Short Papers

An Evaluation of Space Time Cube Representation of Spatiotemporal Patterns

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Abstract—Space time cube representation is an information visualization technique where spatiotemporal data points are mapped into a cube. Information visualization researchers have previously argued that space time cube representation is beneficial in revealing complex spatiotemporal patterns in a data set to users. The argument is based on the fact that both time and spatial information are displayed simultaneously to users, an effect difficult to achieve in other representations. However, to our knowledge the actual usefulness of space time cube representation in conveying complex spatiotemporal patterns to users has not been empirically validated. To fill this gap, we report on a between-subjects experiment comparing novice users' error rates and response times when answering a set of questions using either space time cube or a baseline 2D representation. For some simple questions, the error rates were lower when using the baseline representation. For complex questions where the participants needed an overall understanding of the spatiotemporal structure of the data set, the space time cube representation resulted in on average twice as fast response times with no difference in error rates compared to the baseline. These results provide an empirical foundation for the hypothesis that space time cube representation benefits users analyzing complex spatiotemporal patterns.

Index Terms—Information visualization, evaluation/methodology, space time cube.

1 Introduction

The space time cube is an information visualization technique that displays spatiotemporal data inside a cube (sometimes called an "aquarium") [8]. The height axis is used to denote time. The space time cube was originally proposed by Hägerstrand in the early 1970s in a seminal paper on time geography [7] and has since then been mainly used to display geospatial data [9]. The space time cube representation has been proposed by Kraak [6] and others [3], [5] as a tool in spatiotemporal visualization [3], [5], [6]. Recent applications of space time cube representation include geospatial visualization [3], [5], [6], and visualization of sport [10]. Fig. 2 shows an example of space time cube representation.

Information visualization researchers have stated that the theoretical advantage of the space time cube is the ability to efficiently convey complex spatiotemporal patterns to users [3], [5], [6]. The argument is based on the fact that space time cube representation presents users with the full spatiotemporal data set in a single view, in contrast to traditional 2D displays where complex spatiotemporal information is often conveyed using time slider controls, animation, or resolution-limited pseudocolor sequences [14].

However, before we research and build complex space time cube applications, a solid understanding of the costs and benefits of presenting users with space time cube representation is desirable. To our knowledge, no formal empirical experiment comparing space time cube against a baseline 2D visualization has been carried out. Hence, we do not know if there is any empirically supported advantage in using space time cube representation. As has recently been argued in the literature (e.g., [15]), evaluation is an important contribution toward changing some parts of the information visualization field into a "hard" science.

1.1 Contributions

In this paper, we present empirical results of a baseline comparison investigating users' ability to quickly and correctly answer a set of questions in varying difficulty and complexity about a data set in the continuous spatiotemporal domain.

We provide empirical data that highlight the trade-offs in space time cube representation. Our results show that space time cube representation results in more errors for novice users answering a category of "simple" questions such as "Are two persons at the same place at 9:00?" More interestingly, the results also reveal that using space time cube representation the average response times were reduced from 121 to 60 seconds when novice users were asked to answer questions that required an overall understanding of the spatiotemporal patterns in the data set. The latter result supports the claim that space time cube representation is advantageous in conveying complex spatiotemporal data to users. Further, it motivates research and evaluation of new space time cube representations for a plethora of application domains.

1.2 Research Questions

Given the lack of foundation from previous empirical research results, we decided to focus this investigation on the most fundamental questions:

1. Can novice users understand and use a space time cube system effectively after a short amount of practice?
2. Are there measurable performance differences in terms of error rates and response times between a space time cube system and a baseline 2D system?
3. Are there measurable performance differences in terms of error rates and response times between a space time cube system and a baseline 2D system for specific categories of questions?

The two dependent variables were error and response time. The error variable measures if users understood the data set under a particular visualization. Response times show how long it took participants to make an informed decision using a particular visualization.

We decided to concentrate on novice users for the following reasons. First, it is hard to find expert users that have proficiency in either a space time cube system, or in another visualization system that can be used as a suitable baseline [13]. Most likely, expert users have varying knowledge of a collection of different visualization systems and tools. This makes it difficult to directly compare two systems. Second, if we can show that space time cube representation is advantageous to novice users, this would provide a useful empirical building block: researchers then know that novice users understand space time cube representation relatively

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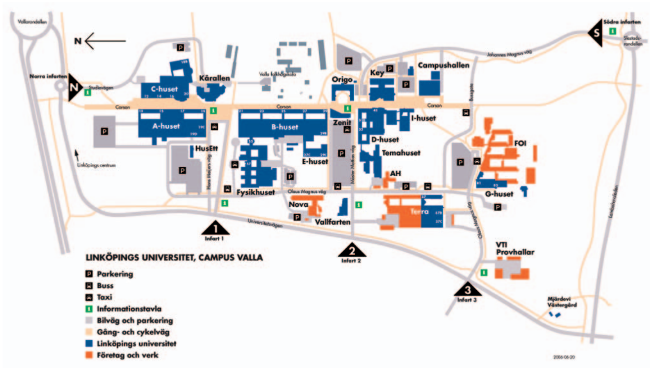

Fig. 1. The campus map used in the experiment (in Swedish). This campus map is the official campus map. It is used by the university in brochures, on the Web, and on notice boards.

quickly and can easily recruit nonexpert participants for many different experimental setups. Third, if novice users are shown to use space time cube representation effectively, there is no reason to believe expert users would not be able to do the same. In fact, expert users are perhaps better.

Note that we do not rule out the possibility of a study of expert users' experience with space time cube representation. However, we do believe such a study is probably more interesting from another perspective, for example, to study *how* expert users analyze complex spatiotemporal patterns.

2 Domain

We decided to use human walking traces overlaid on a schematic of a university campus area as our domain. Fig. 1 shows the campus map. Note that we cropped the outside areas of the map (e.g., road entrances). Clearly, the map choice may affect experimental results. Different maps can be designed for many different purposes, and no map is "perfect" unless (possibly) it is specifically tailored for a particular set of analytic questions. We settled on using the official campus map that was designed by university staff and has been in use on, for example, notice boards all over the campus for many years. We chose a walking data analysis application given recent research interest in human mobility patterns [4] and social visualization. For example, Aipperspach [1] describes recent work on visualizing walking data. We acquired the walking data by tracking volunteer students' movement along the campus during a day.

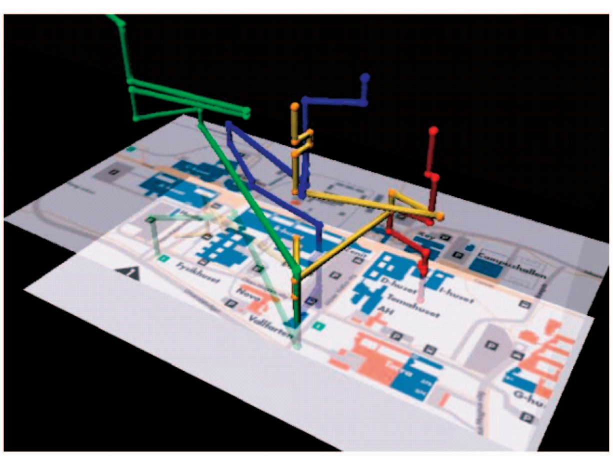

Fig. 2. Human walking data visualized in the space time cube system that we developed. Different colors represent different persons. When a person stands still, the trace segment is perpendicular to the map plane.

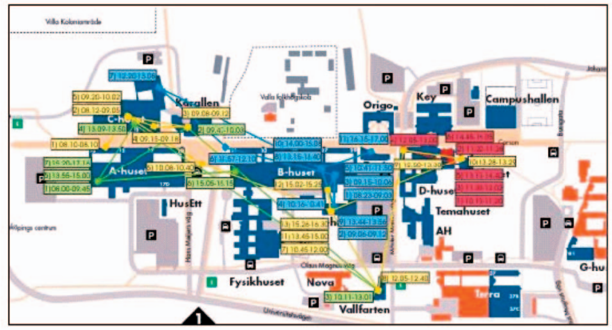

Fig. 3. Human walking data visualized in the baseline 2D system that we developed. Different colors represent different persons. The labels show the start and end times for a person at a specific time point in the map. In the figure, the labels have been turned on. Labels can be turned on and off with the press of a key.

3 Systems

A dilemma when comparing a visualization method (such as space time cube representation) with another is the choice of a suitable baseline. Clearly, no baseline representation will ever be "fair" from all perspectives of information visualization. This dilemma makes costly empirical experiments risky and may be a factor influencing the limited number of user studies in the information visualization field [13]. In the rest of this section, we first explain the design space we explored for our 2D baseline system, then we present the space time cube and 2D baseline systems that we developed.

In some specific instances, researchers can compare different interfaces such as 2D and 3D against each other using the same system. For example, in [12], search results were visualized in text, 2D, and 3D. Sebrecths et al. approached the "fairness dilemma" by constructing the 2D interface by simply flattening their 3D interface.

With regard to space time cube representation, we believe that *some* approach needs to be taken to gain any clarity in the issue. However, unlike the search results task used in Sebrechts et al. [12], the more complex task of assessing users' overall understanding of spatiotemporal data does not lend itself toward a direct comparison of 2D versus 3D. This is because space time cube conveys information to users along each of the three axes, and a "2D space time cube" would therefore need to collapse one axis (say the time axis) and thereby be unable to convey critical information to users. Therefore, we decided to create a fair baseline based on assumptions inherent in the hypotheses that we set out to answer with our experiment, rather than creating a 2D baseline that is as closely related to the 3D (space time cube) system as possible.

We focused on a comparison where both the 2D baseline and the space time cube representations aimed at providing users with an overall understanding of the spatiotemporal patterns in the data set. After all, it is precisely this advantage of space time cube representation that is most often argued in the literature [3], [5], [6]. We rejected time sliders and animations that partition the temporal dimension of data sets into discrete time steps, because users cannot get an overview of the data set at a glance with such representations. We also decided not to use sophisticated color scales to reveal time information, given the limitation of granularity with ordinal pseudocolor sequences [14]. After considering all the above options, we compromised for an approach where critical time points in 2D are indicated with semantic markup (text), see Fig. 3. This choice gives users the ability to perceive an overview of the spatiotemporal patterns at a glance, even in 2D. Note that the labels (markup) in Fig. 3 can quickly be turned on or off by the user by pressing a key on the keyboard.

Both the space time cube system and 2D baseline system are interactive. With the space time cube system, users can pan, rotate, and zoom in and out. With the baseline 2D system, users can toggle the display of time labels, pan, and zoom in and out of a portion of the map.

It is important to note that the purpose of the baseline 2D system is to provide the space time cube representation with a reasonable *baseline*. That is, the space time cube should preferably beat the baseline in at least some aspect to merit further research by the information visualization community. The purpose of the 2D baseline system is not to investigate how 2D visualization can be made more effective. This in itself is an interesting research question but out of the scope of this paper.

3.1 Space Time Cube System

To perform our investigation, we developed a space time cube system capable of rendering walking data traces inside a cube (see Fig. 2). The system has a "measurement" plane that can be moved up and down along the height axis to make it easier to read when a particular event occurred. The exact time of the measurement plane's current position is displayed to the right of the space time cube's display area (not shown in Fig. 2).

The space time cube system is controlled via either the keyboard or a graphical user interface (GUI). Using the GUI or a keyboard, the user can rotate, zoom, and move the measurement plane up or down.

3.2 Baseline 2D System

The baseline 2D system displays walking data traces using different colors (green, blue, yellow, red; see also Fig. 3). The colors were the same as in the space time cube system.

The colored line traces indicate different persons, and the labels indicate the start and end times for a person at a specific point in the map. Users can toggle the display of labels and zoom in and out with the keyboard.

4 METHOD

We used a between-subjects experimental design where participants were exposed to one of two conditions: either the space time cube system or the baseline 2D system.

Often within-subjects experimental design is preferable since 1) variation between conditions is controlled within the participant; and 2) generally, a smaller number of participants are required. However, in this experiment, it is plausible that participants become increasingly familiar with the material and task during the experiment. With a within-subjects design, there is a risk that one condition (call it condition A) better aids participants in understanding the material and the task than the other condition (call it condition B). This asymmetrical skill-transfer effect would in fact penalize the performance of condition A when preceded by condition B and unfairly benefit condition B when preceded by condition A. To avoid this confound, a between-subjects design was used, and the number of participants in the experiment was increased accordingly $(n = 30)$.

4.1 Participants

Thirty participants, 15 male and 15 female, were recruited from the university campus. The participants were screened for color blindness. None had any previous experience in using information visualization tools. The two groups were gender balanced to the extent possible.

4.2 Apparatus

The experiment was conducted on two laptops with $15''$ screens and 32-bit color depth. Although the physical dimensions of the laptop screens were identical, the screen resolution varied slightly in the vertical dimension. The first laptop had a screen resolution of 1,280 $\times$ 1,024 while the second laptop had a screen resolution of 1,280 $\times$ 800. The laptops were balanced between the conditions.

4.3 Material

To assess the participants' understanding of the data set, a set of 15 questions was designed. The questions were grouped into four different question categories of varying difficulties and complexities according to Andrienko et al. [2]. Along with a description of each question category, we supply an example from the material used in the conducted study (translated from Swedish).

4.3.1 *Question Category 1*

Simple "when" and simple "what + where": describes an object's property at a given point in time, e.g., "Where is the red person at 14:00?"

4.3.2 *Question Category 2*

Simple "when" and general "what + where": describes the situation at a given point in time, e.g., "Are any two persons at the same place at 9:00?"

4.3.3 *Question Category 3*

General "when" and simple "what + where": describes an object's characteristics over time, e.g., "Which buildings are visited by the yellow person during the day?"

4.3.4 *Question Category 4*

General "when" and general "what + where": describes the development of an entire situation over time, e.g., "Who is on the campus area for the longest time?"

Fifteen questions were used in the experiment. Question categories 1-3 had four questions, question category 4 had three questions.

The questions were graded as either "correct" or "incorrect" based on a predefined marking scheme.

4.4 Procedure

The participants were divided into two gender-balanced groups. One group used the baseline 2D system while the second group used the space time cube system. The experiment consisted of two sessions: a practice session and a testing session. After the two sessions, participants were interviewed. The experiment was designed to require a maximum of 1 hour of participants' time.

4.4.1 *Practice Session*

Participants were asked to answer a set of written questions with the help of either system (space time cube or the baseline 2D system). The practice session lasted around 20 minutes. The domain and the questions used for the practice session were different from the material in the testing session. In the practice session, lightning strike data were used. The space time cube system visualized lightning strikes as small red spheres in the cube. The practice 2D system used a corresponding system generously provided by the Swedish Meteorological and Hydrological Institute (SMHI). The purpose of the practice session was to introduce information visualization tools to the participants and get them used to answering spatiotemporal questions with the help of the system under investigation. The systems used in the practice session were not designed to be directly comparable against each other. Therefore, we do not report the results from the practice session.

4.4.2 *Testing Session*

After a brief break, participants proceeded with the testing session. The domain used in the testing session was the human walking data, explained earlier in Section 2. The procedure in the testing session was otherwise identical to the one used in the practice session.

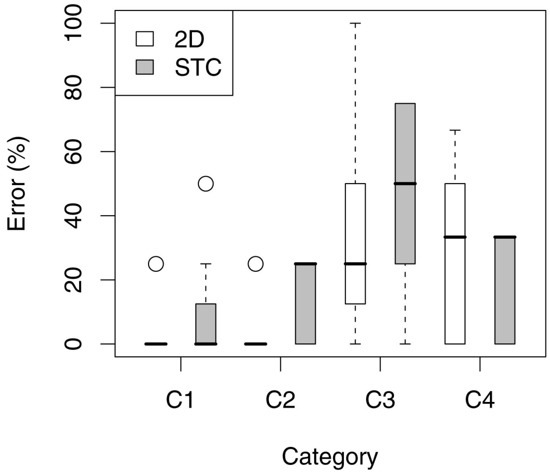

Fig. 4. Box-and-whisker plot of error rate (in percent) as a function of question category. STC stands for space time cube.

5 RESULTS

All statistical tests in this paper were carried out using analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. Assumptions underlying the ANOVA procedure were taken into account before performing any significance testing. We did not apply any transformations to the data (such as logarithmic transformations) when testing for significance.

5.1 Error

Obtained error rates (and their residuals) were not normally distributed (cf. Fig. 4). This does not necessarily imply that the population distribution was not normal. Related, the homogeneity of variance assumption was not met (cf. Table 1). However, ANOVA is rather robust against such violations, as long as both groups have the same sample size. Therefore, rather than employing a weaker nonparametric test (e.g., Kruskal-Wallis), we proceeded to use ANOVA to determine significances in error rates. Table 1 lists the error rate statistics for all the four individual question categories.

Error rates were lower with the baseline 2D representation for the simple question categories 1 and 2 that asked about objects' properties, or a situation, at a given time. For these question categories, the baseline 2D system had close to zero percent error rate (Fig. 4). In question category 2, the baseline 2D system resulted in significantly fewer errors $(F_{1,28} = 9.800, p = 0.0041)$. Error rates were particularly high in question category 3, but no statistical significant difference between the systems was found $(F_{1,28} = 2.3430, p = 0.1371)$. Question category 4 was unique in the sense that the space time cube had a lower average error rate in comparison to 2D (31 percent for the 2D baseline system versus 20 percent for the space time cube). However, the difference was not significant $(F_{1,28} = 1.8622, p = 0.1832)$. From the results, it is clear that participants found it harder to answer questions in categories 3 and 4 (cf. Fig. 4).

These results are somewhat expected since the participants were novice users of visualization tools and only had a single session of practice before the testing session. The fact that there was no statistical difference found between the baseline 2D and space time cube system in neither question category 3 nor category 4 suggests that the higher error rates can most likely be attributed to the difficulty increase of the question answering task in general, rather than a particular deficiency in either system. Surprisingly, error rates are more pronounced for question category 3 than category 4, even though questions in category 4 demand much more understanding of the data set than questions in category 3.

TABLE 1
Error Rate Statistics

	2D		STC			
Cat.	Mean	sd	Mean	sd	F	p
1	1.67	6.46	10.00	18.41	2.7344	0.1094
2	1.67	6.46	13.33	12.91	9.800	0.0041
3	33.33	29.38	48.33	24.03	2.343	0.1371
4	31.11	26.63	20.00	16.90	1.8622	0.1832

From left to right: The question category (1-4), the mean and standard deviation for each representation (2D baseline and space time cube), the F-score, and the p-value. STC stands for space time cube.

Fig. 5 plots the error rate for individual participants in each condition for question categories 1-4, ranked by performance (top performer using baseline 2D representation against top performer using space time cube representation, and so on). Question category 4 in Fig. 5 is particularly interesting because this question category concerns the most difficult questions on the data set. Note that, for question category 4 in Fig. 5, at all corresponding ranking positions, every participant that used space time cube representation consistently had the same or lower error rate than his or her counterpart who used the baseline 2D representation.

5.2 Response Time

Table 2 and Fig. 6 summarizes the response times for all the individual question categories.

We found a high-magnitude statistically significant difference in question category 4 where space time cube representation halved the average response time from 121 seconds in the baseline 2D system down to 60 seconds $(F_{1,28} = 6.957, p = 0.0135)$. This result supports the hypothesis that space time cube representation is efficient in supporting users' understanding of complex spatiotemporal patterns in data sets.

Fig. 7 plots the response times for individual participants in each condition for question categories 1-4, ranked by performance. As can be seen in question category 4 in Fig. 7, at all corresponding ranking positions, every participant using space time cube representation consistently outperformed his or her counterpart using baseline 2D representation.

5.3 Open Comments

Participants gave us some open comments at the interview part in the experiment. When interpreting these comments, it is important to keep in mind that participants had only experienced one representation.

The baseline 2D system was perceived as easy, interesting to use, and "fun," and participants thought it had a "professional" feel. Eight participants stated that they thought the interconnected lines (walking paths) made the visualization easier to interpret, one participant stated the opposite.

Space time cube representation was perceived as intuitive, engaging, easy to understand, and "cool." Three participants stated difficulties with using the measurement plane (along the time axis). Eight participants explicitly stated that they had no problem manipulating the measurement plane.

6 DISCUSSION

In relation to the research questions that we posed in Section 1, we found that novice users could indeed work effectively with the space time cube representation after a short amount of practice. Overall, there are no measurable performance differences in neither error rates nor response times between the space time cube system and the baseline 2D system. However, in individual question categories, we found significant differences in both error rates and response times.

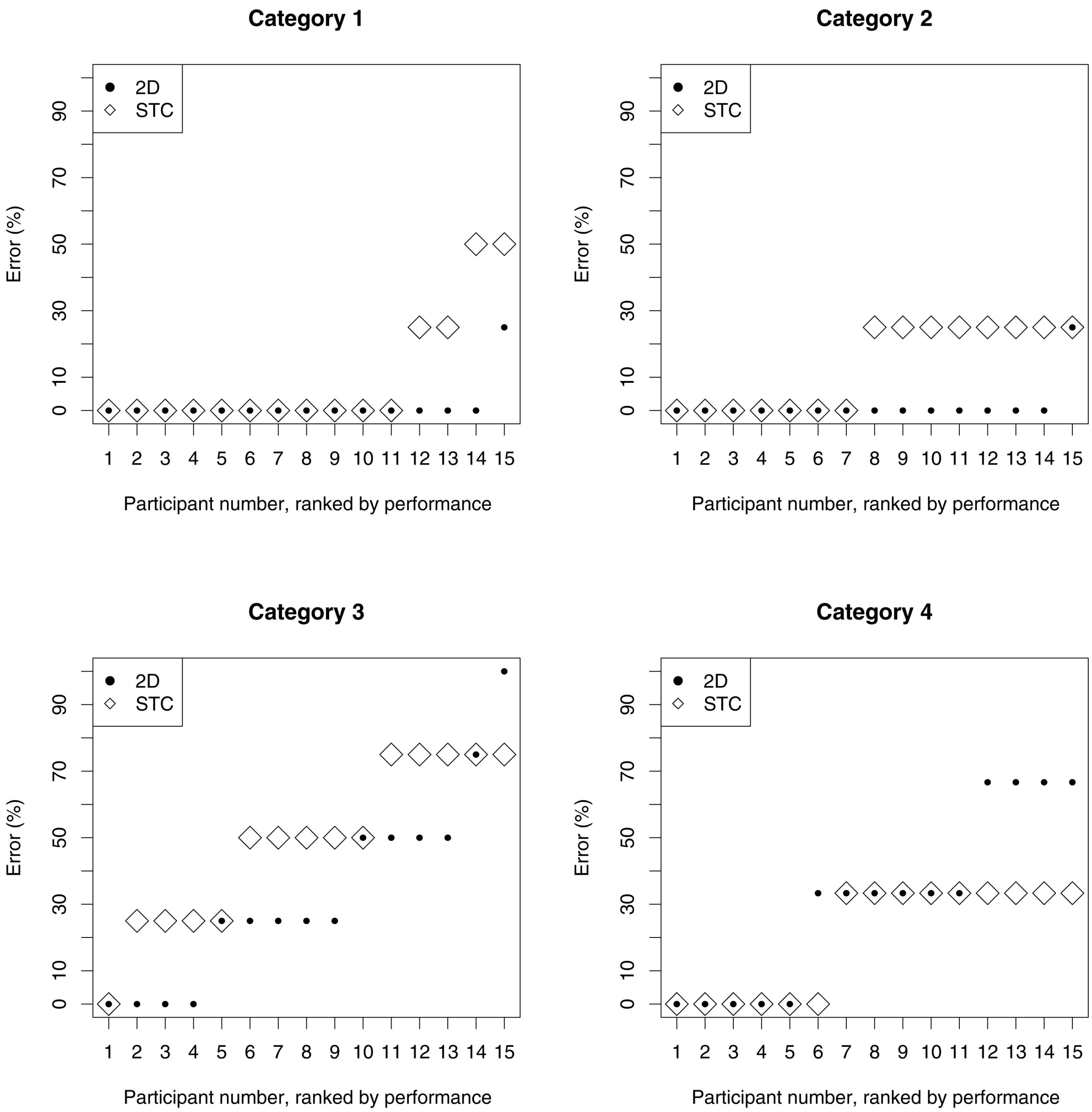

Fig. 5. Error rate (in percent) for question categories 1-4 as a function of participant number, ranked by performance. Some data points overlap in the figure. STC stands for space time cube.

It has been argued that the real benefit of the space time cube is in supporting users when observing nontrivial spatiotemporal patterns that require a "bird's-eye" view of the data set [3], [5], [6]. The dramatic reduction in response times for the most complex and demanding questions in category 4 supports this hypothesis. We hope this result stimulates further investigation and design of space time cube systems.

TABLE 2
Response Time Statistics

	2D		STC			
Cat.	Mean	sd	Mean	sd	F	p
1	36.57	16.65	45.77	16.37	2.326	0.1384
2	67.74	24.05	55.30	15.07	2.8835	0.1006
3	60.02	17.51	82.73	39.80	3.8563	0.0599
4	120.64	83.32	60.34	29.95	6.9571	0.0135

From left to right: The question category (1-4), the mean and standard deviation (in seconds) for each representation (2D baseline and space time cube), the F-score, and the p-value. STC stands for space time cube.

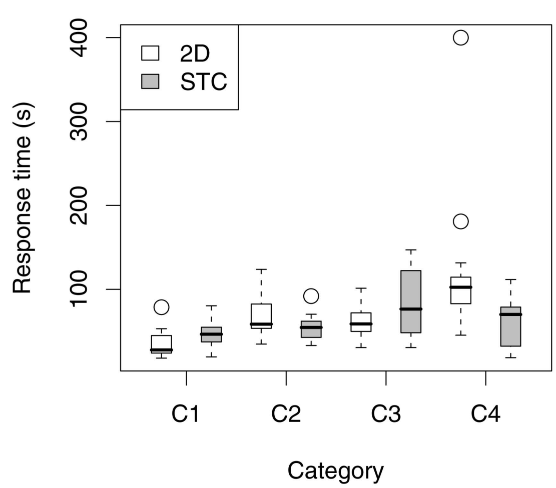

Fig. 6. Box-and-whisker plot of response time (in seconds) as a function of question category. STC stands for space time cube.

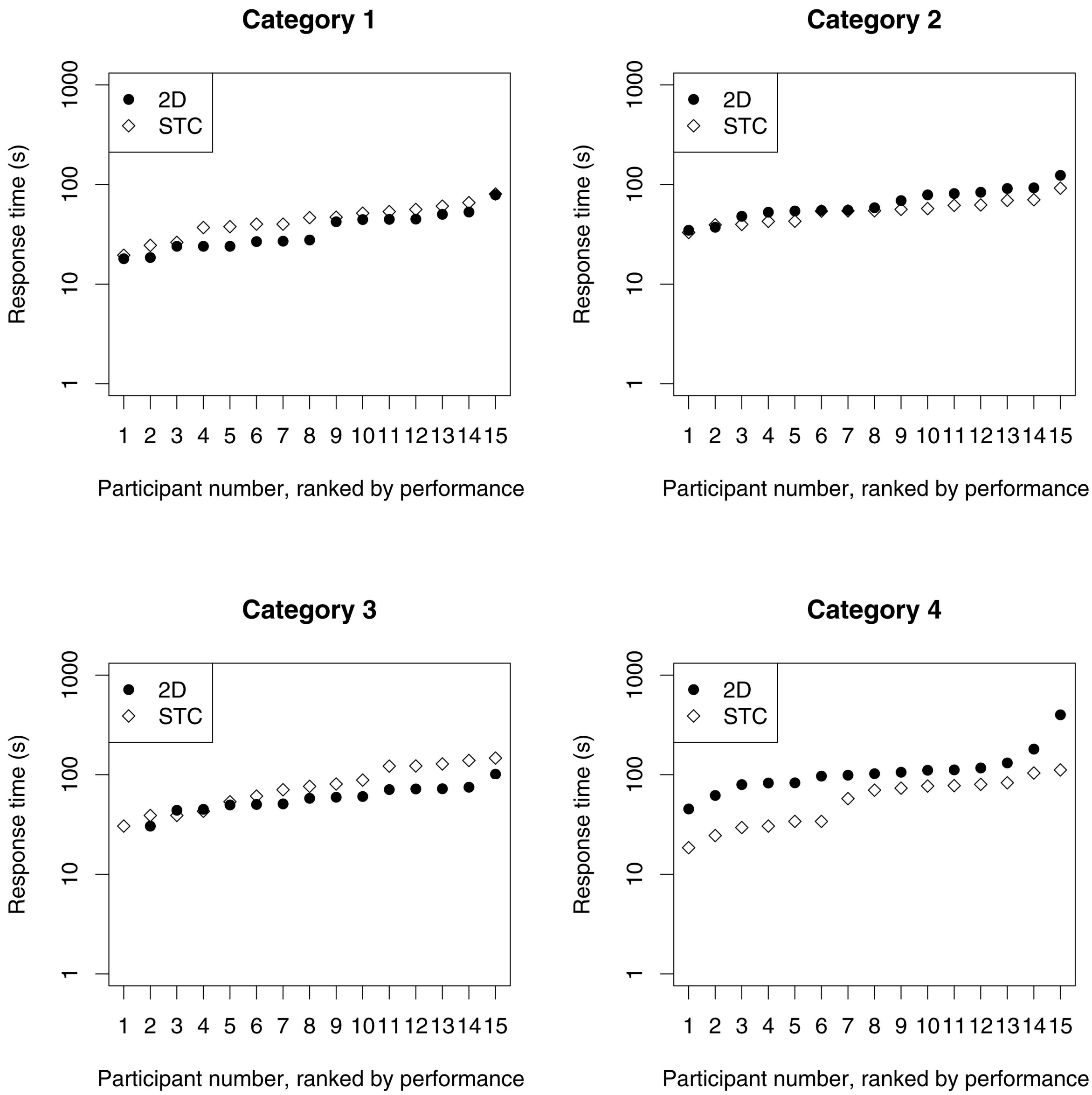

Fig. 7. Average response time (in seconds) for question categories 1-4 as a function of participant number in each condition, ranked by performance. STC stands for space time cube.

Our results also show that novice users are generally more error prone when answering a category of "simple" questions, such as "Are any two persons at the same place at 9:00?" (question category 2), when using space time cube representation. When developing systems that are expected to be used by nonexperts (e.g., teaching support), we suggest implementing an alternative visualization view that more effectively aids novice users' perception of individual data points at specific locations or points in time.

6.1 Limitations and Implications

Information visualization interfaces tend to be hard to evaluate. Once evaluated, there is a delicate trade-off between drawing too wide and too narrow conclusions from the findings. There is also a danger that empirical evaluation of information visualization interfaces might be avoided altogether due to the difficulties in producing results that generalize convincingly. Several researchers, such as van Wijk [15] and Tory and Möller [13] have reflected on this before.

We believe two design choices we made are particularly sensitive to variations. First, we suspect the map choice may affect results, particularly if participants do not know the terrain of inquiry. In our setup, participants were already well versed in how the university campus was laid out. Therefore, we probably made a good choice when using the official well-known campus map. However, maps come in many different flavors, some influenced by different cultures and traditions. We do not have data to rule out that different map choices may lead to different or modified conclusions.

Second, the design of a 2D baseline is always going to be controversial. Clearly, a multitude of variations is possible. A particular limitation of our choice of 2D baseline is that we relied on semantic markup (text) that could be toggled on or off in the 2D baseline. The space time cube condition was free from any similar markup.

However, we reemphasize that every effort was made to ensure that the experiment would be as unbiased as possible. For example, the map and the walking data participants analyzed consisted of real data as opposed to being artificially constructed for the purpose of the experiment. Moreover, the questions asked were designed and distributed into several categories according to a formalism proposed by Andrienko et al. [2]. Further, recognizing that no 2D baseline comparison will ever be "fair," we opted for one that matches the motivations of space time cube visualization in the first place: the possibility for users to get a spatiotemporal overview of the data set.

Another open question is how data density affects the conclusions. In the experiment, the continuous spatiotemporal data were relatively small and well separated. In practice, data density may be higher. A possible line of future work is to investigate how space time cube representation compares against a 2D baseline when data density increases.

Like all complex user interfaces, no specific evaluation strategy is likely to shed light on all aspects of space time cube representation. What we have primarily shown is that there is empirical evidence that space time cube representation does indeed give users a better understanding of complex continuous spatiotemporal patterns compared to a baseline 2D representation. Our result is one component toward a complete understanding of space time cube representation. It is unlikely all components in such an evaluation need or can be framed within the tight framework of controlled experiments. For example, insights about long-term professional real-world use of visualization tools have previously been gained by analyzing scientists' professional diaries (e.g., [11]).

7 Conclusions

Our results suggest two hypotheses. The first hypothesis is that for simple and direct queries space time cube visualization results in a higher error rate than a baseline 2D representation. The second hypothesis is that when observing complex spatiotemporal patterns, space time cube visualization results in much lower response times than a baseline 2D representation. We suggest future research in system designs and studies in this area to be framed around these two hypotheses.

We advise implementors of space time cube systems to focus on building space time cube interfaces that aid users in comprehending complex spatiotemporal patterns (Category 4), while also maintaining an easily accessible alternative visualization for simple direct queries (Categories 1-2).

We suggest two lines of future work. First, further empirical work can be carried out by varying data density, choice of map and domain, and level of expertise among the participants. Second, qualitative work investigating how novice and expert users explore spatiotemporal data can aid our understanding of when space time cube representation is particularly suitable for data analysis.

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