# Visual Communication of Spatio-temporal Semantics

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## Abstract

In a cognitive sense, geographic information system can be regarded as a computer simulation system of human environmental cognition. Spatio-temporal semantics could be understood to be objective laws about time-varying geographic phenomena, human cognition on geographic environment, or information hidden in geographic data. To reveal spatio-temporal semantics of geographic objects and model them in a visual way are significant in the design of humanized or intelligent GIS. In this paper, we present some of our initial ideas about visual communication of spatio-temporal semantics. Particularly, time and motion are differentiated conceptually. Basic spatio-temporal semantics are given. A visual communication model of spatio-temporal semantics is proposed. Moreover, spatio-temporal visual syntactics, including visual variables and its application to different measured data, is further investigated. It is seen that our work is useful to develop the theory of spatio-temporal cartography.

## 1 Introduction

From 1970s to the present, GIS has become relatively mature in data management and general cartography. Comparatively speaking, the functions of spatial analysis need to be developed greatly in upcoming days. This trend becomes increasingly apparent as spatial infrastructure is established. Semantics modeling of geographic data should be emphasized more. In general, semantics can be understood to be objective laws about time-varying geographic phenomena, human cognition on geographic environment, or information hidden in geographic data. A geographic object basically has temporal, spatial and thematic properties. Spatio-temporal and thematic properties and relationships constitute the full semantics of geographic objects. Spatio-temporal semantics modeling is a key issue in temporal GIS or so-called next generation GIS. Object-oriented methodology is widely used to enrich semantics modeling of geographic objects in GIS databases. In recent years, maps are thought of to facilitate geographic analysis as well as presentation of geographic data. Again, geographic object recognition or extraction of semantic information in remotely sensed images is a challenging research topic all the time. These show that the development of GIS is developing into a phase of rich semantics modeling and advanced analysis.

It is known that the aim of developing GIS is to support human geographic decisions. Here we have two perspectives of GIS. One perspective is to consider GIS as a computer simulation system of human environmental cognition. It stresses more about importance of computation technology or GIS. The other perspective is to view GIS and human cognition as two open but relatively independent systems. In this view, GIS (or computer) can cooperate with human beings to solve geographic problems. In any perspective, it can be seen that the study of human cognition on geographic environment is quite important for intelligent GIS development.

Formally, human cognition covers all human mental activities such as sense, perception, thought, learning, memory, attention, emotion, etc. The specified cognition in this paper refers to human thoughts. Sometimes it is called mental model, cognitive model, or memory structure. Chinese scientist Xuesen Qian (1992) classified human thoughts into three kinds: 1) visual thinking, 2) logical thinking, 3) inspirational thinking. The visual and logical thinkings are very consistent with the western views of analogous/imagistic, propositional/linguistic mental models. In cartography, the mostly often-mentioned mental model is cognitive map. It is believed that an alive map exists in our brain. Although a lot of arguments have been made, the significance of mental models (form, structure, content, etc.) is consistently acknowledged.

In this brief analysis, we realize the significance of spatio-temporal semantics in intelligent GIS. Our work aims at exploration of basic spatio-temporal semantics and its visual communication ways. Some innovative views are presented. For the outline of paper, basic spatio-temporal semantics are analyzed in section 2. Inspired by the theory of cartographic communication, a visual communication model of spatio-temporal semantics is suggested in section 3. The spatio-temporal visual syntactics of communication, including visual variables and their application to different measured data, is investigated in section 4. Some shortcomings are pointed out in conclusion.

## 2 Spatio-temporal semantics of geographic objects

In philosophy, time and space are two general forms of existence of motion objects. Also, time and space are two basic forms of relevance of motion objects. The relevance somewhat implies interaction of motion objects. In psychology, time is recognized by a sequence of events. Spatio-temporal semantics are implicitly reflected by spatial changes or motions of spatial objects. Essentially, time is a count of motions or a sequence of events occurred periodically. An example is calendar time defined by the rotation and revolution of the earth. Fiscal time is often determined by periodical financial transactions. Absolute time is to use a consistent or global motion reference system. And relative time is to use relative or local motion referents. In this paper, time is constrained to be real world time rather than computer time (database time, display time, etc.). And changes or events happened in geographic world rather than in computer world or other places. Database events, viewpoint changes and light changes are excluded from our discussion.

In GIS, we can classify spatial changes into four kinds: 1) spatial property changes; 2) object identity changes; 3) spatial distribution changes; 4) thematic or functional changes. Functional changes, which can be explained at different levels of abstraction, are application dependent. The number of functional changes is indefinite. The general spatial changes consist of spatial property changes, object changes and scene changes. Although the scene change, like the spatial distribution change, is a kind of global changes which are composed of spatial property changes and spatial object changes. However, configuration is a global property of a scene. Again, time semantics can be divided into time-varying patterns {discrete change, stepwise change, continuous change}.

### 2.1 Three levels of spatial change

In a bottom-up order, three levels of spatial change are spatial property change, spatial object change and spatial scene change (Figure 1). Spatial property changes refer to geometrical property changes and geometrical dimensionality changes. Spatial object changes are associated with object identifier changes. Spatial scene changes are composed of spatial property changes and spatial object changes. Meanwhile the spatial scene change as a whole has its own properties as illustrated later.

- **Spatial property changes**

We argue that primary spatial properties, in a visual sense, consist of location, distance, direction, shape and size. Location may be absolute or relative. Distance may be absolute or relative too. Direction may be intrinsic, extrinsic or deictic. Size and shape are overall properties of a set of spatial components. Absolute size is measured with the number of equivalent interval spatial units. Relative size is a partial ordering relation between an object and its referent. Shape is often described with contours (convexity, concavity, a chain of vertices, etc.), components construction, or compact ratios. In terms of geometrical dimensionality, spatial objects fall into three classifications: point objects, linear objects, and areal objects. Like that it is easy to obtain a set of primary spatial property changes {location change, distance change, direction change, shape change, size change}, and a set of geometrical dimensionality changes {point change, linear change, areal change}. When geometrical dimensionality changes are combined with location change, it turns out a set of moving object changes {moving point, moving line, moving region}. This was firstly proposed by Wolfson S., Erwig M., R.H. Güting, et al.(1997). Figure 2 shows a set of primary spatial property changes of a region object.

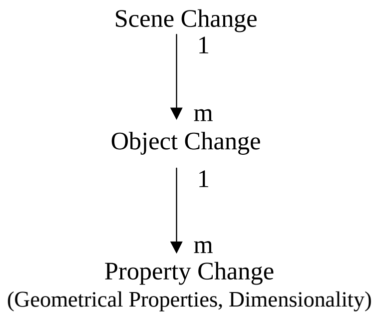


Figure 1. Three levels of spatial changes

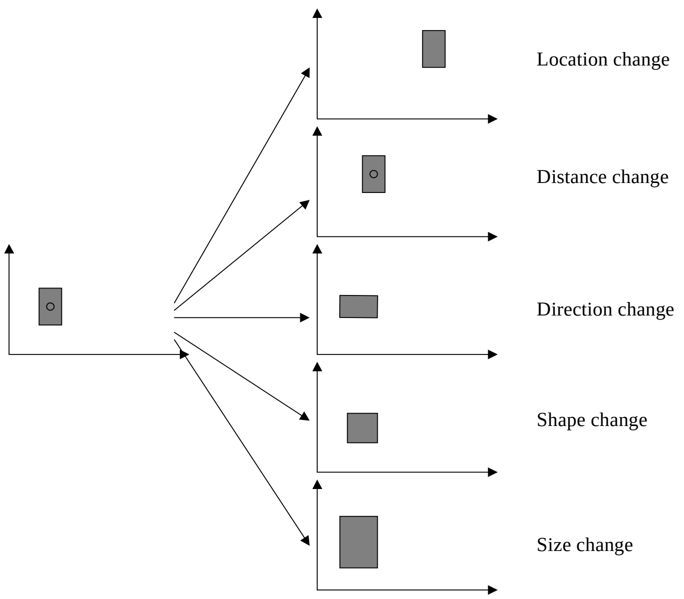


Figure 2. Primary spatial property changes

- **Spatial object changes**

The spatial object change is associated with object identifier changes. According to mapping relationships among source objects and result objects, we define six kinds of spatial object changes (Figure 3):

1) 0:1 change, which indicates that an object is born. Existence, appearance, creation and birth show the same meaning.
2) 1:0 change, which indicates that an object died. Extinction, disappearance, destruction and death shown the same meaning.
3) 1:1 change, which indicates that an object is transformed into other object. If the source object is the same as the result object, then changes are property changes such as metamorphosis. Identifier changes are further studied by Hornsby K. and Max J. Egenhofer (1998).
4) 1:m (m≥2) change, which indicates that a source object is divided into several result objects. The source object may be included in a set of result objects. If all result objects are the same as source objects, then the

change is called reproduction. If one of result objects is the same as the source object and the others are different, then changes may be spawn, splinter or production. If each result object is different from the source object, then changes may be division, dissolution or secession.

5) m:1 (m≥2) change, which indicates that many source objects are aggregated into one result object. If the result object is the same as one of source objects, then changes may be accommodation or enlargement. If the result object is different from any source object, then changes may be merging or generation.

6) m:n (m,n≥2) change, which indicates that m source objects produce n result objects. Changes may be property inheritance, passing on, permutation, exchange, object reallocation, etc.

| Relationships | Object Changes | Graphs | Geographical Functional Changes |
|---|---|---|---|
| Object 0 → 1 Object | Existence | A → A | |
| Object 1 → 0 Object | Extinction | A → A | |
| Object 1 → 1 Object | Transformation | A → B | Property changes (B=A)<br>Metamorphose (B<>A) |
| Object 1 → m Object | Splitting | A → $B_1$, $B_2$, ..., $B_m$ | Reproduce (B1..m=A)<br>Spawn, Splinter, Produce (B1=A, B2<>A)<br>Divide, Dissolve, Secede (B1..m<>A) |
| Object m → 1 Object | Merging | $A_1$, $A_2$, ..., $A_m$ → B | Accomodate, Enlarge (A1=B)<br>Merge, Generate (A1..m<>B) |
| Object m → n Object | Reallocation | $A_1$, $A_2$, ..., $A_m$ → $B_1$, $B_2$, ..., $B_m$ | Property Succeed, Pass on,<br>Permutate/Exchange<br>Objects Rellocate |

Figure 3. Primary spatial object changes

- **Spatial scene changes**

Spatial scene is the distribution of spatial objects, but as a whole it has its own properties. Like population stated by Gagnon P., Yvan Bedard and Geoffrey Edwards (1992), primary changes of a spatial scene have location (position) changes, direction (orientation) changes, shape changes and size changes (cumulative size changes or population size changes), and the changes of spatial distribution types (regular, random or grouped distribution). These are shown in Figure 4. The spatial scene change is usually caused by changes of its components.

## 2.2 Detailed time semantics

In time dimension, time semantics are subdivided into three kinds of time-varying patterns {discrete change, stepwise change, continuous change} (see Figure 5). Three kinds of time-varying patterns structuralize temporal data or spatio-temporal data.

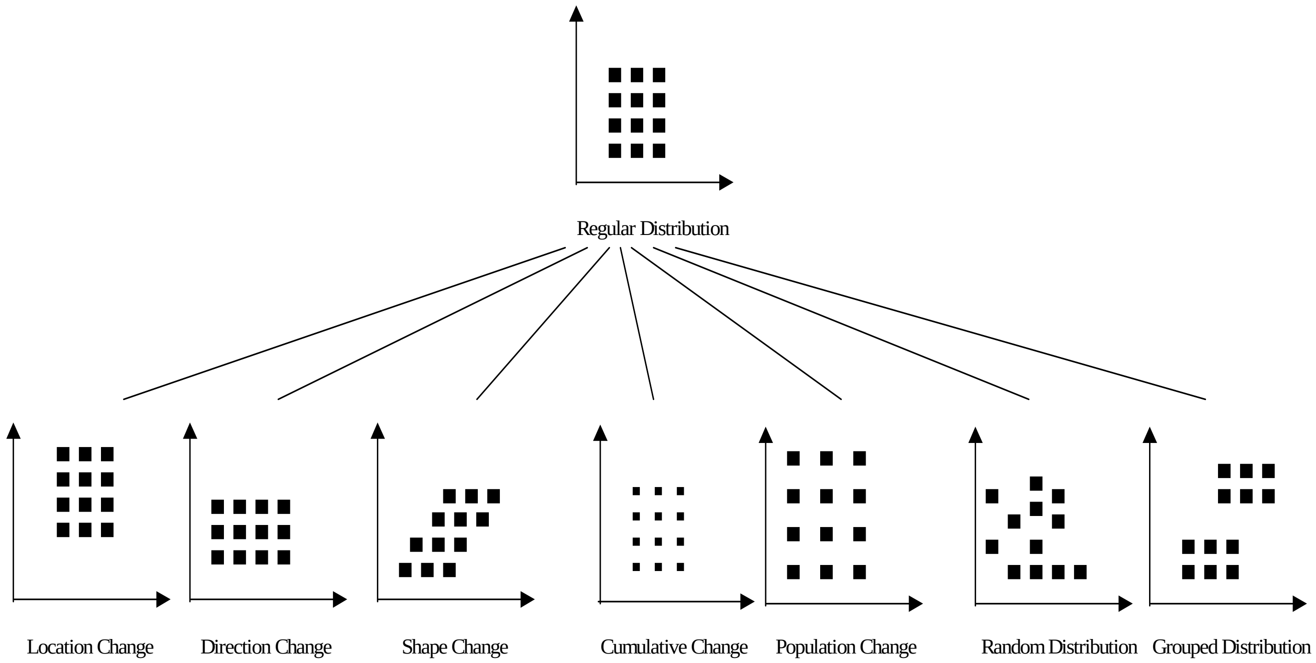


Figure 4. Primary spatial scene changes

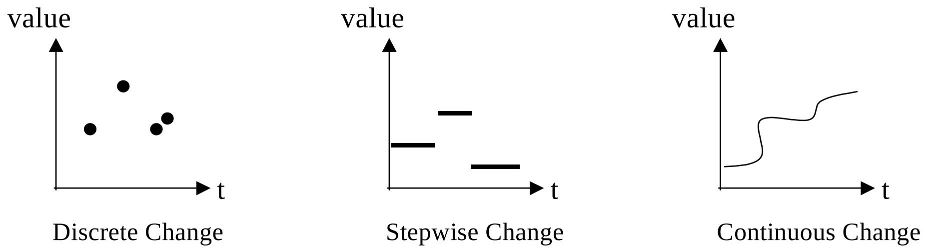


Figure 5. Primary temporal changes

## 3 A visual communication model of spatio-temporal semantics

The original meaning of communication is transmission of information. The whole communication process is that signal (coded information) is transferred through channel, then signal is decoded and received by receivers. One criteria of communication is to maintain efficiency and effectiveness of information transmission. The efficiency is involved with the speed and bandwidth of communication. It is partly dependent on ratio of signal compression and the quality of communication channels. The effectiveness is to avoid loss of original information and appearance of noise.

Cartographic communication introduced by Board C. (1967), Kolancy A. (1969), Morrison J. (1974), Robinson A., et al.(1978) is one of basic cartographic theories parallel to cartographic semiotics, cognitive maps, and cartographic models. The cartographic communication refers to ideas or information exchange rather than electronic communication. Ideas or information exchange are also called semantics communication here. In compared to electronic communication, involved hardwares in cartographic communication have the real world (geographic reality), humans (cartographers and map users), and maps (paper or digital maps). With reference to Kolancy's communication model, a visual communication model of spatio-temporal semantics is given (figure 6).

In this model, the reality is geographic environment around human beings. For different people in different time periods, the scopes of activity are different by virtue of individual difference in aspects of experience, knowledge, preference, objectives, etc. It is observed that the scope of geographic space defined in textbooks is continuously enlarged. In ancient times, geographic space is from the earth surface to the top of vegetation. In those times, main activities of humans are hunting, fishing and fruit-picking for their survival. As human activity abilities become strong, the scope of geographic space is expanded into atmosphere and under earth. Airplane was invented. People can take an airplane to fly over the sky. People learn how to do ore mining. In modern times, satellites have been launched, people can take space ships to travel the moon. Recently geographic space is termed earth space. Earth space is considered as a part of the universe.

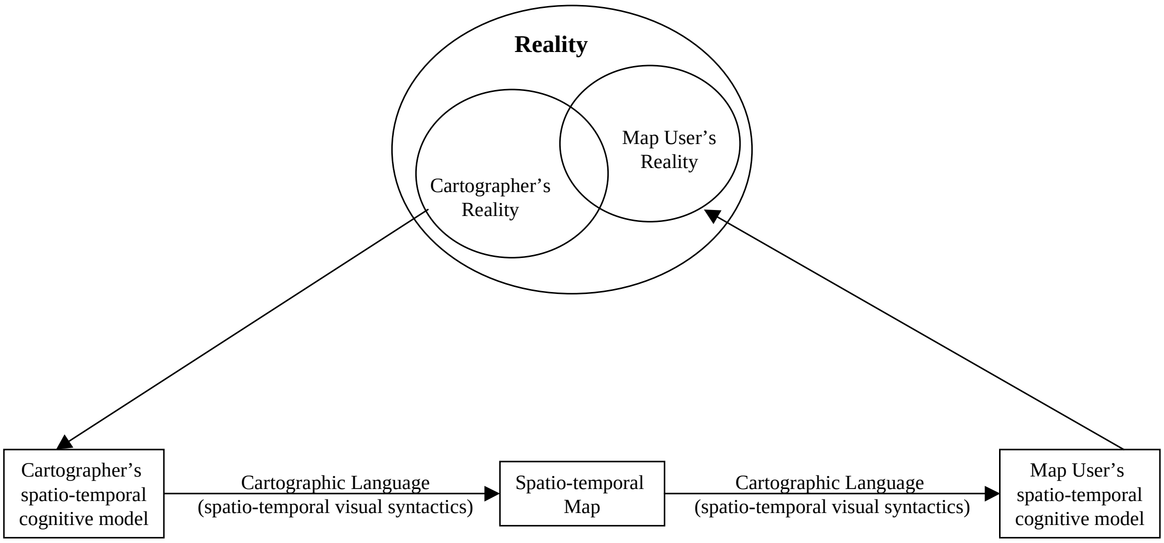


Figure 6. A visual communication model of spatio-temporal semantics

Here the reality is our geographic environment which is a large-scale space. The large-scale space is perceptually defined. In contrast, small-scale space is often called desktop space, which can be perceived at first sight. The large-scale space is built by linking our local perspectives while we navigate through it. Certainly, each person has a slightly different space concept by virtue of individual difference. That is why cartographer's reality and map user's reality are not completely equivalent in Figure 6.

Space and time are basic properties of geographic objects or geographic environment. So we can think of human cognition on geographical reality as spatio-temporal cognitive models. Semantics are fundamental in a cognitive model, but it is also concerned with mapping tasks, personal experience and knowledge, preference, emotions, etc. The formation of map user's cognitive models is similar to cartographer's. However, cartographer's cognitive models are not completely consistent with map user's cognitive models. Some information loss or noises are unavoidable.

The other factor of resulting in information loss is cartographic language. Cartographic language is used to design maps. It is a system of cartographic signs. According to American philosophers Peirce and Moris's statements, a system of sign has three basic parts: syntactics, semantics, and pragmatics. The syntactics is some general rules for signs to construct a sentence. Signs are termed sign-vehicles somewhere. The syntactics regulates relationships among sign-vehicles. The semantics is what signs refer to. It is associated with referents or objects. The pragmatics is what interpretants understand about signs. If the semantics of a sign and its pragmatics are the same, it is called a monosemic sign. If one semantics corresponds to many different pragmatics, or many semantics correspond to one pragmatics, the sign is called a polysemic sign.

It is ruled out of our communication model. In our views, cartographer's cognitive models and map user's cognitive models are more close to pragmatic models. It is assumed that semantics and pragmatics are equivalent in this paper. Therefor, the paper is titled with semantics rather than pragmatics. We simply consider cognitive models as semantics models, and consider spatio-temporal cognitive models as spatio-temporal semantics models.

The spatio-temporal map can be viewed as a communication channel of spatio-temporal semantics. It can be say that spatio-temporal maps are the externalization of human spatio-temporal cognitive models. With the help of cartographic language, cartographers put spatio-temporal semantics into spatio-temporal maps. At the other end, map user's extract semantics information from maps. It is widely acknowledged that communication is a basic function of maps. However, by using maps we can often found some unexpected things, which are not explicitly expressed in maps. That is, maps offer some cues to invoke our mental activities. In this sense, maps are not only the presentation of our cognition about time-varying geographic environment, but also help us to build cognitive models. So maps have two functions of communication and exploration (or map presentation and map analysis).

## 4 Spatio-temporal visual syntactics

The spatio-temporal visual syntactics of cartographic language is significant for the design of spatio-temporal maps. If the spatio-temporal map is viewed as a cartographic product, then spatio-temporal visual syntactics has shown some general meanings about spatio-temporal maps. In other words, spatio-temporal semantics of maps are somewhat shown by spatio-temporal visual syntactics. On the other hand, spatio-temporal visual syntactics can be considered as general laws of our visual thinking, and the spatio-temporal map can be viewed as the externalization of our cognitive models or semantics models. As stated before, there exists two human thinking ways: visual thinking and logical thinking. Equivalently, the cognitive model is formalized in mental imagery and mental linguistics (analogous and propositional knowledge). To use visual syntactics is equal to use visual thinking. The semantics (commonsense and anomalies) are the result of our visual thinking.

By definition in linguistics, syntactics refers to the rules of a sentence construction. The syntactics is concerned with relationships among words. In cartography, the visual syntactics usually include visual variables and their application rules for visualizing different measured data. The visual variable is arisen from visual perceptual difference about objects. It is also termed cartographic variable. Visual variables are variants in a narrow sense, but are affordances in a general sense. Often-mentioned visual variables are stated at the level of human perception but not at the level of cognition (or thinking).

It should be distinguished between dynamic visual variables and spatio-temporal variables. This is directly related to differentiation of motion and space-time. It is known that space and time are two basic existing forms of motion objects. Motions or a sequence of events show the deep meanings of space and time. In other words, spatial changes have shown spatio-temporal semantics. Motions or spatial changes given in section 2 are real changes. They should be basic spatio-temporal semantics, or motion cognition. However, dynamic maps are mainly concerned with motion perception. Only if objects change very quickly, our visual nerves receive visual stimulus not less than 24 frames per second, then continuous motion is perceived. For instance, movies are played at the speed of 24 frames per second, PAL and NSTC video programs are played at the speed of 25 and 30 frames per second respectively. For motion itself, not all motions are cognized as space-time. Although animation is a best means of visualizing motions, not all animated maps are spatio-temporal maps. Animated maps consist of temporal animation maps and atemporal animation maps. Only temporal animation maps are spatio-temporal maps. The examples of atemporal animation maps are fly-by animations (viewpoint changing animations), classification animations, map generalization animations, reexpression animations, and so on. In the atemporal animation, described geographic objects are not really changed. In the view of Gibson J. (1979), objects consist of a set of affordances, which can be extracted actively from optic flow. The optic flow is formed since objects or viewpoints change. Spatio-temporal semantics are extracted from the optic flow caused by spatial object changes. Viewpoint changes are excluded from the scope of our paper. We needs to say that some static map signs can communicate spatio-temporal semantics as well. For example, the arrow sign often represents a flow of commodities or population effectively. So we know that spatio-temporal semantics can be communicated by dynamic or static map signs. Some dynamic maps are spatio-temporal maps, and some of them are not.

As the externalization of spatio-temporal cognitive or semantic models, spatio-temporal maps map time-varying geographic objects onto spatio-temporal map signs. It is a kind of transformations from large-scale space (geographic space-time) to small-scale space (paper, screen or mental spaces). In the process of transformation, spatio-temporal map generalization is needed.

Let spatio-temporal visual syntactics be signed with G, then

$$G = (V, R)$$

V stands for a set of spatio-temporal visual variables, and R for a set of application rules of visual variables for different measured geographic data. Moreover,

$$V = \{v_i \mid i \in N\}, \text{ if } \sum_{i=0}^{N} k_i v_i = 0, \text{ then } k_i = 0;$$

$$R = \{r_j \mid j \in N\}, r: D \rightarrow V$$

That is, $v_i$ is perceptually independent on each other in vision. $v_i$ may be a composite visual variable, $v_i = \{ v_{ik} \mid k \in N\}$. The rule r is to map measured data onto visual variables. D is a domain of measured data.

In past three decades, a number of spatio-temporal visual variables have been proposed by cartographers before or later. Bertin J. (1967, 1983) firstly presented a set of visual variables {position, orientation, size, shape, texture, color/color hue, color value}. Morrison J. (1974) further divided color value into color intensity and color saturation, and the variable of arrangement was proposed again. Caivano J. (1990) put forward a composite visual variable of texture, which is composed of texture orientation, texture size and texture density. Moreover, MacEachren defined a higher-level composite visual variable of pattern, which is composed of the configuration of pattern, pattern size (like texture size), pattern orientation (like texture orientation), pattern distribution (like Bertin's grain), and pattern arrangement (like Morrison's arrangement). For dynamic variables, DiBiase D., MacEachren A., Krygier J., and Reeves C. (1992) firstly proposed three dynamic variables {order, duration, the rate of change}. MacEachren A. (1994) proposed another three dynamic variables {display date, frequency, synchronization}. It is our assumption that these proposals for visual variables are based on perceptually independence in vision.

Perhaps it is meaningful to separate which visual variables are for spatio-temporal semantics communication, and which visual variables for thematic semantics communication. At least this can help us to distinguish GIS and enterprise information management systems, to distinguish spatio-temporal maps and historical transaction data graphs. It is clear that the variable of color value should be ruled out of spatio-temporal visual variables. To summarize the pioneer's work, it is known that spatial visual variables have {position, orientation, size, shape, texture, pattern, …}. Among them, texture and pattern are two composite visual variables, but still keep their visually perceptual independence. We have seen that proposed temporal visual variables have {order, duration, the rate of change, display date, frequency, synchronization}. In like manner, the perceptual independence is an important criterion for proposals of temporal visual variables. We argue that spatio-temporal variables, which are formed with combination of spatial visual variables and temporal visual variables, are visually perceptual independence too. We call them lower-level spatio-temporal visual variables as compared with cognitively independent variables. We contend that {position change, distance change, orientation change, shape change, size change, distribution/arrangement change, scene change, time-varying pattern} can be regarded as visually cognitive independent variables for spatio-temporal semantics communication. They are called higher-level spatio-temporal visual variables.

Table 1. The spatio-temporal visual syntactics - the rules of application of lower-level spatio-temporal visual variables to four kinds of measured data

| **Lower-level Spatio-temporal Visual Variables** | | **Nominal Data** | **Ordinal Data** | **Interval/Ratio Data** |
|---|---|---|---|---|
| **Static Variables** | *Position* | *Effective* | *Effective* | *Effective* |
| | *Size* | *Not Effective* | *Effective* | *Effective* |
| | *Orientation* | *Effective* | *Marginally Effective* | *Not Effective* |
| | *Shape* | *Effective* | *Not Effective* | *Not Effective* |
| | *Texture {orientation,size,density}* | *Effective* | *Marginally Effective* | *Marginally Effective* |
| | *Arrangement* | *Marginally Effective* | *Not Effective* | *Not Effective* |
| | *Pattern* | *Effective* | *Marginally Effective* | *Marginally Effective* |
| **Dynamic Variables** | *Duration* | *Marginally Effective* | *Effective* | *Effective* |
| | *Order* | *Not Effective* | *Effective* | *Not Effective* |
| | *Rate of Change* | *Marginally Effective* | *Effective* | *Effective* |
| | *Display Date* | *Effective* | *Marginally Effective* | *Not Effective* |
| | *Frequency* | *Marginally Effective* | *Effective* | *Marginally Effective* |
| | *Synchronization* | *Effective* | *Not Effective* | *Not Effective* |

For the syntactics rules R, here we only discuss about the application rules of lower-level visual variables to different measured data. The similar visual syntactics rules for higher-level visual variables will be explored in the future. However, some relevant syntactics like shape grammar and space syntax are needed to be noticed.

Geographical data are usually measured on four kinds of scale. They are nominal, ordinal, interval and ratio scales. On the nominal scale, data is only classified. On the ordinal scale, data is classified and ordered. For interval-scale measured data, not only data is classified and ordered, but also the distance can be measured on data. For the ratio scale, data is interval-scaled data and absolute zero is further specified. From nominal, ordinal, interval, through ratio scale, data is observed more and more precisely. Vice versa, data is gradually generalized. The nominal and interval scales are mostly often used in geographic data mapping. Table 1 shows the rules of application of spatio-temporal visual variables to four kinds of measured data.

## 5 Concluding remarks

In summary, we have differentiated concepts of time and motion. Following that, dynamic maps and spatio-temporal maps are considered as two different types of maps. Motion is a cognitive unit different with time. Usually motion, continuous motion in particular, is directly perceived by our retina and motion cortex. Factors resulting in our motion perception may be real changes of geographic objects, light source changes, or our viewpoint changes. Time is argued to be another cognitive unit. It is certain that temporal semantics can be communicated with motions or changes. However, static signs like arrow sign can also be used to communicate temporal semantics.

In a bottom-up order, we suggested several kinds of spatial changes. They are property changes, object changes and scene changes. We believe that they can show some basic spatio-temporal semantics. Based on Kolancy's work, we proposed a visual communication model for spatio-temporal semantics. Some static and dynamic visual variables proposed before are re-termed lower-level visual variables. It is argued that lower-level visual variables keep perceptually independent in vision. Our proposed spatial changes are termed higher-level visual variables. Higher-level visual variables keep cognitively independent. Again, we presented a formal definition of spatio-temporal visual syntactics for spatio-temporal semantics communication. A spatio-temporal visual syntactics, the rules of application of lower-level spatio-temporal visual variables to four kinds of measured data, is tabulated.

Although some views on the visual communication of spatio-temporal semantics are given, this paper is not self-complete. What are complete and unique spatio-temporal semantics? What are complete and unique spatio-temporal visual variables? These need our further exploration.

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