Quantitative Data Visualisation on Virtual Globes

Kadek Ananta Satriadi
Monash University
Melbourne, Australia
kadek.satriadi@monash.edu

Barrett Ens
Monash University
Melbourne, Australia
barrett.ens@monash.edu

Tobias Czauderna
Monash University
Melbourne, Australia
tobias.czauderna@monash.edu

Maxime Cordeil
Monash University
Melbourne, Australia
maxime.cordeil@monash.edu

Bernhard Jenny
Monash University
Melbourne, Australia
bernie.jenny@monash.edu

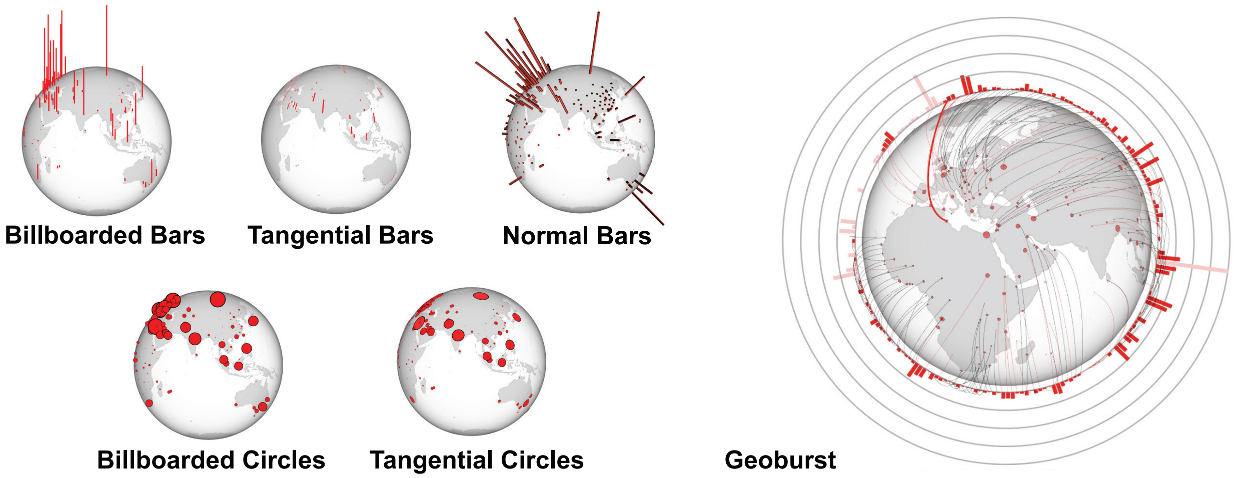


Figure 1: The five globe visualisation idioms evaluated in our study (left) and the *Geoburst* design (right).

ABSTRACT

Geographic data visualisation on virtual globes is intuitive and widespread, but has not been thoroughly investigated. We explore two main design factors for quantitative data visualisation on virtual globes: i) commonly used primitives (*2D bar*, *3D bar*, *circle*) and ii) the orientation of these primitives (*tangential*, *normal*, *billboarded*). We evaluate five distinctive visualisation idioms in a user study with 50 participants. The results show that aligning primitives tangentially on the globe's surface decreases the accuracy of area-proportional circle visualisations, while the orientation does not have a significant effect on the accuracy of length-proportional bar visualisations. We also find that tangential primitives induce higher perceived mental load than other orientations. Guided by these results we design a novel globe visualisation idiom, *Geoburst*, that combines a virtual globe and a radial bar chart. A preliminary evaluation reports potential benefits and drawbacks of the *Geoburst* visualisation.

CCS CONCEPTS

- **Human-centered computing → Visualization.**

KEYWORDS

geovisualisation, virtual globes, quantitative data visualisation

ACM Reference Format:
Kadek Ananta Satriadi, Barrett Ens, Tobias Czauderna, Maxime Cordeil, and Bernhard Jenny. 2021. Quantitative Data Visualisation on Virtual Globes. In *CHI '21: ACM Conference on Human Factors in Computing Systems, May 08–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Virtual globes are widely used for visualising quantitative data (such as global pandemic data [10], earthquake epicentres [33], or human population [46]) and virtual globes often serve as a device for narrative storytelling in news media [10, 29] or for public installations [55]. Furthermore, emerging technologies such as tangible interfaces and extended reality displays have brought new means to visualise and interact with virtual globes [20, 52, 55, 62]. Common

---

CHI '21, May 08–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-XXXX-X/18/06…$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

visualisations for quantitative data on virtual globes use circles that vary in area or three-dimensional bars that vary in length. Despite the prevalence of quantitative data visualisations on globes, their effectiveness has not been thoroughly studied, and there is very little guidance for designing quantitative data visualisations with virtual globes. Considering the increasing popularity of visualisation on interactive virtual globes, design guidelines and an evaluation of different globe visualisations are crucial.

We focus on the visualisation of quantitative data on virtual globes. We first identify visualisation idioms for virtual globes by exploring commonly used primitives and the orientation of these primitives. From these design considerations, we derive five distinctive quantitative visualisation idioms for virtual globes that use area-proportional circles or length-proportional bars as a visual channel, and vary the way the primitives are placed on the globe (tangential, normal and billboarded). We then evaluate the five idioms by conducting a user study with 50 participants. The results of the study indicate that area-proportional circles with a tangential alignment have poor reading accuracy. The reading accuracy of length-proportional bars on the other hand does not seem to be affected by the orientation. The study results also show that aligning primitives tangentially on a globe leads to a higher perceived mental load, whereas bars perpendicular to the globe surface (normal) are effective and aesthetically pleasing.

Motivated by the results of the study, we explore *Geoburst*, a new approach to visualising quantitative data by combining a virtual globe with a radial bar chart. We propose an interaction design and create a prototype of the *Geoburst* visualisation using a city population dataset. We showed the prototype to visualisation expert users in a preliminary evaluation. The results uncover potential benefits, challenges, and key factors in designing the *Geoburst* visualisation.

This paper explores the effectiveness of different idioms for data visualisation on globes. The key contributions of this paper are:

1. an evaluation of globe visualisation idioms using graphic perception tasks,
2. discussion of design implications for visualising quantitative data on globes, and
3. *Geoburst*, a novel visualisation that links a virtual globe with a radial bar chart.

For the remainder of the paper, we use 'globes' and 'virtual globes' as synonyms.

2 BACKGROUND AND RELATED WORK

2.1 The Ubiquitous Globe Visualisations

The development of computer-generated globes was underpinned by Al Gore in 1992 [22, 23] with his "Digital Earth" vision, and since then, data visualisation on virtual globes has become very popular in various contexts. Nowadays, virtual globes such as Google Earth or Cesium are commonly used for urban planning [58], climate data [34], education [41] and communication in news media. For example, the current Coronavirus pandemic is often visualised on virtual globes, such as the number of COVID-19 cases or the pandemic's effect on international flights (Figure 2, A, B). Professional data analysis software such as Power BI[1] (Figure 2, C) or Esri's geographic information systems[2] (Figure 2, D) support globe visualisations. Globes are also increasingly used beyond the 2D desktop in mixed reality applications (Figure 2, E, F).

In a broader context, the advancement of computing technology has opened up new means to visualise and interact with virtual globes. Recent examples include globe visualisations combining tangible spheres and virtual reality rendering [20], flow maps on virtual reality globes [62], augmented reality globes [52], as well as 3D printed globe visualisations [51, 52]. Vega et al. [55] explored opportunities of globe visualisations and suggested that globes are highly compelling and versatile for information visualisation and public space installations. This argument aligns with recent studies on maps and globes in virtual reality that found that globes are intuitive and familiar to users [62]. Other studies supported the user preferences towards globes over flat maps for flow maps and prism maps [56, 60].

However, placing quantitative visualisations on globes is arguably not always the most effective way to visualise geographic data. Globes suffer from distortion near the horizon [44] and complete occlusion of an entire hemisphere. Nevertheless, data visualisation on virtual globes is highly popular.

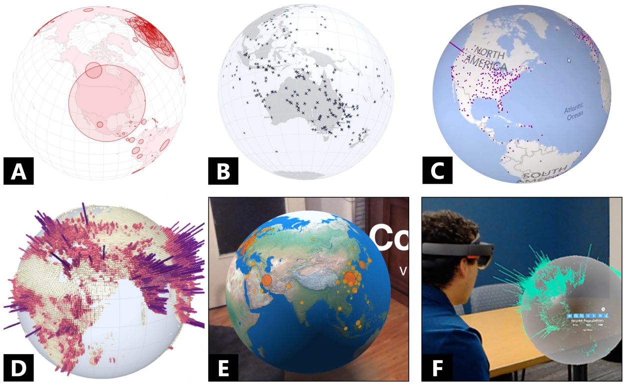


Figure 2: Examples of globes and visualisation. From A to F: COVID-19 cases [10], flight numbers visualisation [29], Power BI globe [37], population count visualisation [46], COVID-19 number of cases in augmented reality [35], data globe on HoloLens [39].

2.2 Visualising Quantitative Data on Maps and Globes

This research focuses on the visualisation of discrete phenomena on virtual globes, that is, geographic phenomena that are best visualised with value-proportional point symbols, such as bar and circle primitives [54]. This section summarises related past studies on quantitative data visualisation on maps and globes. In general, very little empirical evidence has been gathered to understand quantitative idioms for virtual globes, and research on virtual globes and virtual globes using a three-dimensional surface as spatial reference is surprisingly scarce.

---

[1] https://powerbi.microsoft.com/en-us/

[2] https://www.esri.com/

Data visualisation encodes values with marks and channels of visual primitives [38]. For globes, the types of primitive used are mainly bars sticking out of the globe [37] and circles that are aligned tangentially on the globe's surface [10]. White et al. [56] explored the visualisation of continuous geographic phenomena using choropleth and prism maps on 2D maps and globes. They found no effect on accuracy between 2D maps and globes but the response time for globes was higher than for 2D maps. A study by Popelka et al. [44] compared proportional symbols on perspective maps and zoomed-in views of a virtual globe. Their study confirmed the increased response time for globes and also found that the distortion of the symbol near the horizon decreases reading accuracy [44].

For maps, we focus on studies that evaluated quantitative geographic data visualisation on maps that use a three-dimensional reference space [18] or evaluated three-dimensional visual primitives for encoding quantitative information [4–6, 45, 50]. In a relative size estimation task, Bleisch et al. found that 2D bars were more accurate than 3D bars, and 2D circles were the least accurate [4]. They also found that 2D circles were the least performative while 3D bars were the fastest idiom [4]. Researchers in cartography and geovisualisation have explored the effects of different types of reference spaces, that is, 2D flat maps or 3D surface maps, but could not find significant differences between flat 2D maps and 3D terrain maps when using 2D bar chart primitives [5, 50].

3 QUANTITATIVE DATA VISUALISATION IDIOMS FOR VIRTUAL GLOBES

In this section, we identify five sensible and distinctive quantitative visualisation idioms for virtual globes. Two-dimensional and three-dimensional bars, as well as area-proportional circles and squares are the most common value-proportional primitives for representing quantitative data on maps [17, 54]. Round shapes, like circles, are commonly preferred to angular shapes, like squares [14, 53], and are visually stable [54]. We therefore limit our exploration to bar and circle primitives. The bar and circle primitives can be oriented in different ways on the globe. We use normal vectors and orthogonal tangent vectors on the globe surface to describe the orientation of primitives.

We focus on the type of primitives and their orientation, because these are the two most fundamental properties. We do not explore other design considerations in more details, such as the effect of the camera's field of view [24], the globe's scale, or the graphic design of primitives (e.g. considerations for choosing the primitives' dimensions and colour).

Normal vectors of a sphere's surface vary from pointing towards the camera in the centre of the view to being perpendicular to the camera's viewing direction on the horizon of the globe (Figure 3). Variations in direction are also present for the sphere's tangent vectors that vary with the location on the globe. Flat primitives placed on the globe can also be "billboarded" [1]; that is, oriented to consistently face the user's viewpoint, which prevents distortion due to an oblique viewing angle.

By combining these three orientations with the three commonly used primitives, we created a 3 × 3 matrix of visualisation idioms for quantitative information on virtual globes (Figure 4). This matrix combines the three identified orientations (tangential, normal and billboarded) with the three primitives (2D bar, 3D bar and 2D circle). However, we discard four of the nine combinations that are not unique or sensible. The 2D bar and circle with normal orientation (Figure 4, top middle, bottom middle) are not sensible because their flat geometry makes them invisible when positioned near the centre of the globe, pointed toward the viewer. Tangential and billboarded 3D bars (Figure 4, middle left and middle right) are not unique because they look very similar to 2D bars from the viewer's perspective. The remaining five visualisations used in our study are discussed below.

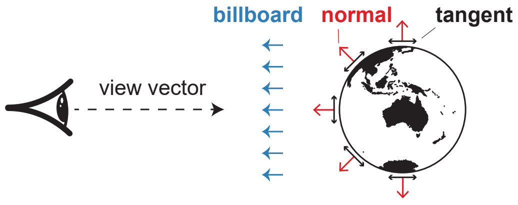


Figure 3: Possible orientations of primitives on a globe.

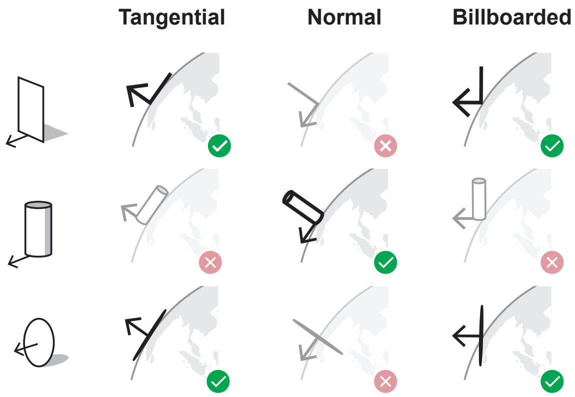


Figure 4: Visualisation idioms for quantitative data visualisation on globes. Idioms with a cross are discarded.

Billboarded Bars (Figure 4, top right). Billboarding flat primitives harnesses "the power of planar" [38], and makes bar lengths easily comparable by aligning them in the same orientation. However, this causes two issues: First, bars that pass behind others are occluded. Second, bars on the southern hemisphere point towards the interior of the globe and are hidden by the globe surface. This can be fixed easily by positioning the upper end of the bars on the globe surface, but this introduces a perceptual inconsistency, potentially limiting the usefulness of this idiom.

Tangential Bars (Figure 4, top left). This idiom aligns 2D bars tangentially on the globe's surface as if they are printed on the globe's surface. The visual channel of the *Tangential Bars* idiom is the spherical arc length. This approach preserves the visibility of the globe surface and allows all bars to be presented in the same direction (e.g. towards the north pole). However, this representation is prone to view distortion when bars are placed close to the horizon of the globe.

Normal Bars (Figure 4, centre). In this idiom, three-dimensional bars or tubes are aligned with the normal of the sphere's surface. This representation is arguably the most common representation of quantitative values on a globe that we found in media (e.g. Figure 2, C, D, F). This idiom shares the occlusion issue of billboarded bars, and has an additional issue of perceptually shrinking bar lengths when bars are positioned at the visual centre of the globe view.

Billboarded Circles (Figure 4, bottom right). In this idiom, 2D circles are oriented towards the camera's position, ensuring viewers see perfect circles. Like *Billboarded Bars*, this idiom "preserves the power of planar" but has an occlusion issue where a part of a circle near the horizon penetrates the sphere and is invisible. In addition, since the depth of each circle is determined by its location on the globe surface, we lose the flexibility of sorted drawing, that is, rendering large circles first and small circles later as is conventional for proportional symbol maps to reduce occlusion [7].

Tangential Circles (Figure 4, bottom left). This idiom uses 2D circles placed tangentially on the globe's surface. Each circle becomes a spherical cap, with the visual channel of the idiom being the cap's area. As opposed to *Billboarded Circles*, the orientation of *Tangential Circles* allows for sorted drawing, that is, large circles are rendered first to reduce occlusion of small circles. Examples of this idiom are shown in Figure 2, A, E.

4 USER STUDY: RELATIVE SIZE ESTIMATION

We conducted a user study to empirically evaluate the five globe visualisation idioms defined in the previous section. In particular, we aimed to better understand the effects of primitive types and orientations on the interpretation of encoded data values. To collect results from a diverse set of participants, we used crowdsourcing with a custom-built online virtual globe.

4.1 Task and Study Design

In this section we describe the design of our user study and the motivation behind it. We use a relative size estimation task, which has been used in related studies [4, 11, 12, 25]. Our study is similar to Cleveland and McGill's graphic perception studies [11, 12] but with two key differences: we evaluate arc length and spherical cap area which were not included in their studies, and we use a globe rather than a flat 2D plane. This task asks participants to inspect two values and estimate the size of the smaller value relative to the larger one. In our study, the answers range from 0% to 100% where 100% means both primitives have the same value.

Idiom is the primary factor of our study, which includes the five idioms discussed in section 3. We include several other factors that affect the presentation of elements within each idiom, as described below.

Distance. Similar to a previous study [61], the *Distance* factor in our study defines the angular distance between the two values to be compared. We define three angular distances, 20°, 60°, and 120°, with increasing levels of distortion caused by the placement of values further from the view centre (Figure 5, top).

RelSize. Another factor is relative size (*RelSize*) which is a common factor for studies with relative size estimation tasks [11, 25]. It is the relative difference between the values represented by two visual primitives. This factor has never been tested on a spherical surface, so we include this factor in our study. We define five relative sizes: 10%, 30%, 50%, 70%, and 90%.

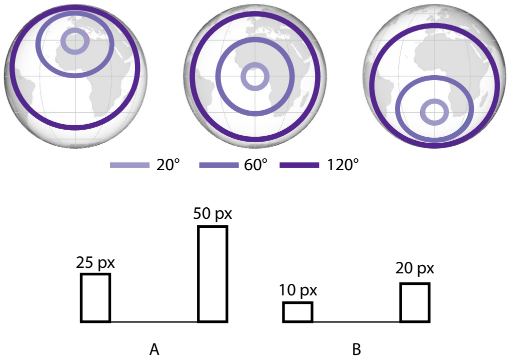


Figure 5: Top: the variation of angular distances with varying latitude from left to right as used in our study. Bottom: illustration of two pairs of bars (A, B) with the same relative size (50%) between the larger and smaller bars but with different maximum sizes (50 px in pair A, 20 px in pair B).

MaxSize. Similar to Cleveland and McGill's experiment [12], the *MaxSize* factor determines the maximum size of the primitives in each idiom (Figure 5, bottom). For each task, the larger of each pair of values will be determined by the maximum size, while the second value is determined by the relative size factor. Since the absolute size of the primitives will affect the ability of participants to perceive differences, we include two different values to evaluate how this affects different idioms: *Large* and *Small* maximum size.

To summarise, our study design consists of the following four factors.

- *Idiom* = {*Tangential Bars*, *Billboarded Bars*, *Normal Bars*, *Tangential Circles*, *Billboarded Circles*}
- *Distance* = {20°, 60°, 120°}
- *RelSize* = {10%, 30%, 50%, 70%, 90%}
- *MaxSize* = {*Large*, *Small*}

The total number of responses per participant is 5 *Idiom* × 3 *Distance* × 5 *RelSize* × 2 *MaxSize* = 150 responses.

4.2 Mapping Data Values to Visual Channels

The equations for mapping data values to visual channels are shown in Table 1. We use a linear data mapping for all bar visualisations. For *Billboarded Circles*, we encode the data value to be proportional to the circle's area by calculating the radius [54] without perceptual adjustment, such as the one suggested by Flannery [21]. The equation for mapping a data value to the area of a spherical cap for the tangential circle idiom is given in Table 1. The formula determines the central angle θ (Figure 6) of the spherical surface area equation [43]. Steps we took to derive the equation are provided in Supplementary Material 1.

To define the *Large* and *Small* sizes, we first created visualisations with an actual dataset and varied properties, such as the width and height of bars. We then chose suitable property values for each idiom. For the *Billboarded Bars* and *Normal Bars*, the *Large*

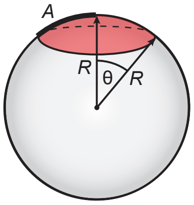


Figure 6: The central angle θ as calculated in Table 1. The red area is the spherical cap.

size is equal to the radius of the sphere while *Small* size is 25% of the sphere radius. To make *Tangential Bars* comparable with *Billboarded Bars* and *Normal Bars*, we assume that the length of the bar for *Billboarded Bars* and *Normal Bars* is equal to the length of the arc in *Tangential Bars*, which allows us to calculate the associated maximum central angles ($Large = 57.3°$, $Small = 14.3°$).

Defining a circle's area that is comparable with a length is a difficult design problem. We use a pragmatic approach in defining the primitive *MaxSize* by evaluating the appearance of the visualisation with an actual dataset. For *Billboarded Circles*, we choose a circle radius of 10% of the sphere radius for the *Large* maximum size and 5% for the *Small* maximum size. Since the calculated value for the *Tangential Circles* idiom is the central angle of the spherical cap, we assume that the radius of the *Billboarded Circles* idiom is equivalent to the length of the arc of the spherical cap (Figure 6, A), which results in a *Large* maximum size of 5.7° and a *Small* maximum size of 2.9° for the central angle of *Tangential Circles*. All globe visualisation idioms with the *Large MaxSize* are shown in Figure 1.

4.3 Apparatus

We composed a dataset containing 30 value pairs for each idiom (3 *Distance* × 5 *RelSize* × 2 *MaxSize*). Each idiom had the same set of pairs, but we randomised the order to reduce the learning effect. Since the *Distance* factor does not determine where values should be placed on the globe, we created 10 (5 *RelSize* × 2 *MaxSize*) predefined locations by varying latitudes (Figure 5, top). For billboarded idioms, we placed visual primitives on the three-dimensional model, which means we allowed minor perspective distortion. We created an online study apparatus using Unity WebGL[3] on a 1280 pixels × 700 pixels canvas and hosted the study apparatus on our own web server. To ensure the study ran smoothly, we used a hardware screening criterion of a minimum of 8GB of memory. Study apparatus materials and the questionnaire are provided in the Supplementary Material 3.

4.4 Procedure

The *Idiom* order for each participant was assigned according to the Latin square order. For each idiom, we provided four training trials with random relative size values. In the beginning of each trial, we rotated the globe such that the globe was centred on the middle point between the two visual primitives. We also drew an arc connecting the two primitives to minimise the time required by participants to locate them. We intentionally did not show the graticule (regularly spaced lines of meridians and parallels) to prevent participants from using it as a measurement tool.

A time limit of 10 seconds was given for each trial, which is roughly the time to complete a brief task [8], to limit study duration and to motivate participants to perform quick judgement. Participants provided their estimations using an answer panel containing a slider with a range from 1% to 100% with three labels (1%, 50%, and 100%) and representative icons of the label values. We allowed participants to perform a limited rotation of the globe using the mouse. Since we did not allow participants to zoom, we set the camera's field of view such that the globe appeared similar to a globe in Google Maps.

In general, our study consisted of three main steps: *briefing*, *trials*, and *post-study questionnaire*. The briefing stage consisted of approximately 5 minutes of reading the task descriptions. We deliberately asked participants to perform one block of trials to ensure the total study time was manageable. Each participant performed a total of 170 trials (150 actual trials + 20 training trials) in a maximum of 30 minutes time. After the trials, the participant was redirected to a 5-minute post-study questionnaire. In total, the duration of the study was around 40 minutes.

4.5 Participants and Data Collection

For the data collection, we recruited a total of 52 participants, 35 participants from the Prolific.co [40] crowdsourcing service (9 females, 25 males, 1 participant preferred not to say) and 17 participants from convenience sampling (demographics not collected). We collected three types of data: *i*) task-related data, *ii*) interaction log data, *iii*) subjective measures data. For the task-related data, we recorded participants' relative size estimations and response times. The response time was recorded from the start of the trial until the participant pressed the space button on their keyboard to show the answer panel. The interaction log data mainly contained the globe rotation and mouse position which was sampled 10 times per second. In the post-study questionnaire, we asked participants to rate confidence, aesthetics, and perceived mental load for each of the idioms on a Likert scale (1 – strongly disagree to 5 – strongly agree). We also asked participants to briefly explain their strategy to estimate the values for each idiom.

We created a study on Prolific.co and that we linked with our web server. We set a pre-screening criterion on normal and corrected vision, English language proficiency, minimum approval rate of 95%, and minimum number of previous submissions of 10. We also limited our study to desktop only. We provided a payment [9] of £5 with a rate of £7.5/h which is considered as a "good" payment according to Prolific.co.

5 RESULTS

5.1 Analysis

We reviewed the data collected from the participants using statistical methods and visualisation (details provided in the Supplementary Material 2). After discarding the data of two of the crowdsourced participants, we finally had data from 50 participants (33 crowdsourced, 17 non-crowdsourced) with a total of 7500 observations. We removed a total of 1.8% trials (135 trials) that either had a

---

[3] https://docs.unity3d.com/Manual/webgl-building.html

Table 1: Idioms, visual channels, calculated values, and equations. R **= globe radius,** d_i **= data value,** d_{max} **= maximum value,** θ_{max}**,** h_{max}**,** r_{max} **are maximum central angle, maximum height, and maximum radius determined by *Large* and *Small* conditions.**

Idiom	Visual Channel	Calculated	Equation	*Large*	*Small*
Tangential Bars	arc length	central angle (θ_i)	$\theta_i = \frac{d_i}{d_{max}} \times \theta_{max}$	$\theta_{max} = 57.3°$	$\theta_{max} = 14.3°$
Billboarded Bars	bar height	height (h_i)	$h_i = \frac{d_i}{d_{max}} \times h_{max}$	$h_{max} = R$	$h_{max} = 0.25\ R$
Normal Bars	bar height	height (h_i)	$h_i = \frac{d_i}{d_{max}} \times h_{max}$	$h_{max} = R$	$h_{max} = 0.25\ R$
Billboarded Circles	circle area	radius (r_i)	$r_i = (\frac{d_i}{d_{max}})^{0.5} \times r_{max}$	$r_{max} = 0.1\ R$	$r_{max} = 0.05\ R$
Tangential Circles	spherical cap area	central angle (θ_i)	$\theta_i = arcos(1 - \frac{d_i}{d_{max}} \times (1 - cos(\theta_{max})))$	$\theta_{max} = 5.7°$	$\theta_{max} = 2.9°$

z-score of absolute error > 3 or, due to technical issues, a response time > 11 seconds.

We performed Shapiro–Wilk tests on the log absolute error and response time of the trials and found that both measures are not normally distributed. Thus, we used the Aligned Rank Transform (ART) [57] approach that allowed us to perform a factorial parametric repeated measure ANOVA test on error and response time data. As per post-hoc analysis, we used the Least Squares Means model with Bonferroni adjustment. The Shapiro–Wilk test of subjective measure data also showed that the data was not normally distributed. We then used the Kruskal-Wallis non-parametric test with Wilcox Bonferroni pairwise comparison test for all subjective measures. We used confidence levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$. Visualisations of the results can be seen in Figure 7.

5.2 Errors

The result of repeated measure ANOVA of log absolute error showed main effects on *Idiom* ($F = 75.24$, $p < 0.001$), *RelSize* ($F = 241.61$, $p < 0.001$), and *MaxSize* ($F = 33.76$, $p < 0.001$). No main effect was found on the *Distance* factor. We also found interaction effects on *Idiom* × *RelSize* ($F = 4.00$, $p < 0.001$), *Idiom* × *MaxSize* ($F = 16.50$, $p < 0.001$), *Idiom* × *Distance* ($F = 2.60605$, $p < 0.01$), and *Idiom* × *RelSize* × *MaxSize* ($F = 3.06371$, $p < 0.001$). However, further analysis of the interaction effects did not show significant differences in disordinal / crossover interactions which supports the generalisability of the result of the main effects.

Post-hoc analysis of main effects revealed several significant differences. In terms of *Idiom*, we found that the two area-proportional idioms, *Billboarded Circles* and *Tangential Circles*, were significantly less accurate than the three length-proportional idioms. The *Tangential Circles* idiom was less accurate than the *Billboarded Circles* idiom, making it the worst in terms of accuracy. We found no differences in accuracy among bar-based idioms (see Figure 7).

The *RelSize* Post-hoc analysis showed that results for extreme values were more accurate than for middle values ($p < 0.001$) with 10% and 90% more accurate than 30%, 50%, 70% and 30% more accurate than 50%, 70%. We found no differences between 50% and 70%. As per *MaxSize*, we found that results for *Large* were more accurate than for *Small* ($p < 0.001$) *MaxSize*.

We also looked at actual relative size vs estimated relative size (Figure 8, left). Our visual analysis shows that participants tended to underestimate the actual size for *Billboarded Circles*. In contrast, the *Tangential Circles* show an overestimation trend where most of the estimated relative sizes are higher than the actual relative sizes.

5.3 Response Time

We found main effects on all factors: *Idiom* ($F = 308.75$, $p < 0.001$), *RelSize* ($F = 18.42$, $p < 0.001$), *MaxSize* ($F = 29.80$, $p < 0.001$), and *Distance* ($F = 156.43$, $p < 0.001$). Interaction effects were found on *Idiom* × *RelSize* ($F = 2.47$, $p < 0.001$), *Idiom* × *MaxSize* ($F = 16.89$, $p < 0.001$), *Idiom* × *Distance* ($F = 8.45$, $p < 0.001$), *RelSize* × *MaxSize* ($F = 2.99$, $p < 0.05$), and *Idiom* × *RelSize* × *MaxSize* ($F = 2.64$, $p < 0.001$).

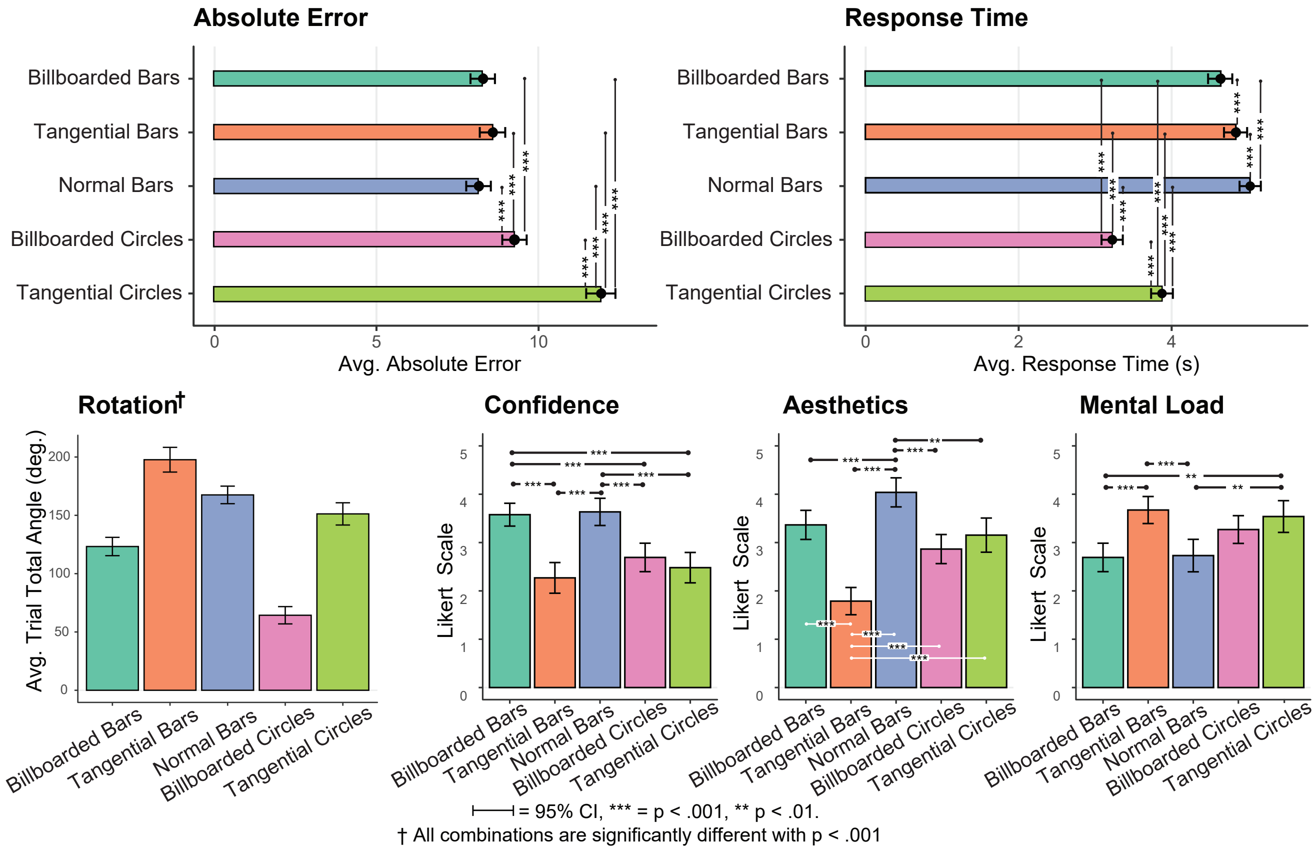
Post-hoc analysis showed that the *Billboarded Circles* idiom was the fastest among all idioms, all circle-based idioms were faster than all bar-based idioms. The *Billboarded Bars* idiom was faster than *Tangential Bars* and *Normal Bars*. The *Normal Bars* idiom was the slowest among all idioms. For *RelSize*, we found that 10% was faster than 30%, 50%, 70% ($p < 0.001$), 90% ($p < 0.01$), and 90% was faster than 50% ($p < 0.05$), 70% ($p < 0.01$). The post-hoc test of *MaxSize* shows that *Small* is faster than *Large* size ($p < 0.001$). In terms of *Distance*, we found that 20° was faster than 60° ($p < 0.001$), 120° ($p < 0.001$), and 60° was faster than 120° ($p < 0.001$).

The analysis of the interaction effects revealed two significant crossovers (Figure 8, right). First, there was a strong crossover between (*Normal Bars* – *Tangential Bars* | *Large*) and (*Normal Bars* – *Tangential Bars* | *Small*). This result indicates that the *Tangential Bars* idiom is much faster than the *Normal Bars* idiom on the *Small MaxSize* condition. The second significant crossover interaction was found between (*Normal Bars* – *Tangential Bars* | 60°) and (*Normal Bars* – *Tangential Bars* | 120°) which indicates that the *Tangential Bars* idiom is faster than the *Normal Bars* idiom for 60°.

5.4 User Interactions

We calculated the mean angle of globe rotation per trial for each of the idioms and performed the Kruskal-Wallis test (Figure 7). We found that the mean total angle of rotation per trial was smallest for *Billboarded Circles* (mean = 64°) and *Billboarded Bars* (123°). Participants used more rotation for *Tangential Circles* (151°), *Normal Bars* (168°), and *Tangential Bars* (198°).

We analysed the user interaction further by looking at the relationship between globe rotation, response time, and error. We found that the amount of total rotation has an effect on the response time, but we could not conclusively find any effect of total rotation on the absolute error. Kendall correlation analysis for all idioms shows low positive correlation between total rotation and response time ($p < 0.001, r = 0.44$) and negligible correlation between total rotation and absolute error ($p < 0.001, r = -0.03$) [26].



⊢⊣ = 95% CI, *** = p < .001, ** p < .01.

† All combinations are significantly different with p < .001

Figure 7: Main measures of all idioms.

Further analysis of correlation per idiom for total rotation and absolute error only shows negligible correlation on *Tangential Bars* ($p < 0.01, r = -0.05$) and *Tangential Circles* ($p < 0.01, r = -0.05$).

To get a better understanding of user interaction patterns per idiom, we grouped user interactions based on the interquartile range of the total globe rotation per trial: *none* ($0° - 3.5°$), *low* ($3.5° - 96.5°$), *medium* ($96.5° - 220.4°$), *high* ($> 220.4°$) and looked for patterns in errors using visual analysis.

The amount of rotation varies across idioms (Figure 9, top). Of all idioms, participants used the highest amount of rotation with *Normal Bars*. When comparing the two billboarded idioms, it is apparent that participants used fewer interaction with *Billboarded Circles* and more interaction with *Billboarded Bars*. We see a similar pattern with tangential idioms where participants use less rotation with circles than bars. Figure 9, bottom, shows absolute error and interaction patterns for all idioms. For *Tangential Bars* more interaction resulted in smaller errors. In general, Figure 9, bottom, does not show a clear pattern between the amount of rotation and absolute error.

5.5 Subjective Measures

The analysis of subjective measures revealed several findings (Figure 7).

Confidence – We found significant differences in confidence ratings ($\chi^2 = 61.13,\ p < 0.05$) with a higher rating for *Billboarded Bars* and *Normal Bars* than for all other visualisation idioms.

Aesthetics – We also found significant differences in subjective rating of aesthetics ($\chi^2 = 78.42,\ p < 0.05$). The *Normal Bars* idiom was found to be the most aesthetically pleasing while the *Billboarded Bars* idiom was the least pleasing.

Perceived Mental Load – Significant differences were found in perceived mental load ratings ($\chi^2 = 31.71,\ p < 0.05$) with both tangential idioms, *Tangential Bars* and *Tangential Circles*, yielding significantly higher perceived mental load than *Billboarded Bars* and *Normal Bars*. No difference was found for *Billboarded Circles*.

5.6 Qualitative Feedback

We looked at participants comments on the interaction strategy and identified common themes for each idiom.

Billboarded Bars. The most common strategy reported by participants for the *Billboarded Bars* idiom was directly estimating values. Although the bars could be directly compared, a notable number of participants tried to align the two bars on a horizontal axis: "*try best to rotate the globe to let two bars have same bottom line* ..." (P49). A few participants also found that the *Billboarded Bars* idiom made it easy to perform comparison and required less effort to rotate the globe (P41, P43, P30).

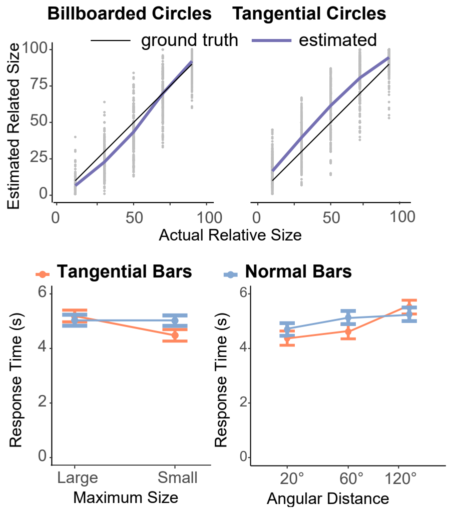


Figure 8: Top: underestimation on *Billboarded Circles* and overestimation on *Tangential Circles* (blue lines connect estimated relative sizes mean values). Bottom: crossover interaction effects on response time between *Tangential Bars* and *Normal Bars*.

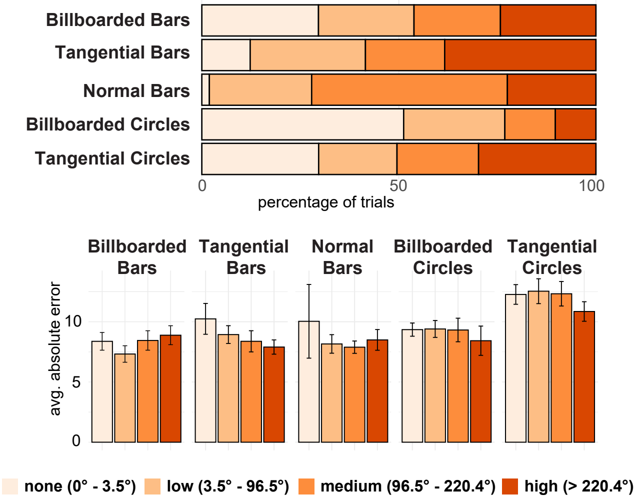


Figure 9: Top: the amount of rotation per idiom for interquartile ranges. Bottom: the average absolute error per idiom and interquartile range. Error bars show 95% CI. (CI of the first quartile of *Normal Bars* is high due to small number of trials.)

***Tangential Bars*.** Some participants reported they were mainly trying to centre the two bars on the globe and to memorise the size of the tangential bars. The *Tangential Bars* idiom was reported by a few participants to be difficult to compare and required memorisation of the bars (e.g. "*This was extremely hard, had to compare them with memory ...*", P9; "*... compare them with a memory of the previous bar ...*", P30).

***Normal Bars*.** As per *Normal Bars*, we found a very common strategy of aligning bars on the horizon of the globe to estimate the value. P45, "*Moved the 3D bars to the perimeter of the globe so that the end of bar that touches the surface is exactly at the horizon*". Two participants also commented that the *Normal Bars* idiom is visually nice (P41) and outstanding (P43).

***Billboarded Circles*.** For *Billboarded Circles*, six participants reported they were trying to imagine the smaller circle being placed inside the larger one and then estimated the size. A few negative comments were also given for this idiom. Participants found *Billboarded Circles* to be hard (P9, P17, P18), very counter-intuitive (P18), and most complicated (P40). Nevertheless, some participants appreciated the billboarding approach to reduce the effort to rotate the globe (P30, P43). "*I did not need to drag around the map too much*", P30.

***Tangential Circles*.** Common comments on *Tangential Circles* were quite similar to *Tangential Bars* where participants tried to rely on memory by quickly switching two spherical caps back and forth to the centre. A few participants reported that *Tangential Circles* idiom was harder than *Billboarded Circles* (P9, P38) while one participant commented that *Billboarded Circles* is the most unpleasant to estimate (P41). P41, "*... it required a lot of moving the globe and I wasn't confident in my comparisons.*"

5.7 Discussion

The *Tangential Circles* idiom (mean absolute error = 11.9) was the worst in terms of accuracy, being 28.5% less accurate than *Billboarded Circles* (9.26). The absence of significant differences in error between the bar idioms came as a surprise considering that, unlike *Billboarded Bars* (8.28), the *Normal Bars* (8.15) and *Tangential Bars* (8.58) have distortion issues. We found that the increase of primitive size benefits comparison accuracy with *Large MaxSize* causing smaller errors than *Small MaxSize*. We also confirmed the results from a previous study where it was found that relative estimation accuracy was high near extreme values (10% and 90%) and degraded as the actual relative size approached 50% [25]. Surprisingly, the variation in angular distances between the two values did not have any significant effect on the accuracy.

While being more accurate, the length-proportional idioms were slower than area-proportional visualisation idioms. This result aligns with previous graphic perception studies with visualisations in a non-globular space [11, 12] and contributes to the understanding of visual estimation of arc length and spherical cap area primitives. The fastest in response time was the *Billboarded Circles* idiom (mean time = 3.2 s) which is slightly faster than *Tangential Circles* (3.9 s). The *Normal Bars* idiom (5.0 s) was the slowest among all being slightly slower than *Billboarded Bars* (4.6 s) and *Tangential Bars* (4.8 s). The analysis of interaction effects showed interaction between the *Tangential Bars* and *Normal Bars* idioms. We found that the *Tangential Bars* idiom was slower than *Normal Bars* in the *Large MaxSize* condition but half a second faster in the *Small MaxSize* condition. Another factor that affects the response time of the two idioms was *Distance*. We found that the *Tangential Bars* idiom was faster than *Normal Bars* on 60° but slower on 120°.

Analysis of subjective measure suggested that *Billboarded Bars* and *Normal Bars* made participants more confident in their answers compared to the other types of idioms. The *Billboarded Bars* idiom was perceived as easy to compare and requiring less rotation. Not only yielding a high confidence rating, the *Normal Bars* idiom was also considered as the most aesthetically pleasing one. Participants perceived the *Normal Bars* as visually nice and outstanding. The least aesthetically pleasing one was the *Tangential Bars* idiom. In terms of perceived mental load, the tangential visualisation idioms, *Tangential Bars* and *Tangential Circles*, were perceived as mentally demanding. Participants commented that the *Tangential Bars* idiom requires them relying on short term memory to estimate the two values.

6 DESIGN IMPLICATIONS FOR VIRTUAL GLOBES

Based on our graphic perception study, we formulate several implications for the design of globe visualisations.

3D normal bars and billboarded 2D bars on a virtual globe are both accurate. In a desktop 3D perspective map geovisualisation study, Bleisch et al. [4] found that billboarded 2D bars are more accurate than 3D bars. However, we found no differences between the two primitives. We attribute this finding to the less cumbersome navigation on a globe compared to complex camera navigation on 3D perspective maps [15]. The seamless navigation on a globe makes it easy for users to perform value comparisons.

Tangential bars on a virtual globe are accurate to read but are not aesthetically pleasing. Despite the angular distortion of tangential 2D bars, participants in our study were able to read values from tangential 2D bars as accurately as from billboarded 2D bars. However, the *Tangential Bars* idiom received the lowest rating for aesthetics ($Mean = 1.78, SD = 1.01$).

Tangential circles on a virtual globe are difficult to read. The tangential circles idiom has clearly the worst reading accuracy. The differences compared to billboarded circles is rather surprising considering how easy it is to centre the tangential circle (as indicated by qualitative feedback), which results in an undistorted view of the circle. The difference in accuracy could be attributed to the fact that, unlike with billboarded circles, participants could not see two undistorted spherical caps simultaneously which forced them to rely on visual memory rather than eye fixation. We also found that participants tended to overestimate values mapped to tangential circles, i.e. spherical caps (Figure 8, left). While underestimation of size differences in circles is a known issue with proportional symbols [21], overestimation of tangential circles has not been reported. This finding suggests that the spherical cap mapping function would need to be perceptually adjusted.

Tangential bars and circles on a virtual globe have a high perceived mental load. Participants' comments and subjective measures suggest that tangential primitives were unpleasant to use, difficult to read, and required memorisation of visual primitives, which led to a high perceived mental load.

Two normal bars can be accurately compared with globe rotation. Despite inherent angular distortion, orienting bars on the normal of the globe can be as accurate as billboarded bars. The globe with normal bars was liked by the participants and received the highest aesthetic rating. Although this idiom was the slowest overall, the response time was less than 10% slower than the other bar idioms.

Billboarded bars and circles require less globe rotation. From an analysis of the recorded globe rotation interaction, we found that tangential bars, normal bars, and tangential circles have a significantly higher mean total rotation per trial than billboarded idioms. From the qualitative feedback, we also found that participants required rotation interaction to align tangential primitives in the centre and normal bars on the horizon.

Angular distance has no effect on accuracy. The absence of an effect on accuracy of the *Distance* factor is rather surprising since we expected that distortion of the tangential idioms with large distances would negatively affect perception of values. However, it appears from our results that interactive rotation helps participants to overcome this issue, by allowing them to quickly rotate the globe and compare two values.

Large primitives and large value differences are more accurate to read. We found that larger visual elements have a better estimation accuracy than smaller ones. This confirms a previous study [25] that found extreme relative size differences are easier to estimate than moderate ones (near 50%). However, increasing the visual element size leads to increased occlusions in dense maps.

7 *GEOBURST*: EXPLORING A NEW GLOBE VISUALISATION DESIGN

We were inspired by the observation in our user study that participants often aligned 3D bars on the globe horizon. We decided to explore the alignment of linked radial bar chart with the globe. In this section, we present the motivation, our design idea, and an implementation of the *Geoburst* prototype, a novel globe visualisation that combines a virtual globe with a radial bar chart (Figure 1, right).

7.1 Motivation

All visualisation idioms that we tested in the study, position the graphical primitives at the exact spatial reference point (and therefore have high locality). This approach is intuitive because it preserves the geospatial distribution, but it does not allow primitives to be arranged on a common axis . However, theory in data visualisation suggests that arranging bars on a common axis has a positive impact on reading accuracy [11, 25, 36].

A second potential issues with the evaluated idioms are occlusion and distortion. Bars on the *Billboarded Bars* and *Normal Bars* can occlude each other. Although occlusion can be circumvented with a highlighting interaction, it would require users' interventions. With the current globe idioms, it is also not possible to show all values at the same time, which requires users to rotate the globe to obtain a good understanding of the global distribution. Distortion with *Normal Bars* makes it difficult to compare values without aligning the primitives on a common axis (e.g. the globe's horizon).

The *Geoburst* idea mainly focuses on providing a virtual globe visualisation that facilitates visual comparison using a common scale, avoids distortion and occlusion, and provides a possibility to show hidden data point values. Table 2 shows a comparison of *Geoburst* with the *Billboarded Bars* and *Normal Bars* idioms. While geolocations on the hidden hemisphere are completely occluded, the

Geoburst design avoids occlusion among visual primitives, which is a shortcoming of the other idioms that we evaluated.

Table 2: Comparison of *Geoburst* with *Billboarded Bars* and *Normal Bars* idioms.

Idiom	Distortion	Occlusion	Locality
Geoburst	None	Hemisphere	Low
Normal Bars	High	Hemisphere + Primitives	High
Billboarded Bars	None	Hemisphere + Primitives	High

7.2 The *Geoburst* Visualisation

We use a composite visualisation approach [28] by integrating a globe with a radial bar chart. A radial bar chart is an elegant choice because of two reasons: i) good use of display space because the circular shape of the radial bar chart wraps the globe nicely, and ii) the wrapping minimises the distance between the spatial location and its associated bar on the radial bar chart without occluding the globe. Linking lines between the two views are used to connect the spatial location on the globe with the bar on the radial bar chart [13, 59], as suggested by the composite visualisation guideline [28]. Also, the radial bar chart is compatible with a wide variation of idioms on the globe surface.

The most important design factor in *Geoburst* is associating the bars with their geospatial positions on the globe. We create the same number of slots on the radial bar chart as there are number of positions on the globe. We first tried a naive approach by minimising the overall distance of *position–bar* pairs and realised that it causes bars "jumping around" when their spatial positions were rotated to the centre of the globe view. This naive approach also led to severe crossings of lines linking the spatial position with the bar. A redesign took into account the spatial distance between positions on the globe. Our current approach arranges bars in groups rather than only considering individual bars and consists of three main steps: i) *grouping*, ii) *bars placement*, and iii) *linking* (Figure 10).

Grouping – The first step is grouping positions using a clustering approach. The grouping process can be done using various point clustering methods; we use the DBSCAN clustering algorithm. Alternatively, the grouping could also be done based on the geographical area or data attributes (e.g. countries or continents).

Bars Placement – We arrange bars in groups using an optimisation algorithm to minimise the distance between the cluster's centre and the bar in the radial bar chart. In our design, we use the Hungarian algorithm [30]. Then, the bars within a group are arranged using the Jarvis march algorithm [27].

Linking – Finally, lines are used to link each spatial position on the globe with its corresponding bar. Interactive rotation of the globe likely breaks the constraint of the minimum distance between the position on the globe and the bar and could cause severe crossings of links. Thus, the bars need to be rearranged after each rotation. To avoid bar rearrangement on a small adjustment, we use a minimum threshold for the rotation angle at which the bar rearrangement is triggered. Moreover, the links can be made transparent or semi-transparent when the globe is being rotated to increase the visibility of the geo-locations.

We designed several link variations for *Geoburst* with the clutter reduction taxonomy by Ellis and Dix [19] in mind. Visual links can be either straight or curved, solid or faded [32] (Figure 11). A straight line is rendered in the screen space while curved lines follow the globe's hemisphere in 3D space. Faded lines are transparent at their mid-point and expected to reduce visual clutter. Alternatively, we could also show a link only when it is needed, e.g. when the mouse pointer hovers over a bar or a linked spatial location.

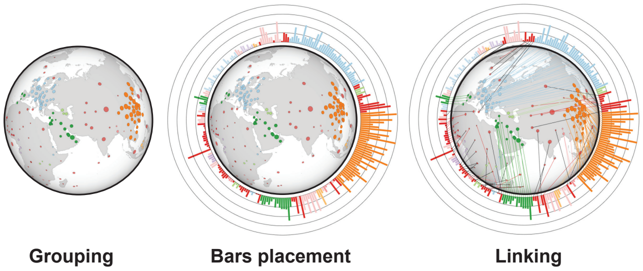


Figure 10: Three main steps to create the *Geoburst* visualisation: 1) group points (here we use the DBSCAN algorithm with $epsilon = 6$, $min.\ points = 3$), 2) arrange bars positions, and 3) link points and bars. Groups are colour-coded for illustration purposes. Bars for values on the hidden hemisphere are faded.

Other visualisation design considerations in *Geoburst* are dealing with hidden values and the radial size of the chart. By disconnecting the visual element from the geospatial locations, we can show all values on the radial bar chart. In our early design, the hidden and visible values can be distinguished by different colour brightness or alpha values (Figure 10). Although this property can be useful to show the global value distribution, showing all values might cause the bars being too small in width. As stated in our motivation, bars aligned on a circle could be easier to compare than if they are located on the globe. A possible variation can reduce the angular size of the radial bar chart to less than the full 360° circle. The use of a radial chart also allows us to place grid lines to help with comparison tasks.

Interaction Design. To support globe exploration, we designed interaction techniques for the *Geoburst* visualisation. *Highlighting* interaction increases the size of a link on mouse over. *Freeze Links* interaction allows users to highlight links permanently to support multiple value comparisons or to bookmark specific locations. A selection can be performed on the point or bar. *Clear Links* allows users to remove an individual frozen link or clear all links. Lastly, *Automatic Rotation* rotates the globe such that a hidden point becomes visible. This is triggered by a mouse action on the bar of the hidden value.

7.3 Prototype and Expert User Feedback

We created a demo prototype of the *Geoburst* visualisation in Unity. We used *Tangential Circles* as the base globe visualisation. Our demo prototype allows users to tweak *Geoburst* parameters such as

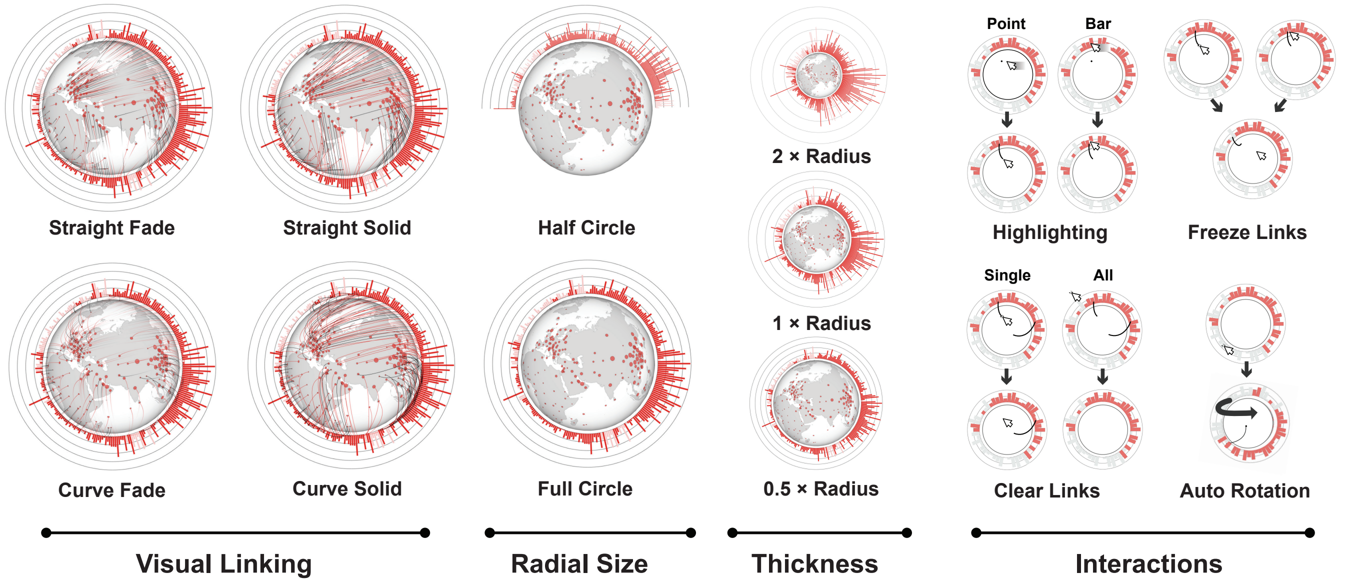


Figure 11: *Geoburst* variations of visual linking, radial size, thickness of the radial bar chart, and user interactions.

type of link and radial size. The dataset used in the demo prototype was a city population dataset[4].

We ran a preliminary evaluation with nine visualisation expert users (seven PhD students in data visualisation, one postdoctoral researcher, and one data visualisation lecturer) to obtain initial feedback about this new globe visualisation approach and to better understand users' preferences of different visualisation design factors. We published our demo on our web server and invited the participants to explore the *Geoburst* demo. To help them with the task, we provided sample questions such as *What is the city with the highest population in Asia, Europe, America, and Africa?* or *What are the top five cities with the largest population?* We asked them to fill a questionnaire while reviewing the demo. We expected a session to last 30 minutes on average per expert user. The questionnaire and demo application are included in the Supplementary Material 4.

7.4 Summary of Feedback

Participants provided generally positive feedback about the *Geoburst* visualisation. "*This is a very cool visualisation*", P3. "*Very well done! I love playing with it. The idea of linking locations to bars is brilliant.*", P5. The Likert's scale rating indicates participants found that *Geoburst* is aesthetically pleasing and that they like the *Geoburst* visualisation in general. Participants also found it easy to associate values with the geographic locations but provided rather mixed feedback about value comparison and for the confidence rating (Figure 12).

We asked participants to comment on tasks that they found to be easy to perform with the *Geoburst* visualisation. As expected, most participants found *Geoburst* useful for finding the highest value or the top #N values (P1, P2, P3, P6), and for comparison tasks of a small number of values and/or of values on the same hemisphere (P1, P2, P4, P5, P9). Two participants also mentioned that *Geoburst* is useful to retrieve information for an individual city (P4, P9).

The interactions received many positive comments. "*It was easy to interact, I understood how to do different task in just a few seconds*" (P6). Auto rotation was found to be smooth (P2) and interesting (P5). The link interactions were found to be useful to mark points (P3) and to identify bars and points (P2, P4). Clear links was found to be intuitive (P2). One participant, P7, also mentioned that showing hidden values on the bar chart allowed them to recall the search they had done before. "*It's a cool idea. I like the separation of bar charts and red dots over the globe surface. ... so, as I pan the globe to see the opposite side, the bar chart still appears on the UI, where I can recall the search I have done so far.*" (P7).

Participants were also asked to comment on difficulties they encountered while exploring the data with *Geoburst*. Two participants mentioned difficulties in following the bar arrangements during globe rotation (P1, P7). A duration of 0.25 s for bar animations was found to be too fast to follow, had unpredictable transitions, and caused significant changes even on small adjustments. "*Performing micro-adjustments is really annoying due to the way animations work*" (P1). "*The bar charts kept refreshing as I panned*" (P5). Six participants also commented on difficulties comparing larger number of values and/or values that were located far apart.

Participants suggested a number of improvements on the visualisation and interaction design. There were a number of suggestions for the interactions including increasing the rotation speed (P1, P2), making the frozen circles, bars, and links more apparent (P2, P5), improving auto rotation to support selection of multiple values (P5), supporting multiple selection of bars for comparison (P4), making links clickable (P3), and a freezing mechanism for bar arrangements similar to the link freezing (P7). For the visualisation, participants suggested to show axis labels (P4), extend *Geoburst* to

---

[4] www.geonames.org

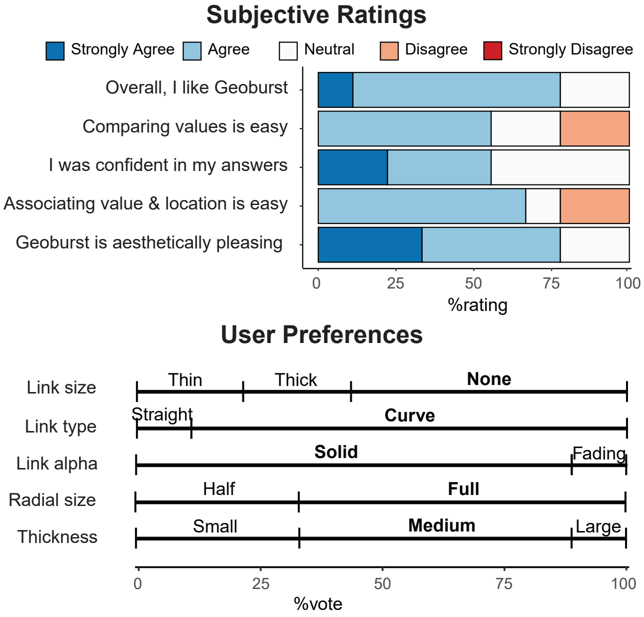


Figure 12: Participants rating (top) and preferred parameters (bottom).

maps (P5), and improve the optimisation algorithm to make the bars rearrangement more predictable (P5).

7.5 Reflection

We received positive feedback from the expert participants about the idea to complement a globe visualisation with a radial bar chart that aligns values on a common scale without distortion and occlusion. Although it needs to be further evaluated in a controlled study, the *Geoburst* visualisation was found to be useful for finding extreme values and comparing values in our preliminary study.

We asked participants to choose their preferences for *Geoburst* parameters such as link variations, chart radial size, and chart thickness. We learned from the expert users' preferences that at least for the chosen dataset size (207 cities in total), the visual clutter from the links is not acceptable. Most participants preferred not to show the links all the time. A possible option to resolve the links clutter issue is aggregating linking [13] per group which we did not implement in our initial design. In terms of link alpha value and link type, most participants liked the curved solid link because they found it intuitive for the spherical geometry (P3, P4), aesthetically pleasing (P5, P7), and easy to follow (P1, P6, P8, P9). They also preferred to have a full 360° radial chart in $1 \times radius$ thickness. The preferred version of *Geoburst* is shown in Figure 13 (left).

The key issue revealed in our preliminary evaluation is that it is unclear how and when bars should be rearranged without introducing a disruption of the users' mental model of the visualisation. In the current design, we set a globe rotation threshold of 5°. Increasing this threshold could prevent bars from being moved during small adjustments of the globe rotation. Alternatively, as suggested by one of the participants, we could have a "freeze bars" interaction where users can stop bars from being rearranged. Furthermore, how to make a comprehensible transition between bar arrangements needs further exploration.

Reflecting on the feedback provided by the expert users, we see several possible directions for further research into the *Geoburst* design. Showing all bars is arguably useful to find extreme values. However, for local tasks such as comparing values within a region, the non-relevant bars could be a distraction. Possible options around this issue include showing only bars for values on the visible hemisphere or determining visible bars based on the geo-location distance to the centre of the view, which presumably is where users would place points of interest. Further exploration on the *Geoburst* idea could be to better understand the role of the radial bar chart in this composite visualisation. Particularly, to see whether the radial bar chart should be used as an on-demand feature or permanent complementary visualisation. Lastly, the perceptual scalability of the *Geoburst* visualisation needs further investigation to see how much data can be visualised with *Geoburst* before it becomes too cluttered.

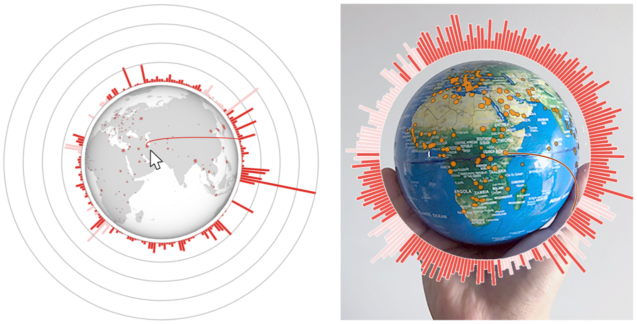


Figure 13: Left: ideal *Geoburst* based on users' preferences. Right: we envision *Geoburst* can be used to augment a tangible globe in AR (a mock-up for illustration purposes.)

8 LIMITATIONS

We acknowledge several limitations in our study evaluating quantitative visualisation idioms for virtual globes. While relative size comparison is one of the key tasks in geovisualisation [47], it is an elementary task that involves a relatively small number of primitives [2]. More complex synoptic tasks [2] such as pattern identification or relational-seeking may yield different results. While we had crowdsourced and non-crowdsourced participants in our study, we did not compare the two groups due to the small number of participants in the non-crowdsourced group. Although Prolific.co participants are found to be more naive, less dishonest, and more diverse, as well as to produce higher quality data than MTurk [42], we acknowledge that the study was not conducted in an ideal lab environment. Lastly, the expert users' feedback is insightful towards improvements of the *Geoburst* design, but we see it as preliminary due to the limited number of participants.

9 CONCLUSION AND FUTURE WORK

Despite its popularity, little attention has been paid to globe-based visualisation. In this paper, we explored and evaluated the design of quantitative data visualisation on virtual globes. We evaluated five visualisation idioms for virtual globes using a graphic perception study. The results of our study show several insights, including but not limited to empirical evidence supporting the value of the *Normal Bars* idiom despite its distortion issue, and an increased perceived mental load when visual elements are aligned tangentially on the globe's surface.

We then designed *Geoburst*, a novel approach of composite visualisations to provide a common scale and avoid occlusion as well as distortion by linking the globe visualisation to a radial bar chart. We provided our initial visualisation and interaction ideas. The feedback from nine expert users in data visualisation was positive and revealed possible improvements for the *Geoburst* visualisation.

Future research should investigate the effectiveness of globe visualisations with more complex tasks such as pattern identification or relation-seeking. The effectiveness of two coordinated globes that show complementary hemispheres and avoid an occluded hemisphere could also be evaluated.

We aim at providing a robust empirical evaluation of the *Geoburst* design and improving it further. One approach is to replace the perspective or orthographic projection commonly used for the visualisation of three-dimensional globes on flat displays. The Gilbert two-world map projection [16, 31] is an interesting alternative that shows the entire sphere inside a circle on a globe-like map. With this cartographic projection, all locations could be shown both on the radial chart and the map.

Looking further, with the advancement of human-computer interaction technologies, more ways are developed to visualise and interact with globe-based visualisations. The effect of stereoscopic and immersive displays and embodied interactions on the visualisation of globes and maps [3, 48, 49] is a direction worth exploring. Lastly, we envision the *Geoburst* visualisation can be used in an augmented reality context to complement tangible globes (Figure 13, right).

REFERENCES

[1] Tomas Akenine-Möller, Eric Haines, and Naty Hoffman. 2019. *Real-time rendering.* CRC Press.

[2] Natalia Andrienko and Gennady Andrienko. 2006. *Exploratory analysis of spatial and temporal data: a systematic approach.* Springer Science & Business Media.

[3] Christopher R Austin, Barrett Ens, Kadek Ananta Satriadi, and Bernhard Jenny. 2020. Elicitation study investigating hand and foot gesture interaction for immersive maps in augmented reality. *Cartography and Geographic Information Science* 47, 3 (2020), 214–228.

[4] Susanne Bleisch. 2011. Toward appropriate representations of quantitative data in virtual environments. *Cartographica: The International Journal for Geographic Information and Geovisualization* 46, 4 (2011), 252–261.

[5] Susanne Bleisch and Jason Dykes. 2015. Quantitative data graphics in 3D desktop-based virtual environments–an evaluation. *International Journal of Digital Earth* 8, 8 (2015), 623–639.

[6] Susanne Bleisch, Jason Dykes, and Stephan Nebiker. 2008. Evaluating the effectiveness of representing numeric information through abstract graphics in 3D desktop virtual environments. *The Cartographic Journal* 45, 3 (2008), 216–226.

[7] Sergio Cabello, Herman Haverkort, Marc Van Kreveld, and Bettina Speckmann. 2010. Algorithmic aspects of proportional symbol maps. *Algorithmica* 58, 3 (2010), 543–565.

[8] Stuart K Card, George G Robertson, and Jock D Mackinlay. 1991. The information visualizer, an information workspace. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 181–186.

[9] Jesse Chandler and Danielle Shapiro. 2016. Conducting clinical research using crowdsourced convenience samples. *Annual Review of Clinical Psychology* 12 (2016), 53–81.

[10] Seán Clarke, Antonio Voce, Pablo Gutiérrez, and Frank Hulley-Jones. 2020. How coronavirus spread across the globe – visualised. https://www.theguardian.com/world/ng-interactive/2020/apr/09/how-coronavirus-spread-across-the-globe-visualised

[11] William S Cleveland and Robert McGill. 1984. Graphical perception: Theory, experimentation, and application to the development of graphical methods. *J. Amer. Statist. Assoc.* 79, 387 (1984), 531–554.

[12] William S Cleveland and Robert McGill. 1986. An experiment in graphical perception. *International Journal of Man-Machine Studies* 25, 5 (1986), 491–500.

[13] Christopher Collins and Sheelagh Carpendale. 2007. VisLink: Revealing relationships amongst visualizations. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (2007), 1192–1199.

[14] Katherine N Cotter, Paul J Silvia, Marco Bertamini, Letizia Palumbo, and Oshin Vartanian. 2017. Curve appeal: exploring individual differences in preference for curved versus angular objects. *i-Perception* 8, 2 (2017), 2041669517693023.

[15] Kurtis Danyluk, Bernhard Jenny, and Wesley Willett. 2019. Look-from camera control for 3D terrain maps. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* 1–12.

[16] Alan A. DeLucia and John P. Snyder. 1986. An Innovative World Map Projection. *The American Cartographer* 13, 2 (1986), 165–167.

[17] Borden Dent, J Torguson, and T Hodler. 2008. *Thematic map design.* McGraw-Hill New York, New York, NY.

[18] Steve Dübel, Martin Röhlig, Heidrun Schumann, and Matthias Trapp. 2014. 2D and 3D presentation of spatial data: A systematic review. In *2014 IEEE VIS international workshop on 3DVis (3DVis).* IEEE, 11–18.

[19] Geoffrey Ellis and Alan Dix. 2007. A taxonomy of clutter reduction for information visualisation. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (2007), 1216–1223.

[20] David Englmeier, Isabel Schönewald, Andreas Butz, and Tobias Höllerer. 2019. Feel the globe: Enhancing the perception of immersive spherical visualizations with tangible proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* IEEE, 1693–1698.

[21] James John Flannery. 1971. The relative effectiveness of some common graduated point symbols in the presentation of quantitative data. *Cartographica: The International Journal for Geographic Information and Geovisualization* 8, 2 (1971), 96–109.

[22] Al Gore. 1992. *Earth in the Balance: Ecology and the Human Spirit.* Houghton Mifflin.

[23] Al Gore. 1998. The Digital Earth. *Australian Surveyor* 43, 2 (1998), 89–91.

[24] Christian Haeberling, Hansruedi Bär, and Lorenz Hurni. 2008. Proposed cartographic design principles for 3D maps: a contribution to an extended cartographic theory. *Cartographica: The International Journal for Geographic Information and Geovisualization* 43, 3 (2008), 175–188.

[25] Jeffrey Heer and Michael Bostock. 2010. Crowdsourcing graphical perception: using mechanical turk to assess visualization design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 203–212.

[26] Dennis E Hinkle, William Wiersma, and Stephen G Jurs. 2003. *Applied statistics for the behavioral sciences.* Vol. 663. Houghton Mifflin College Division.

[27] Ray A Jarvis. 1973. On the identification of the convex hull of a finite set of points in the plane. *Inform. Process. Lett.* 2, 1 (1973), 18–21.

[28] Waqas Javed and Niklas Elmqvist. 2012. Exploring the design space of composite visualization. In *2012 IEEE Pacific Visualization Symposium.* IEEE, 1–8.

[29] Dye Josh, Butt Craig, Lama Richard, and Stehle Mark. 2020. Silent Skies. https://www.theage.com.au/interactive/2020/coronavirus/silent-skies/index.html

[30] Harold W Kuhn. 1955. The Hungarian method for the assignment problem. *Naval Research Logistics Quarterly* 2, 1–2 (1955), 83–97.

[31] Miljenko Lapaine and Nedjeljko Frančula. 1993. Gilbert two-world projection. In *Proceedings 16th International Cartographic Conference.* 66–82.

[32] Fritz Lekschas, Michael Behrisch, Benjamin Bach, Peter Kerpedjiev, Nils Gehlenborg, and Hanspeter Pfister. 2019. Pattern-Driven Navigation in 2D Multiscale Visualizations with Scalable Insets. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (2019), 611–621.

[33] Boren Li, Jianping Wu, Mao Pan, and Jing Huang. 2015. Application of 3D WebGIS and real-time technique in earthquake information publishing and visualization. *Earthquake Science* 28, 3 (2015), 223–231.

[34] Wenwen Li and Sizhe Wang. 2017. PolarGlobe: A web-wide virtual globe system for visualizing multidimensional, time-varying, big climate data. *International Journal of Geographical Information Science* 31, 8 (2017), 1562–1582.

[35] Marlon Lückert. 2020. CovidAR - Data Visualization in Augmented Reality. https://devpost.com/software/covidar-data-visualization-in-augmented-reality

[36] Jock Mackinlay. 1986. Automating the design of graphical presentations of relational information. *ACM Transactions on Graphics* 5, 2 (1986), 110–141.

[37] Microsoft. 2015. Globe Map. https://appsource.microsoft.com/en-us/product/power-bi-visuals/WA104380799

[38] Tamara Munzner. 2014. *Visualization analysis and design.* CRC Press.

[39] Ong Innovations. 2018. Data Globe. https://www.onginnovations.com/data-globe

[40] Stefan Palan and Christian Schitter. 2018. Prolific. ac—A subject pool for online experiments. *Journal of Behavioral and Experimental Finance* 17 (2018), 22–27.

[41] Todd C Patterson. 2007. Google Earth as a (not just) geography education tool. *Journal of Geography* 106, 4 (2007), 145–152.

[42] Eyal Peer, Laura Brandimarte, Sonam Samat, and Alessandro Acquisti. 2017. Beyond the Turk: Alternative platforms for crowdsourcing behavioral research. *Journal of Experimental Social Psychology* 70 (2017), 153–163.

[43] Andrei D Polyanin and Alexander V Manzhirov. 2006. *Handbook of mathematics for engineers and scientists.* CRC Press.

[44] Stanislav Popelka and Jitka Dolezalova. 2016. Differences between 2D map and virtual globe containing point symbol – an eye-tracking study. In *Proceedings International Multidisciplinary Scientific GeoConference SGEM 2016.* 175–182.

[45] Quang Quach and Bernhard Jenny. 2020. Immersive visualization with bar graphics. *Cartography and Geographic Information Science* 47, 6 (2020), 471–480. https://doi.org/10.1080/15230406.2020.1771771 arXiv:https://doi.org/10.1080/15230406.2020.1771771

[46] Nicola Raluca. 2018. World population count. https://ralucanicola.github.io/JSAPI_demos/world-population/

[47] Robert E Roth. 2013. An empirically-derived taxonomy of interaction primitives for interactive cartography and geovisualization. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (2013), 2356–2365.

[48] Kadek A Satriadi, Barrett Ens, Maxime Cordeil, Tobias Czauderna, and Bernhard Jenny. 2020. Maps Around Me: 3D Multiview Layouts in Immersive Spaces. *Proc. ACM Hum.-Comput. Interact.* 4, ISS, Article 201 (Nov. 2020), 20 pages. https://doi.org/10.1145/3427329

[49] Kadek A Satriadi, Barrett Ens, Maxime Cordeil, Bernhard Jenny, Tobias Czauderna, and Wesley Willett. 2019. Augmented Reality Map Navigation with Freehand Gestures. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* 593–603.

[50] Stefan Seipel and Leonor Carvalho. 2012. Solving Combined Geospatial Tasks Using 2D and 3D Bar Charts. In *2012 16th International Conference on Information Visualisation.* 157–163.

[51] Lei Shi, Idan Zelzer, Catherine Feng, and Shiri Azenkot. 2016. Tickers and talker: An accessible labeling toolkit for 3D printed models. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems.* 4896–4907.

[52] Lei Shi, Yuhang Zhao, and Shiri Azenkot. 2017. Markit and Talkit: a low-barrier toolkit to augment 3D printed models with audio annotations. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology.* 493–506.

[53] Paul J Silvia and Christopher M Barona. 2009. Do people prefer curved objects? Angularity, expertise, and aesthetic preference. *Empirical studies of the arts* 27, 1 (2009), 25–42.

[54] Terry A Slocum, Robert B McMaster, Fritz C Kessler, and Hugh H Howard. 2009. *Thematic cartography and visualization.* Prentice Hall.

[55] Karla Vega, Eric Wernert, Patrick Beard, C Gniady, David Reagan, M Boyles, and Chris Eller. 2014. Visualization on spherical displays: Challenges and opportunities. In *Proceedings of the IEEE VIS Arts Program (VISAP).* 108–116.

[56] Travis Maclean White. 2012. *Evaluating the effectiveness of thematic mapping on virtual globes.* Ph.D. Dissertation. University of Kansas.

[57] Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 143–146.

[58] Huayi Wu, Zhengwei He, and Jianya Gong. 2010. A virtual globe-based 3D visualization and interactive framework for public participation in urban planning processes. *Computers, Environment and Urban Systems* 34, 4 (2010), 291–298.

[59] Yalong Yang, Tim Dwyer, Sarah Goodwin, and Kim Marriott. 2016. Many-to-many geographically-embedded flow visualisation: An evaluation. *IEEE Transactions on Visualization and Computer Graphics* 23, 1 (2016), 411–420.

[60] Yalong Yang, Tim Dwyer, Bernhard Jenny, Kim Marriott, Maxime Cordeil, and Haohui Chen. 2018. Origin-destination flow maps in immersive environments. *IEEE Transactions on Visualization and Computer Graphics* 25, 1 (2018), 693–703.

[61] Yalong Yang, Tim Dwyer, Kimbal Marriott, Bernhard Jenny, and Sarah Goodwin. 2020. Tilt Map: Interactive Transitions Between Choropleth Map, Prism Map and Bar Chart in Immersive Environments. *IEEE Transactions on Visualization and Computer Graphics* (2020).

[62] Yalong Yang, Bernhard Jenny, Tim Dwyer, Kim Marriott, Haohui Chen, and Maxime Cordeil. 2018. Maps and globes in virtual reality. *Computer Graphics Forum* 37, 3 (2018), 427–438.