

# Static Representation Exposing Spatial Changes in Spatio-Temporal Dependent Data

Hiroki CHIBA<sup>†a)</sup>, Yuki HYOGO<sup>††</sup>, *Nonmembers*, and Kazuo MISUE<sup>†b)</sup>, *Member*

**SUMMARY** Spatio-temporal dependent data, such as weather observation data, are data of which the attribute values depend on both time and space. Typical methods for the visualization of such data include plotting the attribute values at each point in time on a map and displaying series of the maps in chronological order with animation, or displaying them by juxtaposing horizontally or vertically. However, these methods are problematic in that they compel readers interested in grasping the spatial changes of the attribute values to memorize the representations on the maps. The problem is exacerbated by considering that the longer the time-period covered by the data, the higher the cognitive load. In order to solve these problems, the authors propose a visualization method capable of overlaying the representations of multiple instantaneous values on a single static map. This paper explains the design of the proposed method and reports two experiments conducted by the authors to investigate the usefulness of the method. The experimental results show that the proposed method is useful in terms of the speed and accuracy with which it reads the spatial changes and its ability to present data with long time series efficiently.

**key words:** *spatio-temporal data, geovisualization, information visualization, static representation, spatial changes*

## 1. Introduction

Many kinds of data generated by recording various real-world phenomena include information related to location and time. Data of this nature are generally known as spatio-temporal data. In this research, we focus on a class of spatio-temporal data, in which the attribute values depend on both time and location. We refer to the data as spatio-temporal dependent data. A typical example of such data is weather observation data.

In spatio-temporal dependent data, we are often interested in changes not only of the attribute values at specific locations, but also of the spatial distributions of values satisfying specific conditions. For example, in some data in which the instantaneous values of rainfall intensity have been recorded, it is possible to read a change in the distribution of rain clouds by focusing on the locations at which a value larger than 0 was observed. We refer to such a change in the spatial distribution as a spatial change.

Humans can recognize spatial distributions of attribute values such as the distribution of rain clouds without special processing by computers by simply visualizing the data on

maps in a suitable manner. Typical methods for the visualization of spatio-temporal dependent data involve plotting the attribute values of each point in time on a map and displaying the series of maps in chronological order by animation, or by arranging them horizontally or vertically as small multiples [1]. Animation methods can change the representation as time changes and represent the values of a number of points in time on a single map. These methods therefore facilitate readers' intuitive understanding of the spatial changes. In contrast, a set of small multiples allows the readers to access all information at any time, because it displays the values of multiple points in time simultaneously. These two methods are used differently depending on users' purposes because these advantages can partly compensate for their respective weaknesses. However, these methods have a common problem. In either method, the attribute values of two or more points in time are not represented on the same map at the same time. Therefore, it is necessary to memorize the representations shown on the maps to grasp the spatial changes of the attribute values. This problem causes a high cognitive load and induces misreading in some scenes. Examples of these scenes are where the readers cannot control the display such as when viewing a public display, or at times when the reader cannot gaze at the display for a long time such as when using a car navigation system. Especially, animation requires maintaining the gaze at visual representations for a certain period of time to grasp the changes; thus, it is difficult to use animation in the aforementioned situations.

Solving this problem requires a visualization technique capable of reducing the cognitive load when reading spatial changes. We developed a visualization method with the ability to represent the attribute values of multiple points in time of spatio-temporal dependent data on a static map at the same time. In this regard, spatio-temporal dependent data are data consisting of time series data that have been recorded finely on the space. The proposed method divides the space into cells with a certain size and represents the time series data aggregated within the cells. This method is useful for comparing the locations and the attribute values on a static map, therefore it enables the spatial changes to be grasped in a shorter time.

## 2. Related Work

Small multiples and animation are representative of the visualization of spatio-temporal dependent data. The term

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<sup>†</sup>The authors are with University of Tsukuba, Tsukuba-shi, 305-8573 Japan.

<sup>††</sup>The author is with Dentsu Isobar Inc., Tokyo, 104-0045 Japan.

a) E-mail: chiba@vislab.cs.tsukuba.ac.jp

b) E-mail: misue@cs.tsukuba.ac.jp

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small multiples, which is a term that represents methods that juxtapose multiple small charts with uniform axes and scales, has been popularized by Tufte [1]. Animation has become a popular method for representing time-dependent data and dynamic phenomena since the improvement in the performance of computers and the distribution of moving images through the Internet has been facilitated [2].

Spatio-temporal data is represented by a three-dimensional model in which two axes are assigned to space and the other axis is assigned to time. Such a model is known as a space-time cube, and a prototype of a spatio-temporal model was created in the field of social geography by Hägerstrand [3]. Bach et al. proposed a taxonomy of existing visualization techniques to transform space-time cubes into two-dimensional representations [4]. In their taxonomy, the operation to create small multiples with charts separated by time was named time juxtaposing, and the operation to create animation with the same charts was named animated time slicing. We use terms such as time juxtaposing and animated time slicing to refer to the visualization method for spatio-temporal dependent data explicitly because small multiples and animation are general terms also used for other methods.

Visualization techniques of spatio-temporal dependent data are not limited to time juxtaposing and animated time slicing; thus, many other kinds of studies relating to data of this nature were conducted. Wickham et al. proposed glyph-maps that places a glyph representing data consisting of multiple measured values such as time series data at each location in the space [5]. Li et al. developed a method that represents time series data on the axes extended from the observation point and radially arranged outside the map [6]. We propose a method similar to glyph-maps, but our method is devised to increase the readability of the spatial changes.

### 3. Spatio-temporal Dependent Data

Naturally, the attribute values of spatio-temporal dependent data continuously change spatially and temporally. However, as long as the values are recorded as digital data, the values are actually recorded at regular intervals in time and space. Therefore, we treat spatio-temporal dependent data as data in which time series data are recorded at regular intervals in space.

In the research presented in this paper, specifically, we consider spatio-temporal dependent data consisting of observation points placed in a grid pattern of  $N_y$  rows and  $N_x$  columns equally spaced in each axis direction of an orthogonal coordinate system composed of  $x$ - and  $y$ -axes. We assume that every observation point has time series data of length  $N_t$ . In this case, a set of observation points  $O$  and a set of time points  $T$  are expressed as Eq. (1) and Eq. (2), respectively.

$$O = \{o_{i,j} | i \in \{0, \dots, N_x - 1\}, j \in \{0, \dots, N_y - 1\}\} \quad (1)$$

$$T = \{t_0, \dots, t_{N_t-1}\} \quad (2)$$

By using this notation, the position of an observation point

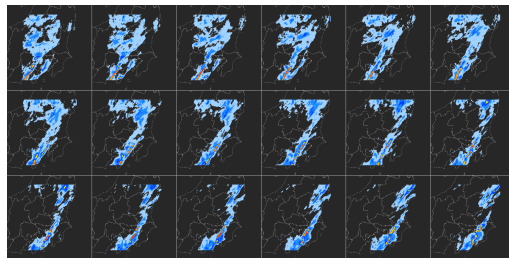


Fig. 1 Example of spatio-temporal dependent data (Visualized by time juxtaposing)

$o \in O$  is denoted by  $p_o \in \mathbf{R}^2$ , and the attribute value at an observation point  $o \in O$  at a time  $t \in T$  is denoted by  $v_{o,t} \in \mathbf{R}$ . The spatio-temporal dependent data considered in this paper are different from other spatio-temporal data such as spatial movement data because an attribute value  $v_{o,t}$  is a variable that depends on two variables: time  $t$  and position  $p_o$ . In spatial movement data, the position as a dependent variable is determined by time, which is the single independent variable. In this study, we further assume that the attribute value  $v_{o,t}$  constitutes one-dimensional quantitative data.

When visualizing spatio-temporal dependent data by using time juxtaposing or animated time slicing, color is often used to represent the values. Figure 1 shows an example of visualizing rainfall intensity data<sup>†</sup> using time juxtaposing and the color scheme used on the website of the Japan Meteorological Agency [7]. The values were recorded every 10 min, Fig. 1 represents 3 h of data.

## 4. Proposed Method

We developed a visualization method to represent spatio-temporal dependent data on a single static map. Figure 2 shows the same data shown in Fig. 1 visualized by using the proposed method. The area and color of the small circles represent an attribute value and its observed time, respectively. Each circle is placed near an observation point. Figure 3 shows the legend of the example shown in Fig. 2.

### 4.1 Basic Idea

Time juxtaposing creates maps each of which represents the values at each point in time and then juxtaposes them in chronological order. Contrary to this, our method first divides the space into a grid, next creates charts, each of which represents the time-series data at each subspace, and then juxtaposes them on a map.

Figure 4 and Fig. 5 show an outline of the visualization procedure using time juxtaposing and the proposed method, respectively. The fineness of grids represents the spatial resolutions of the data. The proposed method decreases the spatial resolution by aggregating several observation points

<sup>†</sup>Real data observed by X band MP radar provided by the Ministry of Land, Infrastructure, Transport and Tourism.

to obtain areas to represent the time series data.

For the visualization of time series data, position is often used for visual attributes. A typical example is a line

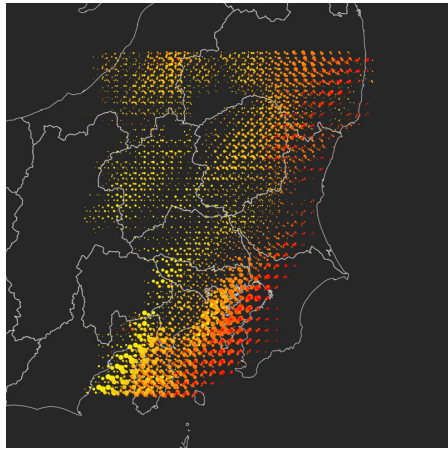


Fig. 2 Example of the use of the proposed method

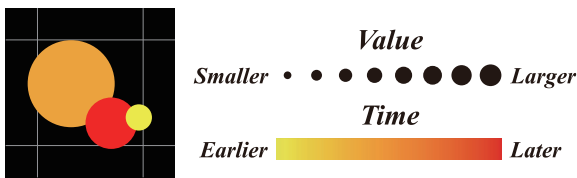


Fig. 3 Legend of the visual attributes

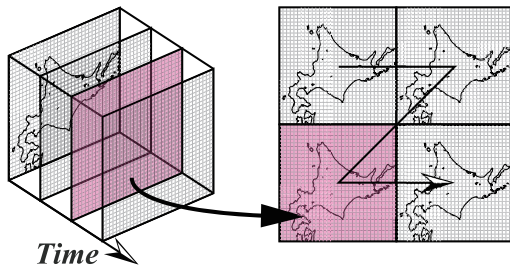


Fig. 4 Flow of visualization of spatio-temporal dependent data by time juxtaposing. Time juxtaposing creates a map of data of each point in time and then juxtaposes a series of the maps in chronological order

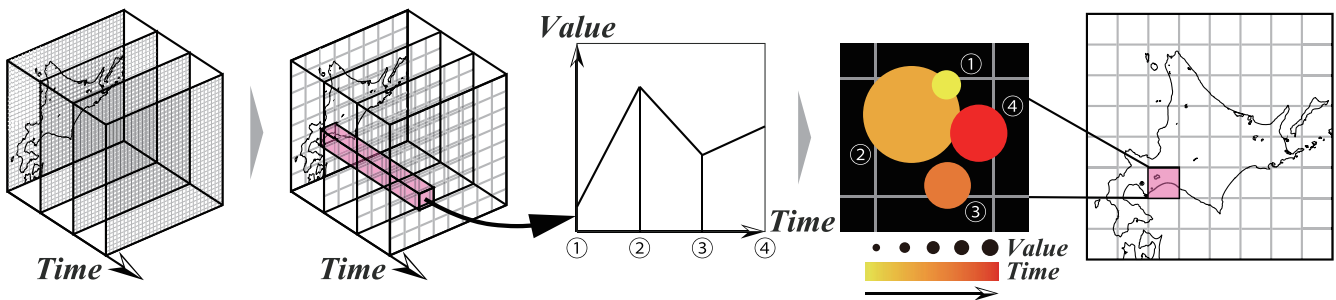


Fig. 5 Flow of visualization of spatio-temporal dependent data by the proposed method. The proposed method divides the space into a grid and aggregates the time series data for each sub-space, and represents them using circles on the sub-spaces

chart that assigns time and attribute values to two orthogonal axes as shown in the middle of Fig. 5, and Wickham et al. showed examples using similar series in glyph-maps. However, if position is used to represent values, a large display area is required to maintain readability. In addition, observing values at the same point in time on the entire space requires the same position to be searched on the time axis across many charts on the map. This makes it difficult to grasp the spatial distributions at a given time and their changes. We solved these problems by using circles in different sizes and colors to represent the values and time in the respective areas. We do not attach any meanings to the positions of the circles. By giving no meanings to their positions, it is possible to display the time series data in small areas, and thereby it is not necessary to greatly decrease the spatial resolution. Furthermore, it enables the gap between the positions at which the value is represented and where the value is actually observed to be reduced; thus, its power to represent spatial data is not greatly lowered as a whole.

#### 4.2 Aggregation of Time Series Data

The proposed method aggregates  $n_x$  and  $n_y$  observation points in the  $x$ - and  $y$ -axis directions, respectively. Assume that  $N_x$  and  $N_y$  are divisible by  $n_x$  and  $n_y$ , respectively, and let  $M_x = N_x/n_x$  and  $M_y = N_y/n_y$ , the observation points be aggregated into  $M_x \times M_y$  groups of observation points arranged in a grid. An aggregated group of observation points  $A_{k,l}$  ( $k = 0, \dots, M_x - 1, l = 0, \dots, M_y - 1$ ) is expressed by Eq. (3), and each of  $A_{k,l}$  is termed a cell.

$$A_{k,l} = \{o_{i,j} | i \in \{n_x k, \dots, n_x(k+1) - 1\}, j \in \{n_y l, \dots, n_y(l+1) - 1\}\} \quad (3)$$

The set of all cells is represented by  $S$ ; that is,  $A_{k,l} \in S$  ( $k = 0, \dots, M_x - 1, l = 0, \dots, M_y - 1$ ). Let  $p_A$  be the center of the observation points included in a cell  $A \in S$ , and let  $v_{A,t}$  be the average value of observation values at a time  $t \in T$ . Equation (4) and Eq. (5) show formal descriptions of  $p_A$  and  $v_{A,t}$ , respectively.

$$p_A = \frac{1}{|A|} \sum_{o \in A} p_o \quad (4)$$

$$v_{A,t} = \frac{1}{|A|} \sum_{o \in A} v_{o,t} \quad (5)$$

These two values are used as the center position of a cell  $A$  and the attribute value at a time  $t$ , respectively.

### 4.3 Conversion to Visual Representation

The proposed method represents the aggregated time series data by using  $M_x \times M_y \times N_t$  circles. In all the data,  $M_x \times M_y$  cells are used, and  $N_t$  circles are used for each cell. Within a cell, for each time  $t \in T$ , one circle is assigned to the representation.

First, the color of the circle is assigned to represent time. Assuming that  $C$  is a set consisting of all 32-bit RGBA colors, the color  $c_t \in C$  corresponding to a time  $t \in T$  is expressed by Eq. (7) using the following function  $f_{color}(u)$ .

$$f_{color}: [0, 1] \rightarrow C \quad (6)$$

$$c_t = f_{color}\left(\frac{t - t_0}{t_{N_t-1} - t_0}\right) \quad (7)$$

Here, the argument  $u$  of the function  $f_{color}(u)$  is always a real number in  $[0, 1]$ .  $f_{color}(u)$  is a color gradient function of which the returning color changes between two colors as  $u$  changes from 0 to 1. The reason for using the two-color gradient is to facilitate understanding the order of time. Various settings are conceivable for this two-color gradient, but we decided to tentatively use a gradient from yellow to red in this study.

Next, the area of the circle is assigned to represent attribute values. The area  $a_{A,t}$  of the circle representing the value at a time  $t \in T$  in a cell  $A \in S$  is expressed by Eq. (8) using the two parameters  $v_{max}$  and  $a_{max}$ . Here, the parameter  $v_{max}$  is the maximum value of the aggregated average value in the entire map, and  $a_{max}$  is the maximum area of one circle.

$$a_{A,t} = a_{max} \frac{v_{A,t}}{v_{max}} \quad (8)$$

The positions of all the observation points included in a cell  $A$  fall within the area near  $p_A$  in the space. Assume that the size of this area is  $w$  in the  $x$ -axis direction and  $h$  in the  $y$ -axis direction. In this study, we tentatively set  $a_{max}$  to be approximately 0.3 times the cell area ( $w \times h$ ).

Further, the circles should be arranged such that they do not hide each other. For simplicity, in this study, however, we tentatively used the function  $f_{rand}(t)$ , which returns the vector  $(x, y) \in [-w/2, w/2] \times [-h/2, h/2]$  randomly assigned to a time  $t \in T$ , and place the center of the circle at the position expressed by the following equation.

$$p_{center_{A,t}} = p_A + f_{rand}(t) \quad (9)$$

To prevent small circles from being hidden by large circles, the order in which circles are overlaid is changed within each cell. Then, the previous  $xy$  orthogonal coordinate system is converted to the coordinate system on the screen for

display purposes.

## 5. User Study 1: Readability of Spatial Changes

We conducted two user studies to evaluate the proposed method. The first study involved investigating the readability of spatial changes of spatio-temporal dependent data. In the user study, we evaluated whether the proposed method compensated for the weak points of existing methods. The other user study aimed to investigate the readability of spatio-temporal dependent data from a broader perspective. In the user study, we investigated the versatility of the representation accuracy of the proposed method. In both of the user studies, we compared the proposed method with time juxtaposing as an existing well-used method. Because time juxtaposing and the proposed method are the same in that both of them are methods that simultaneously represent values of several points in time as a static representation, comparing these two methods was expected to reveal the effect of the difference in these representations.

In this section, we describe the user study conducted to investigate the readability of the spatial changes.

### 5.1 Task

We provided the participants with visual representations of pseudo-generated rainfall-intensity data and asked them to use the answer sheet to describe what they could read. We asked questions about the following items that correspond to spatial changes in rainfall intensity data, and compared the time spent to read all items and the accuracy of answers in response to each item.

- Trajectories of rain clouds  
(Direction of movement, Presence / absence of separation, Number of rain clouds)
- Changes in the moving speed of rain clouds  
(Comparison of cloud speed if two or more rain clouds exist)
- Changes in the shape (size) of rain clouds  
(Comparison of shape (size) if two or more rain clouds exist)

Since we took into account that the time required for writing varies greatly among participants, we measured only the time taken for reading and then compared it.

We required each participant to carry out 10 tasks in total, using five types of data represented by time juxtaposing and five types of data represented using the proposed method. In order to achieve counterbalance, we changed the order in which participants attempted each method. We presented the visual representation only once per task, and measured the time for reading by using the method described in Sect. 5.4. Before starting the tasks with each method, we requested the participants to practice to deepen their understanding of each method.

**Table 1** Features of the datasets used in user study 1

Data	Features of the change of rain clouds
D1	Move linearly from west to east No change in speed and size
D2	Move as though drawing an arc from the southwest to the northeast No change in speed and size
D3	Separate in a Y shape One becomes faster after separation
D4	Merge as an upside-down shape of Y One before merging is small
D5	Intersect using a + shape One moving horizontally is slightly faster
D6	Move from west to east while meandering along a sine curve Slight acceleration / deceleration
D7	Two move in parallel from west to east One is small
D8	The smaller one chases the larger one Smaller one is slightly faster
D9	Move linearly from west to east Gradually become larger
D10	Move linearly from northwest to southeast Gradually become smaller

## 5.2 Presented Data

We prepared 10 sets of pseudo-rainfall-intensity data. We generated them such that one or two circular rain clouds existed in the space at any time. Because we thought that the effects of the methods might be different depending on how the rain clouds changed, we prepared 10 datasets with different features relating to the change in the rain clouds. Table 1 lists the features.

We divided the participants into two random groups. We presented even-numbered datasets using time juxtaposing and odd-numbered datasets using the proposed method to all participants in one of the groups. To the participants in the other group, we presented the same data by using alternative methods. After considering the correspondence between the visualization methods and the groups, the groups were exchanged between even- and odd-numbered datasets. Because there was a possibility that the reading ability and its variation might be biased among participant groups, we took this into account in the entire user study by swapping the group of participants.

We generated data consisting of observation points placed in a grid pattern of 32 rows and 32 columns, and when creating a visual representation by the proposed method, we omitted the processing explained in Sect. 4.2 ( $N_x = N_y = 32, n_x = n_y = 1$ ). The length of the time series in the data was 18, and those intervals were all equal ( $N_t = 18$ ).

## 5.3 Participants

Twenty undergraduate and graduate students (14 males, 6 females, 21-25 years of age) participated. Twelve of the 20 participants majored in the information sciences, six majored in other fields of science and engineering, and the

**Table 2** Time taken for reading [sec.]

	TJ	PM	<i>p</i> -value
D1	16.13 (11.06)	11.81 (9.447)	0.361
D2	20.89 (8.723)	<b>6.985</b> (3.937)	0.000555
D3	18.50 (9.939)	23.83 (17.28)	0.412
D4	32.39 (21.26)	<b>9.797</b> (4.595)	0.00839
D5	18.95 (12.19)	24.43 (20.13)	0.473
D6	31.72 (16.26)	<b>9.659</b> (5.401)	0.00186
D7	15.02 (7.258)	15.51 (15.35)	0.929
D8	54.63 (35.78)	<b>17.30</b> (14.75)	0.0101
D9	12.72 (6.337)	11.65 (8.985)	0.762
D10	15.13 (8.701)	<b>7.227</b> (5.038)	0.0257

remaining two majored in the arts or literature. We interviewed participants about color anomaly in advance and received a declaration from a participant who was a protan.

## 5.4 Environment

We used a program that displays images (produced by using Processing) and a display with a color calibration function (EIZO ColorEdge CG277 27 inch). We asked the participants to press the Enter key when they completed the reading task, and we measured the time [milliseconds] that elapsed from the start of the presentation of the visual representation. When creating a visual representation with time juxtaposing, we juxtaposed the maps in chronological order from left to right, and wrapped back to the left bottom in one row and six columns. We designed the display area to be approximately the same size (px<sup>2</sup>) although the aspect ratio differed between time juxtaposing and the proposed method.

## 5.5 Result

We summarized both the time taken for reading and the result of the responses obtained in the user study.

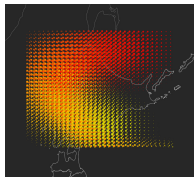
### 5.5.1 Time Taken for Reading

The summary of the time taken for reading is presented in Table 2. In Table 2, TJ and PM in the column header indicates time juxtaposing and the proposed method, respectively. The numerical values to the left of the column for each method indicate the mean values of the time taken for reading, whereas the numerical values in parentheses on the right indicate unbiased standard deviations. In order to investigate the difference in the mean values of the measurement results, we conducted Welch's t test for each dataset. In Table 2, the bold figures show that they are superior with a significant difference at the significance level  $p < 0.05$ . In all of the datasets with a significant difference, the proposed method was superior.

As shown in Table 2, the presence or absence of significant differences between the methods was clearly divided between the datasets with even and odd numbers. In the odd-numbered datasets, no significant difference was observed, but the proposed method was superior with a significant difference for the even-numbered datasets. When com-

**Table 3** Correct answer rate

	Trajectory		Speed		Shape	
	TJ	PM	TJ	PM	TJ	PM
D1	0.8	0.9	0.9	0.9	1.0	0.9
D2	0.7	1.0	0.8	0.7	1.0	1.0
D3	0.9	1.0	0	<b>0.5</b>	0.4	0.6
D4	1.0	1.0	0.7	0.7	0.6	0.3
D5	0.8	1.0	0.7	0.9	0.7	0.8
D6	0.8	1.0	1.0	0.9	1.0	1.0
D7	1.0	1.0	0.9	0.9	0.8	0.9
D8	<b>0.9</b>	0.3	0.2	0.4	<b>0.7</b>	0
D9	1.0	1.0	0.9	0.9	0.9	0.9
D10	1.0	1.0	1.0	0.9	0.8	0.8

**Fig. 6** D8 presented by the proposed method

paring the results of the two participant groups, it can be seen that the group presented with odd-numbered datasets by the proposed method generally has a large standard deviation. This suggested that the group presented with odd-numbered datasets and the proposed method had a relatively large variation in reading ability.

Even if the bias such as the difference in the variation of the participants' ability is taken into consideration, because the proposed method was not inferior with a significant difference despite exchanging the participant groups between the odd- and even-numbered datasets, it can be said that reading by using the proposed method was comparable to or faster than time juxtaposing.

### 5.5.2 Readability of Trajectories

We asked the participants to draw the trajectories of the rain clouds as arrows on the map on their answer sheets. We judged whether their responses were correct or incorrect based on whether the trajectories drawn by each participant could capture the predefined features, and compiled the correct answer rate. Table 3 summarizes these results. We conducted Fisher's exact test for each dataset. In Table 3, the bold figures show that they are superior with a significant difference at the significance level  $p < 0.05$ .

In the proposed method, the answers about the distance and direction of the movements of the rain clouds and the positional relationship with other rain clouds were accurate in all of the datasets except D8. D8 was an exception in that there were a relatively large number of misreadings by the proposed method. D8 is a dataset in which the trajectories of two rain clouds overlap in terms of their time difference. Figure 6 shows D8 that was actually presented to the participants using the proposed method. Seven of the 10 participants who read this data using the proposed method did not notice that there were two rain clouds.

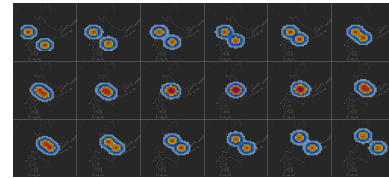
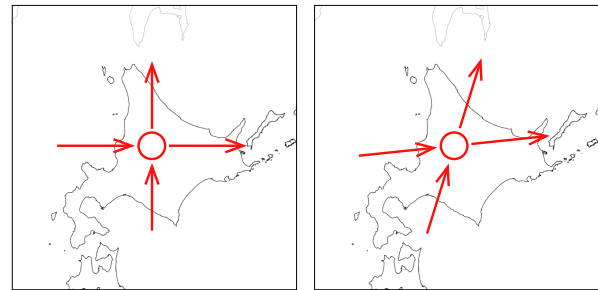
**Fig. 7** D5 presented by time juxtaposing**Fig. 8** Typical answers indicating the trajectories of the rain clouds in D5. The direction North is at the top and East is on the right. We asked the participants to draw circles to indicate places to merge or separate

Figure 8 (a), two rain clouds vertically intersect in the direction from the west to the east and from the south to the north. Eight of the 10 participants who read this data using time juxtaposing drew distorted lines in the upper right direction, and only two participants noticed that the two rain clouds were vertically intersecting. Figure 8 (b) is a typical answer using time juxtaposing in D5. Such distortions of the trajectories were seen overall, but in the scoring of this user study we treated a distorted answer as a correct answer if the distortion was not that large.

On the other hand, the answers by time juxtaposing could capture the features of the trajectories in all of the datasets, but many distorted answers were seen, and this was especially noticeable in D5. Figure 7 shows D5 as actually presented to the participants using time juxtaposing. In D5, as shown in Fig. 8 (a), two rain clouds vertically intersect in the direction from the west to the east and from the south to the north. Eight of the 10 participants who read this data using time juxtaposing drew distorted lines in the upper right direction, and only two participants noticed that the two rain clouds were vertically intersecting. Figure 8 (b) is a typical answer using time juxtaposing in D5. Such distortions of the trajectories were seen overall, but in the scoring of this user study we treated a distorted answer as a correct answer if the distortion was not that large.

### 5.5.3 Readability of Changes in Shape or Motion Speed

Regarding changes in the speed and shape (size), we prepared questions asking participants directly about preset reading items, and asked participants to answer them. We set a model answer in advance, and we scored according to whether the answer corresponded to it. A summary of the results is also provided in Table 3.

As a result of Fisher's exact test, the difference in the correct answer rate of answers relating to changes and differences in the motion speed of the rain clouds was significant in D3, and the proposed method was superior. Among the 10 datasets, D3 is the only dataset with large changes and differences in the motion speed. The other datasets have almost no change or difference in the motion speed. On the other hand, the difference between the correct answer rate of the answers about changes and differences in the shape

**Table 4** Classification of the information readable from spatio-temporal dependent data

Readable Information	Condition	Example
I1 Temporal distribution	Position & Attribute value (single)	Emergence time and duration of the time
I1' Comparison of temporal distribution	Position & Attribute value (multiple)	Order of emergence
I2 Spatial distribution	Time & Attribute value (single)	Position and shape
I2' Comparison of spatial distribution	Time & Attribute value (multiple)	Movement and deformation
I3 Attribute value	Time & Position (single)	Intensity of rain
I3' Comparison of attribute value	Time & Position (multiple)	Comparison of intensity of rain

of the rain clouds was significant in D8, and the proposed method was inferior. As explained in Sect. 5.5.2, in terms of the incorrect answer in D8, most participants did not notice that there were two rain clouds.

### 5.6 Consideration

We found that the proposed method allows the spatial changes to be read in an equal or shorter time compared to time juxtaposing. Moreover, we found that the accuracy of reading was comparable or superior except for data such as that in D8. From these results, it can be said that time juxtaposing is a method that enables a fairly accurate reading of the spatial changes by taking time, whereas the proposed method is a method that enables equally accurate reading in a shorter time.

On the other hand, when reading D8 by the proposed method, it was easy to misrecognize two trajectories as one trajectory. This revealed a weakness of the proposed method, in that it can be seen that the proposed method has low representativeness for data such as that in which multiple rain clouds have the same trajectories with time difference. When the circles representing the different times are adjacent to each other, these appear to be intermediate colors of those obtained by additive color mixing since the proposed method uses a two-color gradient for time coloring. This is considered to be the reason why the two trajectories were read as one. As this is a weak point of the proposed method, it is necessary to improve it in the future.

## 6. User Study 2: Versatility

Through User Study 1, we investigated the readability of changes in the shapes and positions of rain clouds. The spatio-temporal dependent data should enable us to read not only such spatial changes but also a variety of other information such as when and how long the rain clouds remained in a certain place, and how much rain fell in a place at a certain time. Therefore, the proposed method may be used for purposes other than reading spatial changes. Based on this possibility, we conducted another user study to investigate versatility in trying to read various types of information included in spatio-temporal dependent data.

### 6.1 Classification of the Information Readable from Spatio-Temporal Dependent Data

We classified the information that can be read from the

**Table 5** Questions in user study 2

Question (Corresponding item of Table 4)
Q1 Trajectories drawn by the center position of the rain cloud (I2')
Q2 Area covered with rain clouds at a specified time (I2)
Q3 Locations having a peak value at a specified time (I2 + I3')
Q4 Time when rain cloud first emerged at a specified location (I1)
Q5 Duration of time covered with rain clouds at a specified location (I1)
Q6 Whether the value increases or decreases after one hour at a specified location from a specified time (I3')
Q7 Which location was covered with rain cloud earlier, A or B (I1')
Q8 Which location was covered with rain cloud longer, A or B (I1')

spatio-temporal dependent data prior to this user study. The information can be classified according to which of the three attributes of spatio-temporal dependent data, time, positions and attribute values, are used as the filtering condition. In addition, it is also possible to compare such information by giving a range condition or multiple conditions. Table 4 summarizes the information readable from the spatio-temporal dependent data in this way. The example shown in Table 4 shows what kind of information of the rain clouds corresponds to each class. The comparison of the spatial distribution (I2') corresponds to the reading of the spatial changes of which the readability was examined in User Study 1.

### 6.2 Task

Based on the items classified in Table 4, we prepared eight questions and asked participants to read them one by one. The questions and the corresponding items in Table 4 are presented in Table 5. The number of each question indicates the order in which it was actually asked, and the order was set such that prefetching of other questions can be prevented.

Basically, we prepared one or more questions for every item in Table 4, besides I3. When reading information such as I3 from the visual representation generated by the proposed method, the legends of circle sizes will be needed separately from the representation and it is necessary to compare it with the circles on the map. We considered it to be the same as reading I3'; thus, we did not prepare any questions corresponding to I3. The same could be said about I1, but since there were other questions using time as a condition, we prepared the questions for it in order to examine the accuracy of the mapping between times and circles. The question Q3 set the peak value as the condition of attribute values to correspond to I2, but since it is necessary to compare the attribute values in order to find a peak value, it can

**Table 6** Answering methods and number of instances

Answering method	Number of Instances
Q1 Drawing curves	5
Q2 Drawing closed curves	5
Q3 Drawing small circles	5
Q4 Time (number)	5
Q5 Duration of time (number)	5
Q6 Bidirectional (increase or decrease)	10
Q7 Bidirectional (A or B)	10
Q8 Bidirectional (A or B)	10

be said that it is a further combination of I3’.

Since the information to be read differed in the eight questions, we set the answering methods individually. The list is shown in Table 6. Of these, for the questions to be answered by two alternatives, we prepared the option of “don’t know” separately in order to prevent accidental correct answers when those could not be read.

We conducted the user study such that all of the instances prepared for one question were answered continuously. In each instance, we presented the visual representation for a certain period of time. The participants were asked to concentrate on reading the representations and then to write their answer on an answer sheet after the representation disappears. In User Study 1, we did not set any limits in terms of the time to display the representation, and measured the time until the participants finished reading. However, in User Study 2, we used only the accuracy for evaluation by setting limits for the time to display the representation. The reason why we used only the accuracy was to avoid noise due to the difference in participants’ diligence by limiting the time available for reading. Furthermore, in order to investigate the difference in accuracy in more detail than in User Study 1, we set up evaluation criteria to compare scores instead of assessing whether an answer was correct or incorrect.

Due to the difference in the scoring methods, the number of instances we asked varied according to the question. We prepared the instances of the number shown in Table 6 for each method. In addition, in order to achieve a counterbalance, we changed the order in which participants were required to use the methods. In each question and method, before asking the participants to work on the instances to be evaluated, we asked them to work on a training instance and to think how to read the answers to questions in a short time. Moreover, at the beginning of the user study, we asked the participants to work on practice tasks to familiarize themselves with the visualization methods.

### 6.3 Presented Data

We prepared 10 sets of pseudo rainfall intensity data different from the data used in User Study 1. We generated rainfall intensity data such that one or two circular rain clouds existed in the space. We informed the participants of the above facts before starting the user study.

In User Study 1, only for D8 were there many misreadings when using the proposed method. In that dataset

**Table 7** Data types presented in user study 2

Feature
T1 One rain cloud
T2 Two rain clouds, trajectories do not intersect
T3 Two rain clouds, trajectories intersect
T4 Rain clouds branch from one to two or vice versa
T5 Two rain clouds follow the same trajectories with time difference

the trajectories of two rain clouds were particularly different from those in other datasets. We estimated that the accuracy of reading varies depending on the complexity of the trajectories of the rain clouds. Therefore, in this user study, we prepared the datasets by dividing them into five data types by the complexity of the trajectories of the rain clouds and investigated the effect of the proposed method for each data type. The setting of the five types is presented in Table 7. Among them, T5 corresponds to the data of which the spatial changes were often misread when using the proposed method in User Study 1.

There are two different datasets for each data type. In order to obtain trials by both methods from the same participant in all of the data types, we presented the two different datasets to the participant using different methods. As a result, the difference in the methods within a data type is taken as the within-subject factor. Moreover, in order to obtain trials by both methods in all of the datasets, we changed the mappings between datasets and methods depending on participants. Basically, we asked one instance for each dataset, but we asked two instances for each dataset for questions of which the number of instances is ten in Table 6.

As explained in Sect. 5.2, we set  $N_x$  and  $N_y$  to 32 and  $N_t$  to 18 in the data generation. Although we did not inform participants of the time interval of the data in User Study 1, we informed them that it would be 1 hour in this user study. However, we changed the time of the first of the time series depending on the datasets in order to prevent the participants from learning the correspondence between times and positions or colors.

### 6.4 Participants

Twenty undergraduate and graduate students (18 males, 2 females, 21-24 years of age) participated. Fifteen of the 20 participants majored in the information sciences, three majored in other fields of science and engineering, and the other two majored in the arts or literature. There was no declaration of color anomaly, and no duplication of the participants between User Study 1 and User Study 2.

### 6.5 Environment

We used a program in which the visual representation was presented for 12 seconds after counting down for three seconds after the Enter key was pressed. By the program, if conditions such as time and locations were designated for reading, it was displayed to the left side of the screen. The participants were able to check it before they press the Enter



**Table 8** Results of scoring the answers for Q1–Q3

		T1	T2	T3	T4	T5	Total
Q1	TJ	5.35 (2.14)	4.43 (2.18)	2.18 (1.91)	3.93 (1.87)	3.72 (2.33)	3.92 (2.30)
	PM	<b>7.92</b> (1.88)	7.00 (1.33)	<b>7.70</b> (1.68)	<b>6.58</b> (1.83)	4.17 (1.91)	6.67 (2.17)
Q2	TJ	<b>7.55</b> (1.06)	<b>6.75</b> (2.10)	<b>6.60</b> (1.78)	<b>7.32</b> (1.54)	<b>6.73</b> (1.77)	6.99 (1.69)
	PM	2.33 (1.77)	3.15 (1.29)	3.17 (1.60)	3.45 (1.70)	3.38 (1.82)	3.10 (1.66)
Q3	TJ	8.10 (1.86)	<b>7.75</b> (1.43)	<b>7.82</b> (1.28)	8.92 (1.01)	8.17 (1.03)	8.15 (1.39)
	PM	4.40 (2.80)	3.33 (2.26)	3.28 (2.21)	3.82 (2.81)	2.68 (1.81)	3.50 (2.43)

**Table 9** Deviations between the answers and the correct answers in Q4 and Q5 [hour(s)]

		T1	T2	T3	T4	T5	Total
Q4	TJ	0.55 (1.23)	0.20 (0.70)	0.40 (0.50)	0.45 (0.51)	1.75 (3.51)	<b>0.67</b> (1.78)
	PM	1.45 (1.70)	1.65 (1.39)	2.35 (2.41)	1.25 (1.29)	1.95 (1.61)	1.73 (1.73)
Q5	TJ	0.60 (0.68)	<b>0.60</b> (0.82)	<b>1.80</b> (1.01)	0.70 (0.73)	3.55 (2.37)	1.45 (1.71)
	PM	1.10 (1.45)	1.30 (0.80)	4.90 (2.45)	1.05 (1.05)	4.00 (2.53)	2.47 (2.42)

**Table 10** Number of the correct answers for Q6–Q8

	Q6	Q7	Q8
TJ	<b>8.35</b> (1.39)	<b>9.35</b> (0.745)	6.95 (1.76)
PM	5.80 (1.79)	8.95 (0.759)	<b>8.35</b> (1.95)

key, during the countdown, and while the visual representation was being displayed. We set the time of 12 seconds based on the average reading time of 12.78 seconds for the answers in which all of the items were correctly read by the proposed method in User Study 1. In this user study, we wanted to investigate the superiority and inferiority of the proposed method after demonstrating its performance to some extent; thus, we set the time limit on aforementioned basis.

Because selected questions asked the time as a numerical value in this user study, we presented the time by a 24-hour clock in the bottom right of each map in time juxtaposing, and we presented the legend of the mappings of color and time on a 24-hour clock to the right of the map in the proposed method. In the two methods, we used areas of almost the same size for the display including the legend.

6.6 Result

Table 8, 9, and 10 summarize the scoring results of the answers obtained in this user study.

Because in Q1–Q3, we asked the participants to draw shapes on the map, we asked three people who did not participate in the user study to score the grades in eleven steps from 0 to 10 points based on the similarity of the answer to the example in the correct answer prepared beforehand. Table 8 shows the mean values of the scores, with the larger

value indicating greater accuracy. The values in parentheses indicate unbiased standard deviations.

In Q4 and Q5, we asked the participants to answer by providing time or the duration of time. Table 9 contains the mean values of the absolute value of the difference [hours] from the correct answer. Therefore, in this case the smaller value indicates greater accuracy. As in Table 8, the values in parentheses indicate unbiased standard deviations.

In Table 10, because the answers for Q6–Q8 are either correct or incorrect, the mean values and unbiased standard deviations of the number of correct answers of the 10 instances asked in each method are shown.

In Q1 to Q5, in addition to the within-subject factors of the data types and the visualization methods, because the subject group is divided by the mappings between the data and the methods, there are three factors in total. Therefore, in order to test the difference in the mean values due to the difference in each factor, we carried out a three-way repeated measure analysis of variance (RMANOVA). Because we considered the possibility that the assumption of multi-sample sphericity is not satisfied, we adjusted the degree of freedom by the Greenhouse-Geisser correction before calculating the *p*-value for within-subject factors. We set the significance level as *p* < 0.05. In Table 8 and Q5 in Table 9, the mean values that are superior are indicated in bold in the data types corresponding to the following data types as the results of the three-way RMANOVA.

- The data types with a significant simple main effect of the methods, if there was no three-way interaction and there was two-way interaction of the methods × data types (Q2, Q5)
- The data types with a significant simple main effect of the methods and no simple interaction of the methods × participant groups, if there was three-way interaction (Q1, Q3)

In Q4, since the main effect of the methods was significant, the superior total mean values are indicated in bold. If the mean values are shown in bold letters, the effect of the difference in the methods can be admitted.

On the other hand, in Q6–Q8, because the scores were aggregated across the data type, there were two factors, visualization methods and participant groups. Therefore, we conducted two-way RMANOVA for the results of those questions, and no interaction was observed in all of them, and the main effect of the methods was significant at the significance level *p* < 0.05. Again, we considered the possibility that the assumption of multi-sample sphericity is not satisfied, we adjusted the degree of freedom by the Greenhouse-Geisser correction before calculating the *p*-value for visualization methods. In Table 10, the superior mean values are shown in bold.

6.7 Consideration

First, in the question about the temporal distribution, the proposed method was superior only in Q8 among the four

questions Q4, Q5, Q7, and Q8. Time juxtaposing was superior in the remaining three. We set these four questions such that the time taken for reading became longer as the question number was larger when using time juxtaposing. In order to read the answers to these questions accurately using time juxtaposing, it was necessary to judge in chronological order whether a specific location was covered with rain cloud on each map. In Q4, it was only necessary to find the first time a specified location was covered with the rain clouds, but in Q8 it was necessary to count all of the times there was coverage with rain clouds in two locations. The proposed method was superior only in Q8 for such question settings. Thus, the proposed method could be expected to be superior in questions other than Q8 if the presentation time is further shortened or the length of the time series of the data to be presented is increased. Because the proposed method is ambiguous in representing time as it represents time by color, it is inferior to time juxtaposing in terms of accurate reading of a temporal distribution. However, the proposed method does not require two or more maps to be traced. If approximate values are allowed, the proposed method allows such temporal information to be read without taking much time regardless of the length of time series. Therefore, even when reading a temporal distribution, the proposed method can be considered advantageous if the comparison task is performed under such conditions.

Next, for the question about the spatial distribution, the proposed method was superior only in Q1 of Q1 and Q2, and the time juxtaposing was superior in Q2. As Q1 corresponded to reading spatial changes, it was confirmed that the proposed method was useful also in terms of accuracy in addition to the time taken for reading the spatial changes. On the other hand, when looking at each data type, a part lacking in accuracy was seen in the data belonging to T5, the data type in which the two rain clouds follow the same trajectories with time difference. By checking the answers actually drawn by the participants, we found that the proposed method was more misleading with respect to the number of rain clouds. This result indicates a weak point similar to that found in User Study 1. However, because no significant difference in the scores was found in the comparison with time juxtaposing and the evaluation criteria of User Study 1 did not sufficiently consider the distortion of the trajectories, it was determined that neither of the two methods is inferior when we consider the distortion of the trajectories to indicate accuracy. In Q2, a time was specified as a condition for reading; thus, it was a question in which the participants first had to identify which circle corresponds to that time. As with I1, the proposed method is ambiguous in mapping between color and time. This suggested that the circles to be read could not be correctly recognized when using the proposed method. Regarding T5, there were many answers who mistook the number of rain clouds, also in Q2. In Q2, even if the color of read circles deviated somewhat from the color of a specified time, it should not negatively affect reading the number of rain clouds if all of the circles with the same color were read. However, the fact that it was wrong means that

**Table 11** Versatility of proposed method

Suitability	
I1 Unsuitable	Cannot be read accurately
I1' Partially Suitable	Cannot be read accurately, but suitable when reading in a short time or reading data with long time series
I2 Unsuitable	Cannot correctly recognize the circle to be read (depends on I1)
I2' Suitable	Can be read accurately
I3 Unsuitable	Cannot correctly recognize the circle to be read (depends on I1)
I3' Unsuitable	Cannot correctly recognize the circle to be read (depends on I1)

the distributions of the rain clouds for each point in time were not correctly read; in other words, all of the circles representing the same time were not completely recognized. The reason for this is considered to be that the color difference between different times was not particularly secured in the proposed method, and it is thought that it also affected the results of Q1 and User Study 1.

Finally, in the question about the attribute value, time juxtaposing was superior in both of Q3 and Q6. In these two questions, since the time was specified as a reading condition as in Q2, in the proposed method, because the mapping between color and time was ambiguous, it is considered that the circle to be read could not be recognized correctly and this was disadvantageous.

Based on the above considerations, we summarized the suitability of the proposed method for presenting various information included in spatio-temporal dependent data. Table 11 presents the summary.

## 7. Conclusion

We developed a visualization method that represents spatio-temporal dependent data on a single static map. The proposed method aimed to facilitate reading spatial changes of spatio-temporal dependent data. The proposed method aggregates time series data for each region divided by a certain size and represents it using multiple circles. We investigated the usefulness of the proposed method by using two experiments to compare it with time juxtaposing. As a result, it was shown that the spatial changes could be read more accurately in a shorter time using the proposed method; therefore, it can be said that the proposed method is useful for reading spatial changes. In addition, it was found that the reading accuracy hardly depends on the conditions such as the time available for reading and the length of time series of data if using the proposed method, although accuracy may be lost when reading temporal distribution or other information based on temporal distribution. Therefore, the proposed method can be expected to be applied to risk communication through media that cannot be viewed for a long time, such as a car navigation system or a public display.

In this study, we found that the proposed method was limited in terms of reading spatial change in data with certain features. We are working on overcoming the weakness

by introducing animation into the proposed method and extending it to a semi-static representation method [8].

### Supplementary Explanation

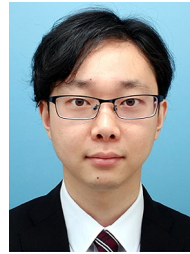
We reused Fig. 1, Fig. 2, Fig. 6, and Fig. 7 from a technical report we previously published [9]. We reused Fig. 4 and reused with realignment sub-figures Fig. 5 and reused with translation Fig. 3 from a university undergraduate thesis of Chiba [10]. The text and each table besides Table 3 were re-edited based on our research report, the Master's thesis of Hyogo [11], and the university undergraduate thesis of Chiba.

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**Hiroki Chiba** is currently a student in the School of Informatics, University of Tsukuba, Japan. His research interests include human-computer interaction, information visualization, geographic visualization. He is a student member of the IPSJ.



**Yuki Hyogo** received his bachelor's degree in Information Engineering from the University of Tsukuba in 2014. He received his master's degree in Engineering from the University of Tsukuba in 2016. He currently works for Dentsu Isobar Inc., a digital marketing agency based in Tokyo, Japan. His research interests include information visualization, geo-spatial data processing, and analyzing lifelog data.



JSAI, and JSSST.

**Kazuo Misue** is a Professor in the Faculty of Engineering, Information and Systems, University of Tsukuba, Japan, where he performs research and development in information technology. His research interests include human-computer interaction, information visualization, automatic graph drawing. He received BSc and MSc degrees from Tokyo University of Science in 1984 and 1986. He received a Ph.D. in engineering from the University of Tokyo in 1997. He is a member of the ACM, IEEE, IEICE, IPSJ,