps. *International Journal of Geographical Information Science*, 33(11), 2305-2333. https://doi.org/10.1080/13658816.2019.1620237

Leppert, R. (2019). Art and the committed eye: The cultural functions of imagery. Routledge. https://doi.org/10.4324/9780429034602

Leung, L. F., & Li, Z. (2002). Experimental evaluation of the effectiveness of graphic symbols on tourist maps. *Cartography*, 31(1), 11-20. https://doi.org/10.1080/00690805.2002.9714176

Li Z (1995) Maps as a visual language: A Chinese perspective (Dissertation), Wilfrid Laurier University.

Li, Z., Li, Y., & Chen, Y. Q. (2000). Basic topological models for spatial entities in 3-dimensional space. *GeoInformatica*, 4, 419-433. https://doi.org/10.1023/A:1026570130172

Li, Z., & Kraak, M. J. (2002). Web-based exploratory data analysis, WEB-EDA: visualisation meets spatial analysis (pp. 281-285). In *ISPRS 2002: Commission II WG II/6*.

Li, Z., & Su, B. (1995). Algebraic models for feature displacement in the generalization of digital map data using morphological techniques. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 32(3), 39-56. https://doi.org/10.3138/H7K9-2160-2765-8230

Li, Z., Li, Y., & Chen, Y. Q. (2000). Basic topological models for spatial entities in 3-dimensional space. *GeoInformatica*, 4(4), 419-433. https://doi.org/10.1023/A:1026570130172

Li, Z., Zhao, R. L., & Chen, J. (2002). A Voronoi-based spatial algebra for spatial relations. *Progress in Natural Science*. 12, 528–536.

Li, Z., Pun-cheng, L., & Shea, G. (2004). Design of web maps for navigation purpose. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*. Istanbul, 353-358.

Li, Z. (2006). Algorithmic foundation of multi-scale spatial representation. CRC Press. https://doi.org/10.1201/9781420008432

Li, Z. (2014). Word Structures of Map Language: spatio-spectral structure of map symbols. Theoretical Cartography and Geo-Information Science. In *conference of the International Cartographic Association*. (Oral presentation)

Li, Z. (2019). Effect of Frame Structure on Interpretation of Map Symbols. In *Abstracts of the ICA*, 1, 217. https://doi.org/10.5194/ica-abs-1-217-2019

Li, Z., Lan, T., Ti, P., Xu, Z. (2022). Advances in cartography from the perspective of Maslow's hierarchy of need. *ActaGeodaetica et Cartographica Sinica*.51(7):1536-1543. https://doi.org/10.11947/i.AGCS.2022.20220170.

Lin, T. Z., & Fan, K. C. (1994). Coarse classification of on-line Chinese characters via structure feature-based method. *Pattern Recognition*, 27(10), 1365-1377. https://doi.org/10.1016/0031-3203(94)90070-1

Liu HC (1993) Modern Chinese. Fudan University press (in Chinese).

Liu, C. L., Jaeger, S., & Nakagawa, M. (2004). 'Online recognition of Chinese characters: the state-of-the-art. *IEEE transactions on pattern analysis and machine intelligence*, 26(2), 198-213. https://doi.org/10.1109/TPAMI.2004.1262182

Liu, Y. C., & Ho, C. H. (2012). The effects of age on symbol comprehension in central rail hubs in Taiwan. *Applied ergonomics*, 43(6), pp.1016-1025. https://doi.org/10.1016/j.apergo.2012.02.004

Liu J.N. (2011) A study on the structure of Chinese characters (Doctoral dissertation), Jilin University. (In Chinese).

Liu, Y. C., & Ho, C. H. (2012). The effects of age on symbol comprehension in central rail hubs in Taiwan. *Applied Ergonomics*, 43(6), 1016-1025.

https://doi.org/10.1016/j.apergo.2012.02.004

Liu, D. L., Zhou, Z. Y., Wu, Q., & Tang, D. (2016). Symbol recognition and automatic conversion in GIS vector maps. *Petroleum Science*, 13, 173-181. https://doi.org/10.1007/s12182-015-0068-z

Lyutyy, A. A. (1984). The language of maps and its principal features. *Mapping Sciences and Remote Sensing*, 21(2), 103-117. https://doi.org/10.1080/07493878.1984.10641538

MacEachren, A. M. (1982). Map complexity: Comparison and measurement. *The American Cartographer*, 9(1), 31-46. https://doi.org/10.1559/152304082783948286

MacEachren, A. M. (1994). Visualization in modern cartography: setting the agenda. *Visualization in modern cartography*, 28(1), 1-12. https://doi.org/10.1016/B978-0-08-042415-6.50008-9

MacEachren, A. M. (2004). How maps work: representation, visualization, and design. Guilford Press: New York.

Mark, D. M., & Frank, A. U. (1996). Experiential and formal models of geographic space. *Environment and Planning B: Planning and Design*, 23(1), 3-24.

McDougall, S. J., Curry, M. B., & de Bruijn, O. (1999). Measuring symbol and icon characteristics: Norms for concreteness, complexity, meaningfulness, familiarity, and semantic distance for 239 symbols. *Behavior Research Methods, Instruments, & Computers*, 31(3), pp.487-519. https://doi.org/10.3758/bf03200730

McDougald, B. R., & Wogalter, M. S. (2014). Facilitating pictorial comprehension with color highlighting. *Applied Ergonomics*, 45(5), 1285-1290. https://doi.org/10.1016/j.apergo.2013.05.008

ICA. (1973). Multilingual Dictionary of Technical Terms in Cartography; Franz Steiner Verlag: Wiesbaden, Germany.

Morrison, C., & Forrest, D. (1995). A study of point symbol design for computer based large scale tourist mapping. *The Cartographic Journal*, 32(2), 126-136. https://doi.org/10.1179/caj.1995.32.2.126

North Atlantic Treaty Organization. (2017). NATO standard APP-6, NATO joint military symbology, edition D, version 1. NATO Standardization Office.

Ommer, B. (2013). The role of shape in visual recognition. *Shape Perception in Human and Computer Vision: An Interdisciplinary Perspective*, 373-385. https://doi.org/10.1007/978-1-4471-5195-1_25

Opach, T., & Rød, J. K. (2022). A user-centric optimization of emergency map symbols to facilitate common operational picture. *Cartography and Geographic Information Science*, 49(2), 134-153. https://doi.org/10.1080/15230406.2021.1994469

Pappachan, P., & Ziefle, M. (2008). Cultural influences on the comprehensibility of icons in mobile–computer interaction. Behaviour & Information Technology, 27(4), 331-337. https://doi.org/10.1179/caj.1995.32.2.126

Peng, G., Yue, S., Li, Y., Song, Z., & Wen, Y. (2017). A procedural construction method for interactive map symbols used for disasters and emergency response. *ISPRS International Journal of Geo-Information*, 6(4), 95. https://doi.org/10.3390/ijgi6040095

Peuquet, D. J., & Ci-Xiang, Z. (1987). An algorithm to determine the directional relationship between arbitrarily-shaped polygons in the plane. *Pattern recognition*, 20(1), 65-74. https://doi.org/10.1016/0031-3203(87)90018-5

Piamonte, D. P. T., Abeysekera, J. D., & Ohlsson, K. (2001). Understanding small graphical symbols: a cross-cultural study. *International Journal of Industrial Ergonomics*, 27(6), 399-404. https://doi.org/10.1016/S0169-8141(01)00007-5

Pickles, J. (2004). A history of spaces: Cartographic reason, mapping, and the geo-coded world. Psychology Press. https://doi.org/10.4324/9780203351437

Plag, I. (2018). Word-formation in English. Cambridge University Press. https://doi.org/10.4000/lexis.4532

Raisz, E. (1948) General Cartography (2nd ed.) New York: McGraw-Hill Book Company

Ramirez, J. R. (1993, September). Development of a cartographic language. In European Conference on Spatial Information Theory (pp. 92-112). Berlin, Heidelberg: Springer

Berlin Heidelberg. https://doi.org/10.1007/3-540-57207-4_8

Robinson, A. H., & Petchenik, B. B. (1976). The nature of maps: Essays toward understanding maps and mapping (pp. 16-17). Chicago: University of Chicago Press.

Robinson, Arthur Howard. (1995). Elements of cartography. New York : Wiley.

Robinson, A. C., Roth, R. E., & MacEachren, A. M. (2010, May). Challenges for map symbol standardization in crisis management. *Proceedings of the 7th International ISCRAM Conference–Seattle*, 1, 14-18. https://doi.org/10.1080/15230406.2013.803833

Robinson, A. C., Roth, R. E., & MacEachren, A. M. (2011). Understanding user needs for map symbol standards in emergency management. *Journal of Homeland Security and Emergency Management*, 8(1), 0000102202154773551811. https://doi.org/10.2202/1547-7355.1811

Robinson, A. C., Pezanowski, S., Troedson, S., Bianchetti, R., Blanford, J., Stevens, J., ... & MacEachren, A. M. (2013). Symbol Store: sharing map symbols for emergency management. *Cartography and Geographic Information Science,* 40(5), 415-426. https://doi.org/10.1080/15230406.2013.803833

Rucklidge, W. (Ed.). (1996). Efficient visual recognition using the Hausdorff distance. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/BFb0015092

Salman, Y. B., Cheng, H. I., & Patterson, P. E. (2012). Icon and user interface design for emergency medical information systems: A case study. International journal of medical informatics, 81(1), 29-35. https://doi.org/10.1016/j.ijmedinf.2011.08.005

Schnabel, O. (2005, July). Map Symbol Brewer–a new approach for a cartographic map symbol generator. In *Proc. 22nd International Cartographic Conference.*

Schnabel, O., & Hurni, L. (2009). Primitive-based construction theory for diagrams in thematic maps. *The Cartographic Journal*, 46(2), 136-145. https://doi.org/10.1179/000870409X459851

Schlichtmann, H. (1985). Characteristic traits of the semiotic system 'map symbolism'. *The cartographic journal*, 22(1), 23-30. https://doi.org/10.1179/caj.1985.22.1.23

Schlichtmann, H. (1988, February). Conceptual Field Structures in Thematic Mapping. In Report *on the First North American Working Seminar on the Concepts of Cartographic Language*, Wilfrid Laurier University, Waterloo, Ontario.

Shariff, A. R. B., Egenhofer, M. J., & Mark, D. M. (1998). Natural-language spatial relations between linear and areal objects: the topology and metric of English-language terms. *International journal of geographical information science*, 12(3), 215-245.

Stevens, J.E., Robinson, A.C., & MacEachren, A.M. (2013). Designing Map Symbols for Mobile Devices: Challenges, Best Practices, and the Utilization of Skeuomorphism. In *26th International Cartographic Conference*, Dresden, Germany, 25–30.

Su, L., & Zhou, D. H. (2008, November). Linguistic characteristics of topographic map symbols. In *Geoinformatics 2008 and Joint Conference on GIS and Built Environment: Geo-Simulation and Virtual GIS Environments* (Vol. 7143, pp. 21-28). SPIE. https://doi.org/10.1117/12.812523

Taylor, I., & Taylor, M. M. (2013). The psychology of reading. Academic Press.

Tan, L. H., & Perfetti, C. A. (1998). Phonological codes as early sources of constraint in Chinese word identification: A review of current discoveries and theoretical accounts. *Reading and Writing*, 10, 165-200. https://doi.org/10.1023/A:1008086231343

Tian, J., Peng, K., Jia, F., & Xia, Q. (2013, June). The concept of symbol-morpheme and its application in map symbols design. In *2013 21st International Conference on Geoinformatics* (pp. 1-6). IEEE. https://doi.org/10.1109/Geoinformatics.2013.6626122

Tian, J.P., You, X., Xia, F.L., & Xia, Q. (2016). The Syntax Model of Mobile Maps Generation. *Acta Geodaetica et Cartographica Sinica*, 45(11), 1352-1360. (In Chinese)

Torrens, P. M. (2022). Data science for pedestrian and high street retailing as a framework for advancing urban informatics to individual scales. *Urban informatics*, 1(1), 9. https://doi.org/10.1007/s44212-022-00009-x

Xing, F. (1993). Modern Chinese. Higher Education Press. (in Chinese).

Wang, A. B., & Fan, K. C. (2001). Optical recognition of handwritten Chinese characters by hierarchical radical matching method. *Pattern Recognition*, 34(1), 15-35.

https://doi.org/10.1016/S0031-3203(99)00207-1

Wang, N. (2002). Lectures on Chinese characters configuration. Shanghai Educational Publishing House. (In Chinese).

Wang, J. (2017). Cartography in the Age of Spatio-temporal Big Data. *Acta Geodaetica et Cartographica Sinica*. 46(10),1226-1237. (In Chinese). https://doi.org/10.11947/i.AGCS.2017.20170308.

Wang, J., Wu, F., Yan, H. (2022). Cartographys its past. present and future. Acta Geodaetica et CartographicaSinica 51(6), 829-842. (In Chinese). https://doi.org/10,11947/j.AGCS.2022.20210661.

Wen Y (1984) The structural system of Chinese characters. Gansu Education (in Chinese).

Wilkinson, L. (1999). The Grammar of Graphics, Springer.. NewYork.

Wood, M. (1972). Human factors in cartographic communication. *The Cartographic Journal*, 9(2), 123-132.

Wood, D. (1984). Cultured symbols/thoughts on the cultural context of cartographic symbols. Cartographica: *The International Journal for Geographic Information and Geovisualization*, 21(4), 9-37. https://doi.org/10.3138/B88T-68X3-L0J1-0226

Wu, M., Zhu, A., Zheng, P., Cui, L., & Zhang, X. (2017). An improved map-symbol model to facilitate sharing of heterogeneous qualitative map symbols. *Cartography and Geographic Information Science*, 44(1), 62-75. https://doi.org/10.1080/15230406.2015.1102083

Yan, H., Chu, Y., Li, Z., & Guo, R. (2006). A quantitative description model for direction relations based on direction groups. *Geoinformatica*, 10, 177-196. https://doi.org/10.1007/s10707-006-7578-1

Zhang, S. (1993). Analysis of General Chinese Character Structure. Hohai University Press (in Chinese).

Zhang, J., & Zhu, Y. (2015). A method based on graphic entity for visualizing complex map symbols on the web. *Cartography and Geographic Information Science*, 42(1), 44-53.

https://doi.org/10.1080/15230406.2014.981586

Zhao, F., Du, Q., Ren, F., et al. (2014). Syntactic characteristics and smart construction mechanism of thematic map symbol. *Acta Geodaetica et Cartographica Sinica*, 45(6), 653-660. (in Chinese)

Zhao, F., Du, Q., & Zeng, X. (2011, June). Syntax-based construction theory for symbols in web thematic maps. In *2011 19th International Conference on Geoinformatics* (pp. 1-5). IEEE. https://doi.org/10.1109/GEOINFORMATICS.2011.5980670

Appendix A Summary and Analysis of Existing Spatial Relation Models

The spatial relationship is a highly generalized result of the geographical space of human cognition, which forms the basis of spatial description, reasoning, and analysis (Goyal, 2000). Spatial relations mainly include metric relations (including direction and distance), order relations, and topological relations. Topological relation describes the qualitative aspect of spatial relation and is the most basic spatial relation; metric and order relationships describe the quantitative aspects of spatial relationships.

Under topological transformation, topological relations are invariant, such as translation, rotation, and scaling (Egenhofer, 1989). Up to now, much work has been done in building topological relation models. The interior, boundary, and exterior are three basic components in topological relations. A standard theoretical and topological spatial relations set called the 4-intersection model has been investigated according to point-set topology (Egenhofer and Franzosa, 1991). The 9-intersection model (Egenhofer and Herring, 1990) is the extension of the 4-intersection model, and it became the most comprehensive model so far for describing the topological relation between two spatial entities. Based on the idea "topology matters, metric refines", Shariff and Egenhofer (1998) developed a formal model which captures metric details for the description of natural language spatial relations

However, some researchers (Li et al., 2000; Chen et al., 2001) pointed out that there exist two imperfections in the extended 9-intersection model. Firstly, the exterior, boundary, and interior of spatial entities are linearly dependent. Secondly, the change of a basic topological property is caused by the adoption of a definition in IR^1 to IR^2, i.e., a line's boundary can't separate the interior from its exterior in a 2-dimensional space IR^2.

Therefore, some researchers modified the topology model in order to solve the above problems. Li et al. (2000) constructed the Voronoi spatial algebraic model by adding the algebraic operators between Voronoi regions of spatial targets. Chen et al. (2001) presented a Voronoi-based 9-intersection model for spatial relations, by using Voronoi-regions of an entity to replace its complement as its exterior. Furthermore, Deng et al. (2007) purposed four topological relations models: the intersection and difference model, the element type and number model, the separation number and dimension model, and the holistic sequence model. The first method reduces computational cost since there are only two intersections. The latter three models provide details of region-region relations, and the last model considers the order nature of transformations between topological relations.

Table A.1 Summary of existing topological models.

Type	Topological model	Set operators	Multi-level	Sources
Decomposition-based	4-intersection	Intersect	No	Egenhofer and Franzosa, 1991
	9-intersection	Intersect	No	Egnhofer and Herring, 1991
	Voronoi-based 9-intersection	Intersect	No	Chen et al., 2001
Whole-based	Randell, Cui and Cohn (RCC)		No	Randell et al., 1992; Cui et al., 1993; Cohn et al., 1997
Mixed	Voronoi-based spatial algebra	Union, intersect, difference, symmetric difference	Yes	Li et al., 2002
	Intersection and difference	Intersect, Difference	No	Deng et al., 2007
	Separation number and dimension	Intersect, difference	Yes	
	Element type and number	Intersect, Difference	Yes	
	Holistic sequence	Intersect, Difference	Yes	

It's conventionally concerned with Directional relation with two-point objects. Deng and Li (2018) extended the conventional definition of direction relations to include line and objects for spatial query and analysis.

Table A.2 Summary of existing direction models.

Type	Models	Quantitative or qualitative	Shape-sensitive	Formal	Single or Group direction	sources
Point-based	Simplest point-based model	Qualitative	No	No	Single	Frank, 1996
	Cone-based model	Qualitative	Sometimes	No	Single	Haar, 1976
	Refined cone-	Qualitative	Sometimes	No	Single	Peuquet

	based model					and Zhan, 1987
	Statistical model	Quantitative	Yes	No	Single	Deng et al., 2008
MBR-based	MBR matrix model	Quantitative	Yes	Yes	Single	Goyal, 2000
	Projective model	Qualitative	Yes	Yes	Single	Billen and Clementini, 2004
Voronoi-based	Voronoi Whole-based model	Quantitative	Yes	Yes	Single	Zhao, 2002
	Direction group model	Quantitative	No	No	Group	Yan et al., 2006

From the previous studies, it is found the maximum distance, the minimum distance, and the centroid distance have already been used. However, the above three types of distances have not included the influence of the shape of the symbols, which must be taken into consideration when it comes to the distance between each symbol's component. The Hausdorff distance (Rucklidge, 1996) considered the shape of the spatial target. The Hausdorff distance between targets A and B refers to the maximum between the minimum distance from A to B and the minimum distance from B to A (https://www.sciencedirect.com/topics/computer-science/hausdorff-distance). However, the disadvantage of Hausdorff distance is that it is easily affected by the remote slender part of the space target to obtain a distance inconsistent with reality. Some researchers put forward the extended Hausdorff distance, which uses the median distance to obtain the distances from A to B and B to A, reducing the influence of remote and slender parts on the overall distance of the space target (Deng et al., 2007).

Table A.3 Summary of existing distance models.

Distance	**Computing Framework**
Minimum distance	$D_{min}(A,B) = \min_{p_a \epsilon A}\left\{\min_{p_a \epsilon B}\{d(p_a,p_b)\}\right\}$
Maximum distance	$D_{max}(A,B) = \max_{p_a \epsilon A}\left\{\max_{p_a \epsilon B}\{d(p_a,p_b)\}\right\}$

Centroid distance	$D_c(A,B) = d\left(\frac{1}{m}\sum_{i=1}^{m} v_{iA}, \frac{1}{m}\sum_{j=1}^{n} v_{jB}\right)$
Hausdorff distance	$\mathrm{H}(A,B) = \max\left\{\max_{p_a \epsilon A}\left\{\min_{p_a \epsilon B}\{d(p_a,p_b)\}\right\}, \max_{p_a \epsilon A}\left\{\min_{p_a \epsilon B}\{d(p_a,p_b)\}\right\}\right\}$
Extended Hausdorff distance	$h^f(A,B) = k^{th}_{p_a \epsilon A} \min_{p_a \epsilon B}\{d(p_a,p_b)\}$ $h^f(B,A) = k^{th}_{p_a \epsilon B} \min_{p_a \epsilon A}\{d(p_a,p_b)\}$

Regarding to the raster distance, it is possible to compute distance transformation on a grid given a symbol. The transform efficiently computes how far each symbol component is from another symbol component. In raster space, the definition of a distance approximates vector distance (Deng et al., 2007). Commonly used raster distances include city block, chessboard, octagon, chamfer 2-3, and chamfer 3-4 distances (Chen et al., 1999).

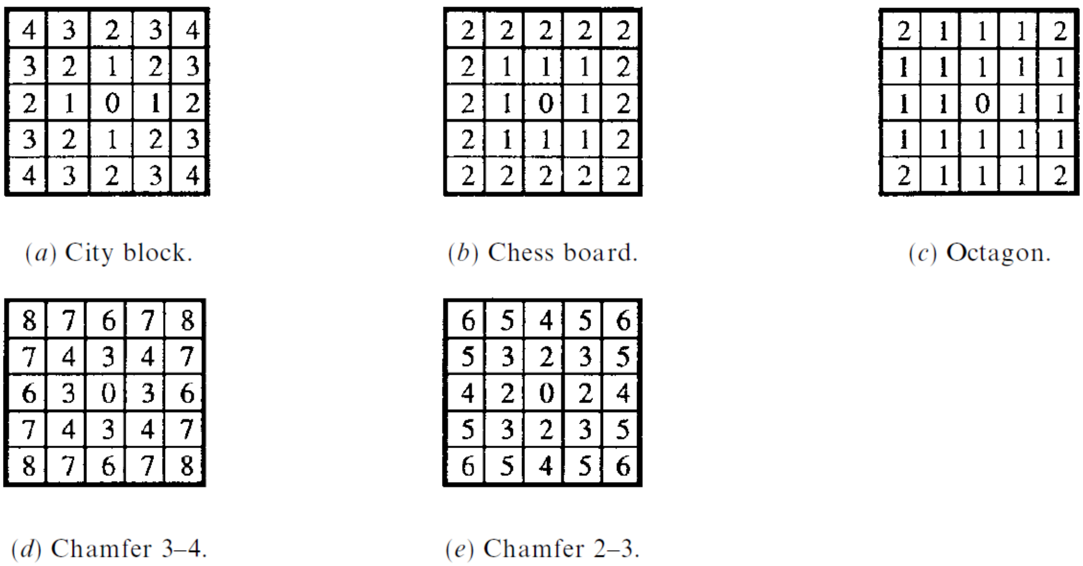


Figure A.1 Various definitions of raster distance (Chen et al., 1999).

Appendix B: Development of Web prototype system

The programming language used to develop user interfaces is Hypertext Markup Language (HTML). The Web test system is developed in two parts. They are user interface and graphics editing. Some of the codes relevant to the user interface shown in Figure 3.29 are: "

```
<div>
    <div style="float: left; padding-left:10px"><h2></h2></div>
    <div style="float: right"><img alt="small logo" src="images/logo_polyu.gif" height="57"
    width="247" /></div>
</div>


<hr style="margin-top:70px; "/>
<div style="padding-left:20px; color: #4682B4"><h2>Introduction</h2></div>
<div style="width:100%; height:650px;">
    <div style="float: left; width:50%; height:650px;"></div>
    <div style="float: right; width:50%; height:750px; background-color: blanchedalmond;">
        <div style="padding-left:40px; width:100%"><h2>Frame shape</h2></div>
        <div id ="example_frame">
            <div class="example_picture" ></div>
            <div class="example_picture" ></div>
            <div class="example_picture" ></div>
        </div>
        <div style="padding-left:40px; width:100%"><h2>Interial structure</h2></div>
        <div id ="example_frame">
```

```
                <div class="example_picture" ></div>
                <div class="example_picture" ></div>
                <div class="example_picture" ></div>
            </div>
            <div style="padding-left:40px; width:100%"><h2>Appearance</h2></div>
                  <div id ="example_frame">
                <div class="example_picture" ></div>
                <div class="example_picture" ></div>
                <div class="example_picture" ></div>
            </div>
        </div>
</div>
"
```

C Sharp (C#) language was used to develop the graphics edit server. Some of the codes relevant to the graphics editing shown in Figure 3.29 are: "

```
protected void ImageButton51_Click (object sender, ImageClickEventArgs e)
    {
   if (button51 == false)
   {
     ImageButton51.BackColor = Color.Yellow;
     System.Drawing.Image image =
System.Drawing.Image.FromFile(Server.MapPath("/morphemes/basketball.tiff"));
     MorphemeList.Add(image);
     button51 = true;
     if (MorphemeList.Count < Morpheme_count)
     {
       Add_morpheme();
       CurrentSequence51 = MorphemeList.Count - 1;
```

```
                    CurrentLocation51 = new int[2] { location_attributes[CurrentSequence51, 0],
location_attributes[CurrentSequence51, 1] };
                    CurrentArea51 = new int[2] { area_attributes[CurrentSequence51, 0],
area_attributes[CurrentSequence51, 1] };
                }
                else if (MorphemeList.Count == Morpheme_count)
                {
                    mainImage =
AdjustArea(System.Drawing.Image.FromFile(Server.MapPath("/morphemes/null.tiff")), 510, 510);

                    Metric_construct();
                    CurrentSequence51 = MorphemeList.Count - 1;
                    CurrentLocation51 = new int[2] { location_attributes[CurrentSequence51, 0],
location_attributes[CurrentSequence51, 1] };
                    CurrentArea51 = new int[2] { area_attributes[CurrentSequence51, 0],
area_attributes[CurrentSequence51, 1] };
                    Button_Disable();
                }
                show_image();
            }
            else if (button51 == true)
            {
                ImageButton51.BackColor = Color.Transparent;

                if (MorphemeList.Count <= Morpheme_count)
                {
                    imposeImage =
AdjustArea(System.Drawing.Image.FromFile(Server.MapPath("/morphemes/null.tiff")),
CurrentArea51[0], CurrentArea51[1]);

                    using (Graphics g = Graphics.FromImage(mainImage))
                    {
                        g.DrawImage(imposeImage, new Point(CurrentLocation51[0], CurrentLocation51[1]));
                        g.DrawImage(CurrentStructure, new Point(0, 0));
                    }
                }
                else
```

```
            {
                if (CurrentLocation51 != null)
                {
                    imposeImage =
AdjustArea(System.Drawing.Image.FromFile(Server.MapPath("/morphemes/null.tiff")),
CurrentArea51[0], CurrentArea51[1]);
                    using (Graphics g = Graphics.FromImage(mainImage))
                    {
                        g.DrawImage(imposeImage, new Point(CurrentLocation51[0],
CurrentLocation51[1]));
                        g.DrawImage(CurrentStructure, new Point(0, 0));
                    }
                }
            }
            if (MorphemeList.Count <= CurrentSequence51)
            {
                MorphemeList.Clear();
            }
            else
            {
                MorphemeList.RemoveAt(CurrentSequence51);
            }
            metric_attributes[CurrentSequence51, 0] = 0;
            metric_attributes[CurrentSequence51, 1] = 0;
            metric_attributes[CurrentSequence51, 2] = 0;
            metric_attributes[CurrentSequence51, 3] = 0;
            metric_attributes[CurrentSequence51, 4] = 1;
            metric_attributes[CurrentSequence51, 5] = 1;
            metric_attributes[CurrentSequence51, 6] = 0;
            metric_scale[CurrentSequence51, 0] = 1;
            metric_scale[CurrentSequence51, 1] = 1;
            show_image();
            button51 = false;
        }
    }
”
```