Vertical Context of Geographic Locations: An Empirical Comparison of Three Visualization Approaches

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Abstract

The vertical context of a geographic location encompasses all known information about that location. Though linked data is suitable for representing the vertical context of geographic locations, there is still a need for means to help users explore this vertical context visually and guidelines for designers of vertical context visualizations. To address this gap, this article compared three visualization approaches: map + table at the location of interest, map + markers at the location of interest and map + circular treemap at the location of interest. The three approaches were tested using two datasets: DBpedia (vertical context of places), and Umweltbundesamt data (vertical context of environmental data). While the approaches were comparable in terms of efficiency and effectiveness for most tasks, the map + circular treemap approach received higher ratings from participants (N=18) for enjoyment, usefulness, and satisfaction. The findings from this empirical study are an initial step towards developing guidelines for visualizing vertical context information extracted from geolinked data and beyond.

Keywords

linked data visualization, geolinked data, geovisualization, vertical context of geographic location

1. Introduction

Geographic locations are more than points on a map; they are only one dimension of the more complex notion of place [1], and often act as the connecting link between many attributes. Following [2], these attributes can be divided into two groups: those belonging to the horizontal context and those belonging to the vertical context. The *horizontal context* refers to the context established by information about surrounding locations. This could involve attributes such as the physical proximity to other landmarks, the accessibility to transportation networks, or the cultural and economic ties with neighbouring regions. By contrast, the *vertical context* pertains to the context established by all things that are known about a location. It encapsulates various attributes such as topography, climate, land use, historical significance, etc. and any other feature that adds depth to the understanding of a location. The topic of this article is the visualization of the vertical context of a geographic location. While linked data is suitable to represent

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Table 1
Examples of approaches to inform about the vertical context of geographic locations. VerticalGeoVis refers to the prototype built during this work with its variants.

Application	User Interface Elements	Windows	Content Categorization
DBpedia Page [11]	table-only	single-window	no
AWI Map [12]	map+table	multiple windows	no
IOER Monitor [13]	map+table+diagram	single-window	yes
TERENO [14]	map+table	single-window	no
VerticalGeoVis (MT)	map+table	single-window	yes
VerticalGeoVis (MM)	map+markers	single-window	yes
VerticalGeoVis (MCT)	map+circular treemap	single-window	yes

contextual information in general [3] and hence, the vertical context of geographic locations in particular, there are currently few means to help users explore this vertical context visually, and limited empirically derived guidelines for designers of vertical context visualizations. Since the spatial dimension is important in organizing knowledge (see e.g. [4]), investigating means to visualize the vertical context is a prerequisite to getting a holistic picture of what happens at a location. Hence, research on visualizing the vertical context of geographic location is relevant to work on linked geographic data [5, 6, 7], linked science [8], open (geo)data reuse [9] and spatial data infrastructures [10], to name a few. Table 1 shows a few examples of applications displaying all attribute information about a place, along with their strategy. While the study presented next considers visualization approaches to answer basic questions as a first step, the work's long-term goal is to build visualization techniques that help users "digest" *all* information available about a location, to the end of formulating spatial hypotheses about places.

This article presents an empirical study addressing the question: 'How to effectively visualize the vertical context of geographic locations?'. The article compared three approaches: map + table at the location of interest (hereafter MT), map + markers at the location of interest (hereafter MM) and map + circular treemap at the location of interest (hereafter MCT). The map is present in the three approaches because it is the most suitable medium to communicate spatial knowledge [15]. Besides, in all three cases, the content is grouped according to thematic categories (e.g. political, weather, administrative) that can be explored. The exploration of the attribute values within the thematic categories happens through different interaction techniques respectively: scrolling (MT), panning (MM) and zooming (MCT). The three approaches were tested using two datasets: DBpedia [16] (vertical context of places), and Umweltbundesamt data (vertical context of environmental data). The Umweltbundesamt is the environment agency of the German government. DBpedia (knowledge graph data) was accessed through the DBpedia Live Sync API[1], while the Umweltbundesamt data (structured data as JSON) was accessed through the 'Air Data API (UBA)'[2]. The contribution of this work is an empirical investigation informing about the respective merits of the three approaches.

[1] https://www.dbpedia.org/resources/live/dbpedia-live-sync/ (accessed: July 10, 2024).
[2] https://www.umweltbundesamt.de/daten/luft/luftdaten/doc (accessed: July 10, 2024).

2. Background

As discussed in [17], there are at least 16 linked data visualization use cases. Visualizing the vertical context can be seen as a case of *visualizing the information related to a specific instance* [17], when the specific instance is a location of interest. The necessity of communicating the spatial context of the data instances is an additional requirement for tools visualizing the vertical context of geographic locations, next to the visualization of all attributes available for that location (the attributes may be provided as linked data or not). Ideally, these tools should also support the follow-your-nose principle, which adds another dimension of complexity. As a first step, all attributes retrieved for a location were treated as RDF-literals in this work, i.e. available links were removed for simplicity.

The existing literature offers several reviews about tools and approaches to visualize linked data (e.g. [18, 19, 20, 21]), but 'vertical context exploration' as a use case is mostly absent from these reviews. Tools visualizing geo-linked data exist, but they often have a different focus than user interfaces' impact on the exploration of all things known about a location. For instance, Mai et al. [22] proposed a multi-view interface (i.e. table view + graph view + map view) to enable the exploration of scientific geographic data sources. Here, the focus was on the discovery of detailed information about an entity, relationships between entities and between entity types, and the spatial distribution of entities. In [23], different configurations can be loaded (and a plugin that interprets the point geometry for locations), to display information about DBpedia cities in the *Phuzzy.link* browser. Attribute information is displayed as a table (similar to DBpedia Page), and hence the *Phuzzy.link* interface would qualify as a vertical context visualization. Nonetheless, vertical context exploration was not the focus of the work, but rather the concept of an adaptable interface to explore SPARQL endpoints from the browser. At last, Potnis and Durbha [24] illustrate how to show country information on a 3D globe, but their focus was on the display of geographic relationships (e.g. "hasBorderWith") between geographical entities.

The study presented next is a user-based evaluation of three strategies to retrieve information about the vertical context of a location (MT, MM and MCT). We consider three information-seeking questions: elementary-level questions (questions about specific values of a property at a given location), intermediate-level questions (questions about a specific category and its subelements at the location of interest) and global-level questions (questions about all categories of topics at the location of interest).

3. Method

We compared the merits of the three approaches through a controlled experiment. The following variables were considered during the experiment:

- Independent variables: the three visualization approaches (map+table, map+markers, map+circular treemap), the type of questions asked (specific attribute values, overview [count of attributes per category], overview [attribute categories]), and the six attribute levels (60, 90, 105, 140, 180, 200).

- Dependent variables: efficiency (task completion time), effectiveness (accuracy of tasks), perceived enjoyment, perceived usefulness, perceived satisfaction and perceived ease of use regarding the visualization approaches.
- Controlled variables: number of screens used (N=1) and screen size (all between 13 inches and 27 inches).
- Subject variables: age, gender, educational background, English proficiency, computer literacy and prior experience with visualization tools (i.e. web maps, Leaflet.js markers and D3.js zoomable circle packing).

We anticipated before the study that the *magnitude* of attributes displayed might influence the performance of the techniques assessed and introduced the notion of 'attribute level' to capture this potential effect. 'Attribute level X' stands for 'number of attribute values *in the order of* X' or 'number of attribute values *roughly equal to* X'. The initial plan was to start with attribute level 60 and increase it incrementally by 30 attributes for each subsequent level. However, due to attributes *actually* offered by the datasets, we adjusted the final attribute levels slightly, i.e. 60, 90, 105 (instead of 120), 140 (instead of 150), 180, and 200 (instead of 210).

3.1. Datasets

Two datasets were used: DBpedia and the Umweltbundesamt data (hereafter UBA). We used each to collect information about the vertical context of 10 cities in Germany (Table 2). While both provide information about the vertical context of places, a difference between the two is that DBpedia provides mostly information in the form of text, while Umweltbundesamt offers primarily numerical information, e.g., for attributes such as Fine dust, Carbon monoxide (CO), Sulphur dioxide (SO2), Ozone (O3) and Nitrogen dioxide (NO2). The DBpedia Live Sync API was used by inputting the city names as query parameters and the data was obtained in N-triples format. Relevant data from Umweltbundesamt was obtained in JSON format from the "Air Data API (UBA) 3.0.0". Raw data obtained from the two APIs underwent cleaning and post-processing before rendering through the visualization approaches.

3.2. Prototype

The application was built using Web technologies (HTML, CSS, JavaScript), a web mapping library (Leaflet) and a visualization library (D3.js). We used Leaflet (version 1.9.4) for the base maps and location markers, D3.js (Version 4) for the circular treemap, and Bootstrap (version 5.3.2) as the CSS framework. The application features search for locations, the choice of datasets, the choice of a visualisation approach, as well as short answers to frequently asked questions. The approaches were renamed into "Visualization Approach 1", "Visualization Approach 2" and "Visualization Approach 3" during the experiment to avoid potential participant bias. A demo of the application is available at https://youtu.be/zLCy3shSOoU. Figures 1, 2 and 3 show screenshots of the three visualization approaches on the two datasets respectively.

- Map+table: The information is presented in a table format, grouped by the main attribute category (Figure 1a). This arrangement enables users to efficiently search for specific data by scrolling through the table. Categorizing the data facilitates swift navigation

Table 2
Datasets used during the experiment, along with the exact number of attributes extracted for a location and the attribute level for which they were used during the experiment.

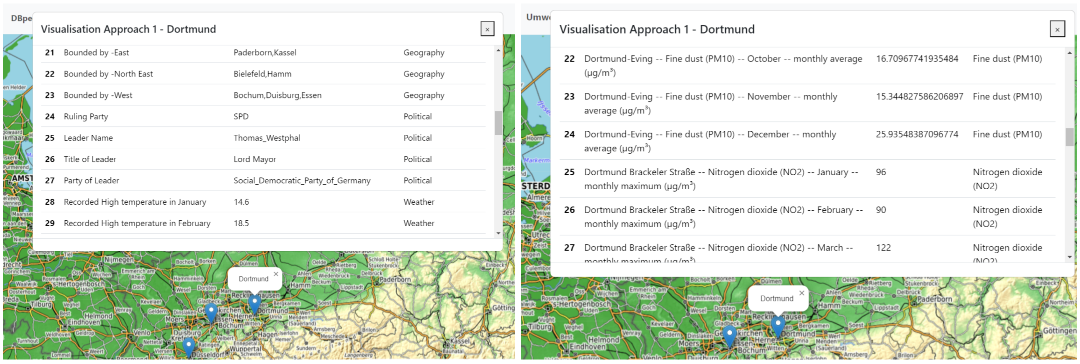
City	DBpedia dataset		UBA dataset	
	Attribute count	Attribute level	Attribute count	Level of attributes
Berlin	103	90	192	180
Hamburg	110	105	204	200
Munich	113	105	168	140
Cologne	112	105	204	200
Frankfurt am Main	114	105	204	200
Stuttgart	113	105	144	140
Düsseldorf	115	105	60	60
Leipzig	108	105	108	105
Dortmund	64	60	60	60
Essen	90	90	120	105

to sections of interest, enhancing the overall efficiency of data retrieval. Additionally, attribute indexing improves the ease of counting the attributes relevant to each group or attribute within the dataset.

- Map+markers: Instead of a traditional table format, the data is represented by leaflet markers arranged in a spiral pattern, i.e. the makers are 'spiderfied' [25]. The spiderify method, described in [25], was originally suggested to tackle the problem of visualizing multiple markers at the same location. Thus, we reused it in this context to convey the idea that all attributes are attached to the same location. The spiderify method takes the markers placed in the same position and arranges them in a spiral. The advantage of the spiral pattern is its compactness, which enables the display of numerous attributes. Each marker represents different attributes, making it possible for users to identify and differentiate between them. When users click on a marker, a pop-up message appears, showing the name of the attribute category and its corresponding values. Colour hue is used to highlight markers belonging to the same category (Figure 2a).
- Map+circular treemap: The visualization organizes information into circles representing distinct attribute categories for a city (Figure 3a). Upon a user's click on a category, the visualization zooms in to display the attribute-value pair information available in that specific circle (Figure 3b). We opted for a circular treemap over a traditional treemap because, for the two hierarchy levels required to display the datasets in this work, the circular treemap reveals hierarchical structures and facilitates interaction between the levels more effectively.

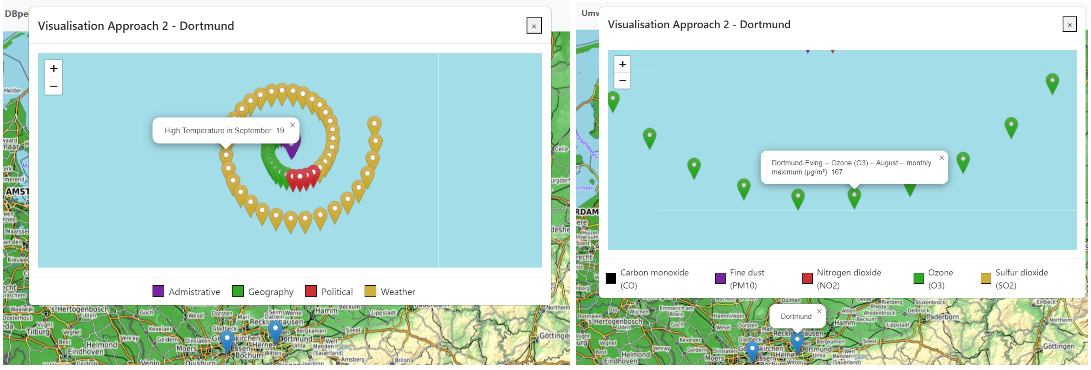
3.3. Tasks

We generated six tasks for the experiment. A task has three dimensions: a city, an attribute level for the vertical context, and a dataset. The six tasks were: Dortmund-60-DBpedia (T1), Düsseldorf-105-DBpedia (T2), Essen-90-DBpedia (T3), Hamburg-200-UBA (T4), Berlin-180-UBA



(a) DBpedia Data (b) UBA Data

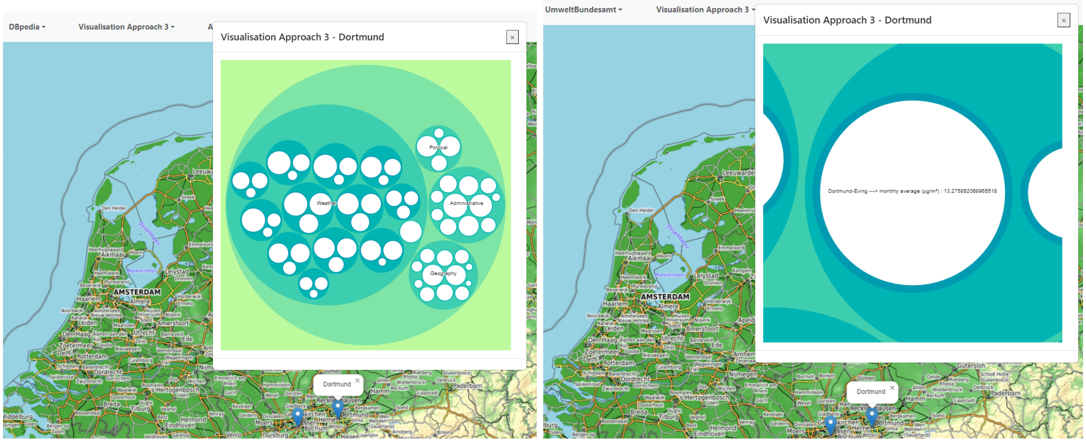
Figure 1: Visualization of the vertical context for Dortmund, using the map+table approach.



(a) DBpedia Data (b) UBA Data

Figure 2: Visualization of the vertical context for Dortmund, using the map+markers approach. (a) overview of available attributes for the DBpedia data; (b) Zoom on Ozone information from the UBA data.

(T5), and Munich-140-UBA (T6). Each task features three types of questions: q1-q3 all deal with retrieving specific attribute values, q4 is about counting the number of attributes belonging to a category, and q5 is about listing all thematic categories of attributes available for a city. Adapting Bertin [26]'s distinction to the current context, we can distinguish questions about a single element (elementary level of reading), questions about a group of elements (intermediate level of reading), and questions about the whole set of visual elements (overall or global level of reading). q1-q3 correspond to the elementary level of reading, q4 touches the intermediate level of reading, and q5 addresses the global level of reading of the dataset at hand. The order of the questions (q1-q5) remained identical for all participants during the study. We provide two examples of tasks below (T1, T4). A description of the remaining tasks (T2, T3, T5, T6) can be found in the supplementary material, Section 7.



(a) DBpedia Data (b) UBA Data

Figure 3: Visualization of the vertical context for Dortmund, using the map+circulartreemap approach: (a) overview of available attributes for the DBpedia data; (b) Zoom on the Fine-dust value for the Dortmund-Evin station in June (UBA Data).

Task (T1) is described as follows (Dortmund, 60 attributes, DBpedia).

specific attribute values

- q1: What is the lowest temperature in Dortmund for September?
- q2: What is the recorded highest temperature in Dortmund for May?
- q3: Who is the leader of Dortmund (Leader Name)?

overview (count of attributes per category)

- q4: How many attributes belong to the 'Weather' category?

overview (attribute categories)

- q5: What are the attribute categories for Dortmund that you can access through this approach?

Task (T4) is described as follows (Hamburg, 200 attributes, UBA).

specific attribute values

- q1: What is the monthly maximum (μg/m³) of "Ozone (O3)" recorded in the "Hamburg Sternschanze" station for April?
- q2: What is the monthly maximum (μg/m³) of "Nitrogen dioxide (NO2)" recorded in the "Hamburg Max-Brauer-Allee II (Straße)" station for October?.
- q3: What is the monthly average (μg/m³) of "Fine dust (PM10)" recorded in the "Hamburg Habichtstrasse" station for December?

overview (count of attributes per category)

- q4: How many data records (vertical attributes) are available for the air pollutant "Fine dust (PM10)"?

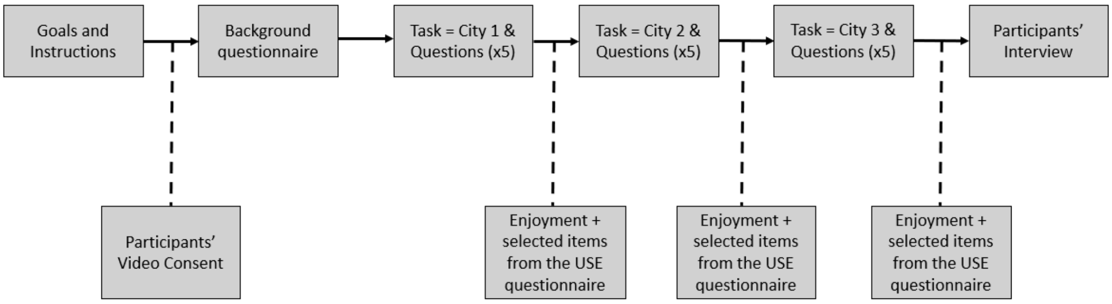


Figure 4: Steps followed by the participants during the experiment.

overview (attribute categories)

- q5: What are the categories of air pollutants that exist in Hamburg city?

The experiment followed a within-group design. The order of the visualization approaches and of the tasks was counterbalanced. The randomization and distribution of the subjects across conditions helped collect 18 data points per visualization approach and 9 data points per attribute level. Additional details about the randomization strategy are shown in the supplementary material, Section 7. Figure 4 shows all experiment steps, including the tasks.

3.4. Procedure

The experiment was held online (Google Meet) and was conducted each time with one participant and one examiner (the first author). The procedure started with a brief explanation of the experiment's goals. Then the participants were asked to provide a video consent before proceeding with the experimental tasks. Afterwards, participants filled in a background questionnaire about personal details, computer literacy, familiarity with web maps, Leaflet.js marker patterns, and the D3.js zoomable circle-packing visualization approach. Once the background questionnaire was completed, the participants performed three tasks using a different visualization approach each time to find information about one of the ten cities (Figure 4). The examiner only observed the entire process. Upon completion of each task, participants were asked to answer one question related to the enjoyment [27] of the visualization approach and three questions selected from the USE questionnaire [28, 29] to measure usefulness, satisfaction and ease of use on a 7-point Likert scale. The three questions selected were: "X makes the things I want to accomplish easier to get done" (Question UU5, Usefulness); "I don't notice any inconsistencies as I use X" (Question UE8, Ease of Use); and "I am satisfied with X" (Question US1, Satisfaction), where X refers to the visualization approach, to find out the extent to which X helps users answer the questions considered (UU5), smoothly navigate the attribute values (UE8) and brings about satisfaction in the process (US1). At the end of the session, the participants were asked to answer three questions: 'Considering the three visualization approaches you've interacted with, could you please rank them in order of preference based on which one you found most effective in helping you answer the questions?', 'Could you please provide reasons for ranking them?' And 'Do you have any suggestions regarding further improvements for the Web Application?'. All answers to questions were recorded through the LimeSurvey platform, which was also used to record the time participants took to answer specific questions. The experiment was pilot-tested with two participants and approved by the institutional ethics board.

3.5. Participants

The study involved 18 participants (6F, 12M), which were recruited through word-of-mouth. Participation was voluntary and the participants were not compensated for their participation. Their age distribution varied: (12/18) participants fell within the age range of 21 to 30 years, while (4/18) participants were between 31 and 40. Additionally, there was (1/18) participant in the age groups of 41-50 and 51-60 respectively. Regarding computer literacy, the participants reported varying levels of proficiency, with (2/18) participants self-identifying as beginners, (7/18) as intermediate, and (9/18) as advanced users. The familiarity with Leaflet.js markers and D3 zoomable circle packing also exhibited a range of expertise among the participants. Specifically, (1/18) participants were highly familiar with Leaflet.js marker patterns, while (8/18) participants reported moderate familiarity and (9/18) participants indicated no familiarity. The familiarity distribution was similar for D3.js zoomable circle packing, indicating a diverse range of expertise levels within the participant pool. All participants used their own laptops with one screen to complete the study and confirmed that their screen size was between 13 and 27 inches, to keep the experimental setup somewhat similar.

4. Results

We now present the experiment's results, starting with the outcomes of the quantitative analysis, before proceeding with the qualitative feedback.

4.1. Results of the pairwise comparison of the three visualization approaches

Figure 5 shows the similarities and differences observed across the visualization approaches and the attribute levels. The Map+Circular Treemap approach yielded the best outcomes in most cases (it was better than at least one of the other two in 32 of all 70 comparison scenarios), followed by the Map+Markers approach (better 9 times) and the Map+Table approach at last (favourable 8 times). We found no significant advantage for any visualization approach in 27 of the 70 comparison scenarios (Figure 5). A detailed presentation of the results is shown in Appendix A (Tables 4 to 13).

- Efficiency [elementary-level]: while the data did not suggest any significant difference cross-attribute-levels, the Map+Table approach recommends itself for the attribute levels 90 and 105, while the Map+Markers approach seems best for the attribute levels 180 and 200 (see also Table 4).
- Efficiency [intermediate-level]: the three approaches are comparable overall, but Map+Table may be preferable at attribute level 105, while Map+Makers or Map+Circular Treemap may be advantageous at attribute level 60 (see also Table 5).
- Efficiency [global-level]: Map+Circular Treemap is preferable at attribute level 60, Map+Table at attribute level 105, and Map+Makers may be a good option for attribute levels 105 and 180 (see also Table 6).

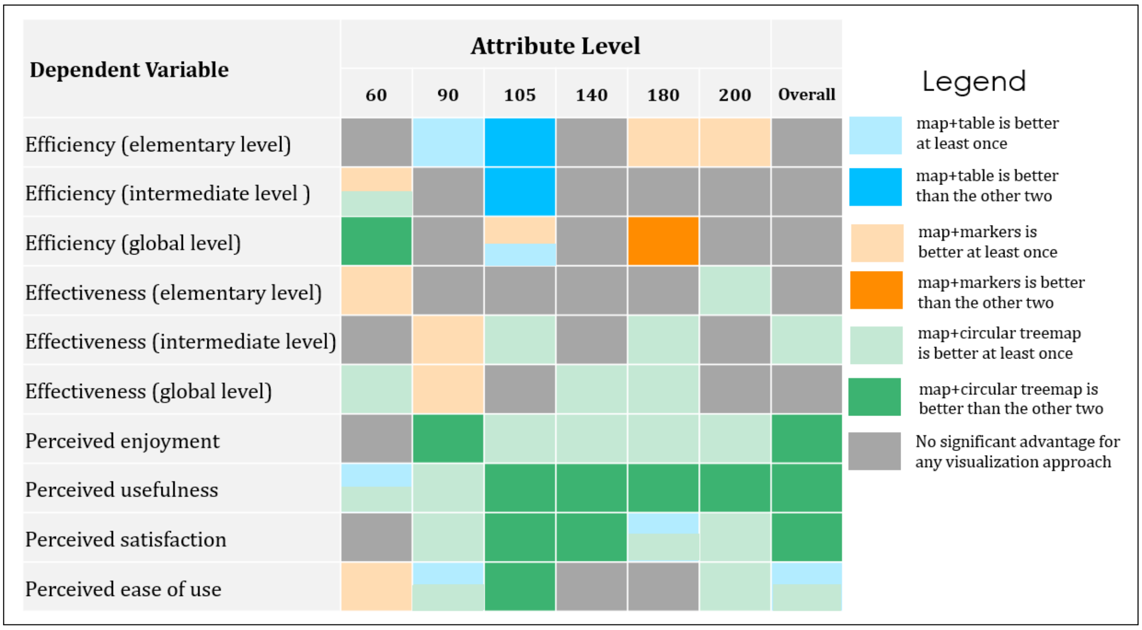


Figure 5: Summary of the differences observed per condition regarding the dependent variables. Two colours in a cell should be read "AND", e.g. for efficiency at attribute level 60 [question type: intermediate-level], map+markers was better than the other two techniques at least once, and map+circular treemap was better than the other two techniques at least once. That is, map+table was worse than the other two techniques for efficiency at attribute level 60.

- Effectiveness [elementary-level]: the approaches may be deemed comparable overall, but Map+Markers provided higher accuracy values at attribute level 60, while Map+Circular Treemap increased users' accuracy during question answering at attribute level 200 (see also Table 7).
- Effectiveness [intermediate-level]: the Map+Circular Treemap approach recommends itself here overall, and at attribute levels 105 and 180. The Map+Markers approach seems best at attribute level 90 (see also Table 8).
- Effectiveness [global-level]: the Map+Circular Treemap approach seems best at levels 60, 140 and 180, and the Map+Markers approach helped users increase their answers' accuracy at level 90 (see also Table 9).
- Perceived enjoyment: there seems to be a clear user preference for the Map+Circular Treemap approach (see also Table 10).
- Perceived usefulness: there seems to be a clear user preference for the Map+Circular Treemap approach both overall and across all attribute levels (see also Table 11).
- Perceived satisfaction: here also, the Map+Circular Treemap approach seems to have provided more satisfaction to participants during the question-answering tasks (see also Table 12).
- Perceived ease of use: overall, the easiest approaches to use according to the participants were either the Map+Circular Treemap or the Map+Table approach. The Map+Makers

approach was perceived as slightly easier to use by participants at attribute level 60 only (see also Table 13).

4.2. Participants' subjective preference

Here, the Map+Circular Treemap approach emerged as the most favoured by participants, garnering 15 out of 18 votes as Rank 1 (Table 3). In contrast, the Map+Markers approach received the least preference with 16 out of 18 votes as Rank 3. As for the reasons for their ranking provided by the users, the key advantages mentioned were:

- Map+Circular Treemap: Users can zoom in for a detailed inspection of specific attributes and easily zoom out to transition to other attributes. The attributes are organized into clusters, grouping similar ones in close proximity. This systematic arrangement enhances navigation, making it easy to locate specific attributes efficiently.
- Map+Markers: the participants did not mention any specific advantage.
- Map+Table: Users can navigate through attributes by employing a rapid scrolling feature, allowing them to efficiently move through the content and explore different attributes without delays.

The key disadvantages mentioned were:

- Map+Circular Treemap: the participants did not mention any specific disadvantage.
- Map+Markers: To locate a specific attribute, users need to click on multiple markers, as it can be challenging to distinguish the desired attribute from others in the same category.
- Map+Table: The list view arrangement makes it difficult to identify attribute counts and discern the attribute categories easily.

Table 3
Participants' feedback about their preferred approach.

Visualization Approach	Rank 1	Rank 2	Rank 3
Map+Table	3	13	2
Map+Markers	0	2	16
Map+Circular Treemap	15	3	0

5. Discussion

5.1. Implications

The display of attribute values as a table is currently the most common - and straightforward - way of presenting vertical context information (e.g. DBpedia Page, Table 1). The preliminary observations from this study suggest that there are usually better alternatives, both in terms of maximizing utilitarian (e.g. efficiency, effectiveness) and hedonic objectives (e.g. perceived user satisfaction). Another consistent observation of the study is that both attribute level *and* question types matter when comparing the merits of the different visualisation approaches. Since this study is a first of this kind, it is still unclear at this point whether the variability observed can be truly attributed to the performance of an approach at an attribute level, or to the current (limited) sample of participants. Still, the study has highlighted that attribute level may be a confounding variable for similar experiments in the future, and this suggests that this dimension should be explicitly controlled for. Moving forward, there are two possible ways of reusing the results from Figure 5: reading a column to find out the most suitable visualization at an attribute level or reading a line to find the best suitable row to maximize the outcomes for a dependent variable (e.g. effectiveness, perceived ease of use). These two ways of reading can be used by visualization designers in the future to formulate hypotheses, as they use any of the three visualization approaches considered in the current work as a baseline. Finally, as mentioned in [30], spatial data collection, processing and sharing is a common thread of various disciplines within the Earth System Sciences. Hence, the observations made here about vertical context visualization are relevant to ongoing efforts to establish (national) infrastructures for the Earth System Sciences.

5.2. Limitations

The prototype was designed exclusively for desktop-size screens (e.g. personal computers) and is not yet optimized for use on mobile devices such as phones and tablets. Hence, no claim can be made as to the generalizability of the results to these devices. Another limitation of the study was the relatively small number of participants and their homogeneous backgrounds. This was necessary because of the exploratory nature of the study, but a larger-scale study would be needed, with a more diversified user base, in follow-up work to learn about the applicability of the results to different user groups. At last, all three techniques overlay the vertical context information on top of the location selected. While this has the advantage that - in the context of the navigation - the location for which the vertical context is currently visualized is unambiguous, this comes at the cost of the occlusion of the map. An alternative worth considering would be the juxtaposition of the vertical context display and the map (i.e. placing the vertical context display alongside the map). This would come at the extra cost of designing effective location emphasis techniques to highlight the current location unambiguously but is worth further investigation in future work.

5.3. Future work

We have mentioned three key requirements of visualizations of the vertical context of geographic locations in Section 2: communicate the spatial context (R1), enable intuitive and effective navigation through the wealth of attributes and their values (R2), and enable the traversal of paths between different datasets, and paths between properties of the same dataset (R3, a.k.a. follow-your-nose principle). The three techniques in this work addressed R1 (through the map) and R2 (through either the table, the marker, or the circular treemap). Hence, an open question is how to address R3 through existing or new visualization approaches. Given the number of attributes to display, the categorization of content comes in handy. Hence, this work tested circular treemaps, which are only one way of visualizing hierarchical data, to display the attribute values. It is an open question whether or not alternative ways of visualizing hierarchical data (for examples, see [31, 32]) would be equally effective in this context, if not more effective. Furthermore, the three approaches have in common that attribute information is displayed in a popup after clicking on the map. Given the necessity for at least two views for the display of vertical context information, geodashboards (i.e. multiple-view systems of geographic data, arranged on a single screen so that the information can be perceived at a glance [33]) may be considered to fulfil the three requirements as well. Besides, Figure 5 has shown that attribute levels matter, hence scalability across several attribute levels needs more scrutiny. In addition, the work only tested the visualization approaches for up to 200 attribute values. The extent to which the observations hold for even greater levels of attribute values also needs to be investigated in future work. At last, we mentioned in Section 1 that, beyond simple question-answering about attribute values at a location, one higher-level goal of vertical context exploration is the formulation of spatial hypotheses. The extent to which existing and novel visualization techniques support that goal would need systematic testing in future work.

6. Conclusion

There are two types of contextual information related to a geographical location: the vertical context (all things known about a location) and the horizontal context (all things known about surrounding locations to a location). While linked data is suitable to represent contextual information in general and the vertical context of geographic locations in particular, we still lack means to help users explore this vertical context visually, and guidelines for designers of vertical context visualizations. This work has provided an empirical comparison of three approaches (map+table, map+marker, map+circular treemap) to address this gap. The merits of the approaches were compared for question-answering tasks involving 60 to 200 attribute values. The map+circular treemap approach yielded the best outcomes in most cases, followed by the map+markers approach, and both can be used as a starting point in further investigations of visualizations that help users explore all that is known about a place.

7. Supplementary material

The supplementary material showing the randomization approach during the experiment, all tasks completed by the participants, as well as the data collected during the experiment, is available at https://doi.org/10.6084/m9.figshare.26264594. The code of the prototype is available on GitHub (https://github.com/Prasadmadhusanka/VerticalGeoVis-prototype).

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A. Appendix - Detailed results

This section presents detailed results about the pairwise comparison of the different approaches across all dependent variables. The R package bootES [34] was used for the analysis. The following applies to all tables. The first two columns of the tables represent the two visualization approaches being compared. The third column represents the mean value difference between the two groups: $Mean_{(Group1)}$ - $Mean_{(Group2)}$. Positive values for both the lower and upper confidence interval bounds (CI_{Low} and CI_{High} values) suggest that the visualization in the first column produced significantly higher values than the one in the second column. Conversely, negative values for both CI_{Low} and CI_{High} indicate that the visualization in the second column resulted in significantly higher values than the one in the first column. A statistically significant difference between the two groups is implied when the confidence interval of the mean difference does not enclose zero. This is highlighted through a light yellow coloured background in the tables. The bias is the difference between the mean of the resamples and the mean of the original sample. The SE (standard error) is the standard deviation of the resampled means [34]. The number of resamples used in the analysis was N=5000.

Table 4
Efficiency results for the elementary-level questions (q1,q2,q3).

Approach A	Approach B	Attribute Level	Mean Difference (Seconds)	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-43.310	-134.190	76.153	0.431	54.013
		90	-11.140	-69.007	26.860	-0.828	24.726
		105	-101.840	-237.563	-23.733	1.342	53.167
		140	-35.120	-124.582	23.467	0.595	38.373
		180	98.113	-38.647	262.097	-0.069	76.213
		200	-169.897	-295.583	11.613	-1.066	78.929
		Overall	-43.866	-110.265	25.693	0.192	34.299
Map+Table	Map+Circular Treemap	60	20.437	-11.610	69.793	0.235	20.829
		90	-72.140	-186.220	-6.927	0.652	43.801
		105	-126.763	-155.253	-90.330	0.297	16.494
		140	-57.557	-150.340	29.053	-0.108	45.853
		180	146.840	13.633	310.823	0.819	76.095
		200	44.660	-30.920	86.480	0.511	28.071
		Overall	-7.421	-52.244	53.610	-0.425	26.507
Map+Markers	Map+Circular Treemap	60	63.747	-58.157	135.720	0.069	50.418
		90	-61.000	-194.047	15.123	0.699	48.904
		105	-24.923	-98.250	97.203	-0.156	49.740
		140	-22.437	-99.923	59.220	-0.928	41.653
		180	48.727	-32.127	118.797	-0.350	40.575
		200	214.557	21.670	320.337	0.099	74.771
		Overall	36.445	-17.974	104.815	-0.026	31.268

Table 5
Efficiency results for the intermediate level/counting questions (q4).

Approach A	Approach B	Attribute Level	Mean Difference (Seconds)	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	61.117	14.913	98.223	-0.470	22.017
		90	-1.493	-33.227	34.497	0.033	18.500
		105	-90.450	-138.650	-11.513	0.345	33.096
		140	13.160	-77.970	104.290	-0.367	47.891
		180	2.197	-48.913	56.037	-0.144	26.311
		200	-65.287	-177.020	4.870	-0.285	47.113
		Overall	-13.459	-49.128	16.653	0.214	16.627
Map+Table	Map+Circular Treemap	60	66.107	20.547	101.897	0.315	21.473
		90	-23.620	-53.177	5.937	0.252	16.035
		105	-59.510	-126.890	-21.377	-0.319	27.364
		140	30.657	-33.353	125.637	-0.630	40.885
		180	4.833	-53.397	58.270	-0.110	29.273
		200	0.397	-15.270	21.097	-0.019	9.475
		Overall	3.144	-19.454	30.724	-0.102	12.979
Map+Markers	Map+Circular Treemap	60	4.990	-13.180	17.063	-0.075	7.144
		90	-22.127	-62.433	3.173	0.121	15.967
		105	30.940	-78.987	102.610	-0.254	43.603
		140	17.497	-26.160	79.467	0.551	27.002
		180	2.637	-63.330	47.120	-0.328	27.482
		200	65.683	-11.977	175.110	-0.022	47.627
		Overall	16.603	-9.914	50.504	-0.130	15.334

Table 6
Efficiency results for the global level/category overview questions (q5).

Approach A	Approach B	Attribute Level	Mean Difference (Seconds)	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-4.390	-41.030	37.610	-0.080	21.318
		90	19.683	-16.667	66.177	0.021	20.717
		105	-0.810	-19.057	15.877	-0.009	8.942
		140	19.260	-22.960	68.283	0.180	23.447
		180	30.757	9.897	64.733	-0.289	14.284
		200	-30.750	-67.843	14.970	0.151	21.372
		Overall	5.625	-12.597	24.235	0.064	9.331
Map+Table	Map+Circular Treemap	60	41.932	13.573	72.240	0.274	15.334
		90	32.127	-8.717	78.620	-0.196	22.393
		105	-40.610	-68.783	-25.167	-0.150	11.062
		140	-4.283	-45.590	42.461	0.151	22.760
		180	10.447	-18.457	44.800	-0.057	16.285
		200	-3.440	-39.480	30.550	-0.211	18.799
		Overall	6.032	-11.024	23.421	0.212	8.727
Map+Markers	Map+Circular Treemap	60	46.313	8.387	71.33	0.560	16.061
		90	12.443	-14.767	31.110	0.108	11.671
		105	-39.800	-72.600	-17.243	0.058	14.161
		140	-23.543	-62.590	15.503	0.180	20.150
		180	-20.280	-39.203	-4.370	0.010	9.249
		200	27.310	-31.107	67.507	0.020	25.442
		Overall	0.407	-16.586	18.957	-0.144	9.106

Table 7
Effectiveness results for the elementary-level questions (q1,q2,q3). ***** indicates identical values in the two conditions, so no possibility of computing a confidence interval.

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-22.222	-33.333	-11.111	0.187	8.921
		90	11.111	-22.222	44.444	-0.291	20.036
		105	22.222	-22.222	44.444	0.160	18.078
		140	11.111	0.000	22.222	-0.007	8.969
		180	11.111	0.000	22.222	0.207	9.280
		200	0.000	-33.333	11.111	0.249	12.722
		Overall	5.556	-7.407	16.667	-0.245	6.402
Map+Table	Map+Circular Treemap	60	*****				
		90	22.222	0.000	33.333	0.151	9.021
		105	0.000	-33.333	11.111	0.044	13.014
		140	11.111	0.000	22.222	-0.071	9.044
		180	11.111	0.000	22.222	0.136	9.036
		200	-11.111	-33.333	-11.111	-0.031	9.049
		Overall	0.000	-12.963	9.259	-0.224	5.277
Map+Markers	Map+Circular Treemap	60	-11.111	-33.333	0.000	0.164	9.140
		90	11.111	-33.333	11.111	0.000	17.718
		105	-22.222	-55.556	11.111	0.124	18.294
		140	0.000	-33.333	11.111	-0.027	12.689
		180	0.000	-33.333	11.111	0.109	12.843
		200	-11.111	-33.333	0.000	-0.022	9.096
		Overall	-5.556	-22.222	3.704	-0.013	6.443

Table 8
Effectiveness results for the intermediate level/ counting questions (q4).

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-33.333	-100.000	33.333	-0.693	38.079
		90	-66.667	-100.000	-33.333	-0.127	27.119
		105	66.667	0.000	100.00	-0.533	27.241
		140	*****				
		180	-33.333	-100.000	33.333	-0.267	38.416
		200	*****				
		Overall	22.222	-16.667	50.000	-0.029	16.266
Map+Table	Map+Circular Treemap	60	-33.333	-100.000	33.333	0.033	38.668
		90	*****				
		105	0.000	-100.000	33.333	0.380	38.493
		140	*****				
		180	-66.667	-100.000	-33.333	0.220	27.061
		200	*****				
		Overall	-16.667	-50.000	11.111	-0.150	15.851
Map+Markers	Map+Circular Treemap	60	0.000	-100.000	33.333	0.353	38.034
		90	-33.333	-100.000	0.000	-0.493	27.445
		105	-66.667	-100.000	-33.333	-0.293	27.114
		140	*****				
		180	-33.333	-100.000	0.000	0.387	26.998
		200	*****				
		Overall	-38.889	-72.222	-11.111	-0.333	15.302

Table 9
Effectiveness results for the global level/category overview questions (q5).

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-33.333	-100.000	0.000	-0.500	38.062
		90	-66.667	-100.000	-33.333	-0.407	26.919
		105	33.333	0.000	66.667	-0.073	27.348
		140	66.667	0.000	100.000	0.293	27.114
		180	33.333	0.000	66.667	-0.667	27.222
		200	-33.333	-100.000	0.000	-0.060	27.526
		Overall	0.000	-38.889	27.778	0.237	16.107
Map+Table	Map+Circular Treemap	60	-66.667	-100.000	-33.333	-0.387	27.039
		90	-33.333	-100.000	33.333	-0.327	38.302
		105	33.333	0.000	66.667	0.353	27.289
		140		*****			
		180	-66.667	-100.000	-33.333	-0.387	27.219
		200	33.333	-66.667	66.667	0.380	38.591
		Overall	-16.667	-50.000	11.111	0.293	14.985
Map+Markers	Map+Circular Treemap	60	-33.333	-100.000	0.000	-0.153	27.429
		90	33.333	0.000	66.667	0.127	27.291
		105	0.000	-100.000	33.333	0.467	38.960
		140	-66.667	-100.000	-33.333	-0.233	27.225
		180		*****			
		200	66.667	0.000	100.000	0.393	27.207
		Overall	-16.667	-50.000	11.111	-0.124	14.805

Table 10
Pairwise comparison of the perceived enjoyment for the visualization approaches.

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	1.333	0.000	2.667	0.014	1.099
		90	0.667	-1.333	2.333	-0.003	0.978
		105	-1.000	-4.000	2.000	0.001	1.553
		140	-0.667	-3.000	1.000	0.008	1.004
		180	2.667	0.333	5.000	-0.027	1.195
		200	-1.667	-4.667	2.000	-0.068	1.708
		Overall	0.222	-1.056	1.389	0.005	0.646
Map+Table	Map+Circular Treemap	60	0.667	0.000	1.333	0.555	0.543
		90	-1.333	-2.000	-1.000	0.002	0.273
		105	-2.667	-4.667	-1.000	-0.008	0.968
		140	-1.667	-3.333	-0.333	0.006	0.766
		180	-0.667	-2.333	1.000	-0.018	0.905
		200	-3.000	-5.333	-0.667	-0.005	1.203
		Overall	-1.444	-2.556	-0.667	0.011	0.478
Map+Markers	Map+Circular Treemap	60	-0.667	-4.000	0.667	0.013	1.218
		90	-2.000	-4.000	-0.667	-0.003	0.928
		105	-1.667	-5.000	0.000	0.004	1.261
		140	-1.000	-2.667	0.333	0.002	0.779
		180	-3.333	-5.333	-1.333	-0.003	1.092
		200	-1.333	-5.333	1.000	-0.009	1.557
		Overall	-1.667	-2.833	-0.722	0.005	0.529

Table 11
Pairwise comparison of the perceived usefulness of the visualization approaches.

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
		60	0.000	-1.000	0.333	-0.003	0.388
		90	2.000	0.000	3.000	-0.006	0.772
		105	0.333	-1.333	2.667	-0.006	1.021
Map+Table	Map+Markers	140	1.667	-0.951	2.667	0.007	0.850
		180	2.333	-0.333	4.000	0.003	1.091
		200	1.333	-4.000	1.333	0.002	1.391
		Overall	0.833	-0.333	1.889	-0.005	0.576
		60	0.667	-1.000	-0.333	-0.003	0.276
		90	-0.333	-1.000	0.333	0.000	0.389
		105	-2.333	-3.000	-2.000	0.001	0.272
Map+Table	Map+Circular Treemap	140	-1.333	-3.667	-0.333	-0.009	0.869
		180	-2.000	-3.667	-0.333	0.001	0.896
		200	-3.333	-5.333	-1.667	0.008	0.900
		Overall	-1.667	-2.667	-0.944	-0.004	0.434
		60	-0.667	-1.000	-0.333	0.001	0.270
		90	-2.333	-3.667	-1.000	-0.005	0.771
		105	-2.667	-5.000	-1.333	0.011	0.979
Map+Markers	Map+Circular Treemap	140	-3.000	-3.667	-2.333	-0.005	0.385
		180	-4.333	-6.000	-2.667	-0.027	0.974
		200	-2.000	-5.333	-0.333	-0.009	1.315
		Overall	-2.500	-3.500	-1.611	0.001	0.483

Table 12
Pairwise comparison of the perceived satisfaction of the visualization approaches.

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
		60	0.667	-0.667	1.667	0.006	0.546
		90	1.333	-0.333	2.667	-0.002	0.851
		105	1.333	-1.333	3.333	-0.002	1.205
Map+Table	Map+Markers	140	0.333	-1.000	1.000	-0.001	0.545
		180	3.667	1.667	5.000	0.005	0.861
		200	-2.000	-4.333	0.333	0.011	1.250
		Overall	0.889	-0.444	1.889	0.002	0.588
		60	0.000	-1.000	0.333	0.003	0.381
		90	-0.333	-1.667	0.667	-0.009	0.547
		105	-1.333	-2.000	-1.000	-0.005	0.271
Map+Table	Map+Circular Treemap	140	-1.000	-2.667	-0.333	0.000	0.599
		180	-0.667	-2.000	0.000	0.006	0.553
		200	-3.667	-5.667	-1.667	0.010	1.078
		Overall	-1.167	-2.333	-0.500	0.010	0.453
		60	-0.667	-2.000	0.000	0.012	0.550
		90	-1.667	-3.333	-0.333	-0.006	0.773
		105	-2.667	-5.000	-1.000	0.015	1.183
Map+Markers	Map+Circular Treemap	140	-1.333	-2.000	-1.333	0.001	0.270
		180	-4.333	-5.667	-3.000	-0.008	0.774
		200	-1.667	-4.000	0.333	-0.020	1.184
		Overall	-2.056	-2.944	-1.222	-0.001	0.452

Table 13
Pairwise comparison of the perceived ease of use of the visualization approaches.

Approach A	Approach B	Attribute Level	Mean Difference	CI Low	CI High	Bias	SE
Map+Table	Map+Markers	60	-0.333	-1.000	-0.333	0.003	0.270
		90	3.667	3.000	4.000	-0.004	0.274
		105	1.333	-0.333	3.667	-0.013	1.016
		140	1.667	-0.333	3.000	0.009	0.862
		180	2.667	-0.667	4.667	-0.005	1.269
		200	-0.333	-4.667	2.333	0.023	1.728
		Overall	1.444	0.167	2.389	-0.003	0.550
Map+Table	Map+Circular Treemap	60	-0.667	-1.000	-0.333	-0.006	0.268
		90	0.333	-0.667	1.333	0.002	0.613
		105	-1.333	-2.000	-1.333	0.003	0.272
		140	0.000	-1.667	2.000	-0.009	0.950
		180	0.000	-1.667	1.667	0.014	1.126
		200	-2.667	-5.667	-0.667	0.013	1.213
		Overall	-0.722	-1.722	0.000	0.007	0.420
Map+Markers	Map+Circular Treemap	60	-0.333	-1.000	0.333	0.004	0.388
		90	-3.333	-4.000	-2.667	0.007	0.548
		105	-2.667	-5.000	-1.333	0.009	0.983
		140	-1.667	-3.667	0.333	-0.012	1.093
		180	-2.667	-5.667	0.333	-0.034	1.650
		200	-2.333	-4.333	0.667	-0.019	1.258
		Overall	-2.167	-3.111	-1.111	-0.005	0.517