Toward Appropriate Representations of Quantitative Data in Virtual Environments

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Abstract

Displays of quantitative data within three-dimensional (3D) virtual environments are quickly created with today's technological options, but we know little about the appropriateness of such representations. Based on two-dimensional (2D) cartographic knowledge and popular symbolization usage, six potentially appropriate proportional symbols for the display of quantitative data in virtual environments are experimentally tested: 2D bars, 3D bars, and 2D circles, with and without reference frames indicating the largest possible value. The results show that 2D bars are most efficient and effective, as evaluated through two elementary tasks (indicating the larger symbol and comparing symbol sizes); 3D bars are less and 2D circles least efficient and effective. The use of reference frames improves the effectiveness but not the efficiency of task completion.

Keywords: 3D, virtual environments, quantitative data, proportional symbols, 2D bars, 3D bars, 2D circles, experiment

Résumé

Grâce aux technologies actuelles, on peut rapidement afficher des données quantitatives dans un environnement virtuel tridimensionnel (3D). Toutefois, on possède encore peu de données sur la pertinence de ces représentations. À partir des connaissances cartographiques bidimensionnelles (2D) et des usages de symbolisation populaire, on a évalué expérimentalement six symboles proportionnels qui devraient être pertinents : les barres 2D, les barres 3D et les cercles 2D, avec ou sans cadres de référence pour la valeur possible la plus élevée. D'après les résultats obtenus, les barres 2D ont été les plus efficaces et efficientes lors des évaluations pour deux tâches élémentaires (indiquer le symbole le plus large et comparer la taille des symboles); les barres 3D ont été moins efficaces que les barres 2D, tandis que les cercles 2D se sont révélés les moins efficaces et efficients. Les cadres de référence améliorent l'efficacité, sans pour autant améliorer l'efficience de l'exécution.

Mots clés : 3D, environnement virtuel, données quantitatives, symboles proportionnels, barres 2D, barres 3D, cercles 2D, expérience

Introduction

Virtual globes or Earth browsers, their interfaces, and the markup languages they support offer numerous possibilities for representing various data sets in a geographic context. Sometimes, it seems that data are displayed in earth browsers just because they can be integrated quickly (e.g., Slingsby, Dykes, and Wood 2008) and because such visualizations can potentially be made available to a large audience. Where data sets relate to the landscape in which they were collected (e.g., data from a sensor network collecting data in a mountainous environment), a visualization of such data sets within the virtual equivalent of the natural environment may help its analysis in relation to altitude and landform. But what are appropriate representations of quantitative data in virtual environments? The required formats for quantitative data representations in virtual environments – for instance, KML (OGC 2008) for Google Earth (Google 2011) – can be created by hand or using various tools, such as the Thematic Mapping Engine (TME, Sandvik 2009) or GE-Graph (Sgrillo 2010).

The visualization shown in Figure 1 was created with the TME and shows mortality rates of children under five by country in 2005, symbolized as 2D circles on billboards. Billboards are 3D computer graphic elements consisting of a raster image rendered onto a transparent 2D polygon

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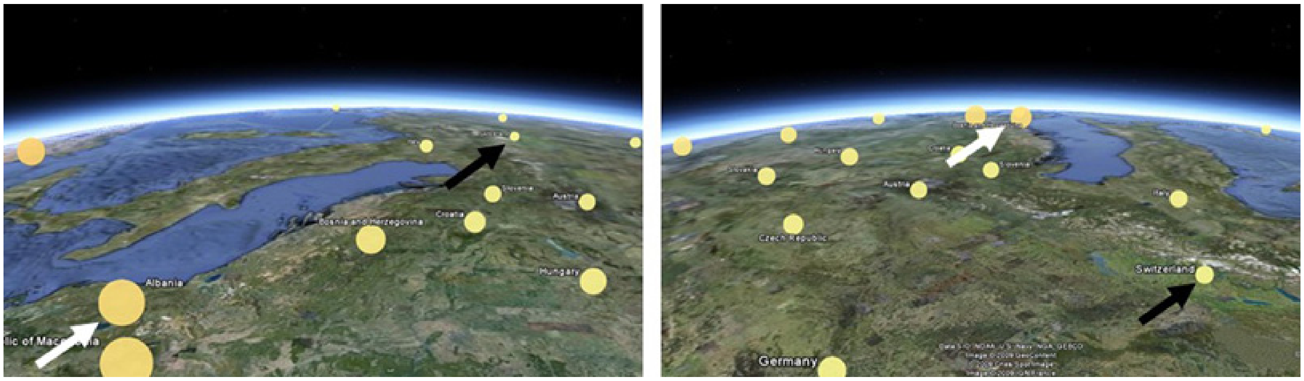

Figure 1. Circular 2D symbols to show mortality rates of children under five by country in 2005 (created with TME, Sandvik 2009) observed from two different viewpoints (black arrow: Switzerland; white arrow: Albania) in Google Earth (Google 2011).
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(Akenine-Möller and Haines 2002). The billboard is positioned at a fixed point within a virtual environment, but it rotates along two axes, so that its graphic face is always aligned vertically with the current viewpoint of the user. The two screenshots (left and right in Figure 1) show the same data, but from two different viewpoints. Another example (see Figure 2) shows quantitative values represented through the length of hexagonal 3D bars (created with GE-Graph, Sgrillo 2010). Comparing the circle sizes showing quantitative values for the two marked countries, Switzerland (black arrow) and Albania (white arrow), in Figure 1 or reading the 3D bar heights in Figure 2 (right) can be difficult. But what are appropriate representations of quantitative data that support efficient and effective data analysis?

TOWARD APPROPRIATE DATA DISPLAYS

Appropriate 2D representations of quantitative data have been studied for a long time, and various guidelines for their creation exist (e.g., Bertin 1974; Cleveland 1994; Tufte 2001). From that broad knowledge, an earlier study (Bleisch, Dykes, and Nebiker 2008) tried to derive the most suitable representation for quantitative data in 3D virtual environments. Three-dimensional visualizations or virtual environments, such as those shown in Figure 1 and Figure 2, are often viewed projected onto 2D screens. In projected 3D virtual environments, the impression of 3D is evoked by different depth cues such as size gradient, occlusion, and motion parallax (Ware 2004). When quantitative data are displayed through the size of different symbols in 3D virtual environments, the depth cue size

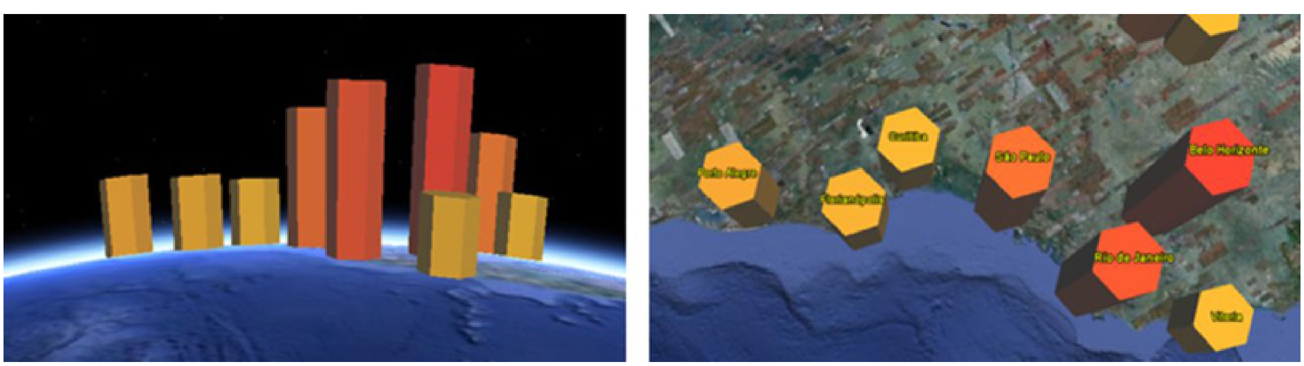

Figure 2. Quantitative values represented through the length of hexagonal 3D bars and also through colour (visible in online version; example created with GE-Graph, Sgrillo 2010), viewed from the side (left) and from near the top (right) in Google Earth (Google 2011).
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gradient produces variations in the size of the proportional symbols displayed in addition to the variations in size caused by the varying values the symbols represent. In a previous study (Bleisch, Dykes, and Nabiker 2008), 2D bars on billboards were tested for the display of quantitative data in 3D virtual environments. Reference frames showing the maximum values possible were added to help the interpretation (an application of Weber's Law; Baird and Noma 1978). The results show that 2D bars on billboards are a valid symbolization method for quantitative data as tested for the elementary tasks of finding the taller bar and comparing bar lengths. The study also found that bars with reference frames are interpreted faster and more confidently (Bleisch, Dykes, and Nabiker 2008). The results suggest that we are able to transfer our natural interpretation of the real world to projected 3D virtual environments. It is hypothesized that the constant width of the 2D bars serves as a depth cue that allows correct interpretation of the varying bar lengths. If this hypothesis holds true, and the width of 2D bars helps the interpretation by providing depth cues, then a symbol type that shows both varying values and depth cues using the same single dimension – for example, a circle where values are mapped to the radius or the area – should be less effective.

For quantitative symbols in 2D, Cleveland and McGill (1984) offer a guideline for graph construction. They propose using length rather than area to decode quantitative data. As mentioned above, 2D bars on billboards are a valid symbolization for quantitative data in virtual environments. However, a potentially cumbersome characteristic of 2D bars on billboards is their suboptimal visual integration into 3D virtual environments. While 2D bars sometimes seem to float in the virtual environment, 3D bars match their surroundings better. Thus, 3D bars may integrate better, but, as exemplified in Figure 2, they can potentially be observed from an unfortunate angle – for example, from directly above – which may produce a distorted or even impossible perception of the data values displayed through the length of the bar. To avoid potential misinterpretation, 3D symbols (e.g., bars, prisms, spheres) that are used to display quantitative data (e.g., Sandvik 2009) often, in addition to varying in size depending on the data values, are also coloured to show the same data values (e.g., Figure 2 online; Tiede and Lang 2010; Gorman 2008), thus using two visual variables to display one data value. Such double encoding is regarded as a waste of "ink," as Edward Tufte (2001) pointedly writes.

In the present study, a selection of three potentially suitable types of symbols with and without reference frames (see Figure 3) – 2D bars on billboards (2D_b), 2D bars with reference frames on billboards (2D_bf), 3D bars (3D_b), 3D bars with reference frames (3D_bf), 2D circles on billboards (2D_c), and 2D circles with reference frames on billboards (2D_cf) – were experimentally tested for their appropriateness in conveying quantitative values when displayed in 3D virtual environments. Based on the above

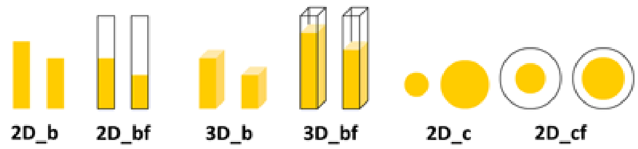

Figure 3. Quantitative symbols (named 2D_b, 2D_bf, 3D_b, 3D_bf, 2D_c, and 2D_cf) as used in the experiment.

discussion, it was hypothesized that symbols with reference frames are more appropriate and that the symbols can be ordered by decreasing appropriateness as follows: 2D_bf, 3D_bf, 2D_cf, 2D_b, 3D_b, 2D_c (see "Research Aims" below for detailed hypotheses). The available tools (e.g., TME, Sandvik 2009; GE-Graph, Sgrillo 2010) map data values to the length and not the volume of 3D symbols. In addition, an informal survey among colleagues showed that they would rather interpret the length than the volume of 3D bars in virtual environments. Therefore, the values to be evaluated in the experiment reported here are mapped to the 2D bar length, the 3D bar length, and the 2D circle radius. The circles are thus mathematically scaled and not corrected for the known underestimation of circular symbols (Slocum and others 2005). Different perceptual sizes of the circles are mathematically evaluated in the "Results" section. Appropriateness of visualizations is often measured based on efficiency and effectiveness (e.g., Mackinlay 1986; van Wijk 2005). Efficiency measures typically include task-completion time, while error rates are used to measure effectiveness (e.g., Chen and Yu 2000); the latter require tasks that have a true or exact answer that can be evaluated.

RESEARCH AIMS

This experimental study aimed to test the efficiency and effectiveness of quantitative symbol-size judgements in desktop-based 3D virtual environments with elementary tasks. The results lay the foundation for future evaluations of more complex data-analysis applications with different domain experts. To achieve this aim, an experiment was designed and analyzed to test the following hypotheses, formulated based on the problem statement and literature review above:

H1: The bigger of two symbols representing quantitative data in 3D virtual environments can be reported independently of symbol type.

H2: Task-performance time is lower for symbols with reference frames.

H3: Task-performance time is lower for 2D bars than for 3D bars and lower for 3D bars than for 2D circles.

H4: Task accuracy is higher for symbols with reference frames.

H5: Task accuracy is higher for 2D bars than for 3D bars and higher for 3D bars than for 2D circles.

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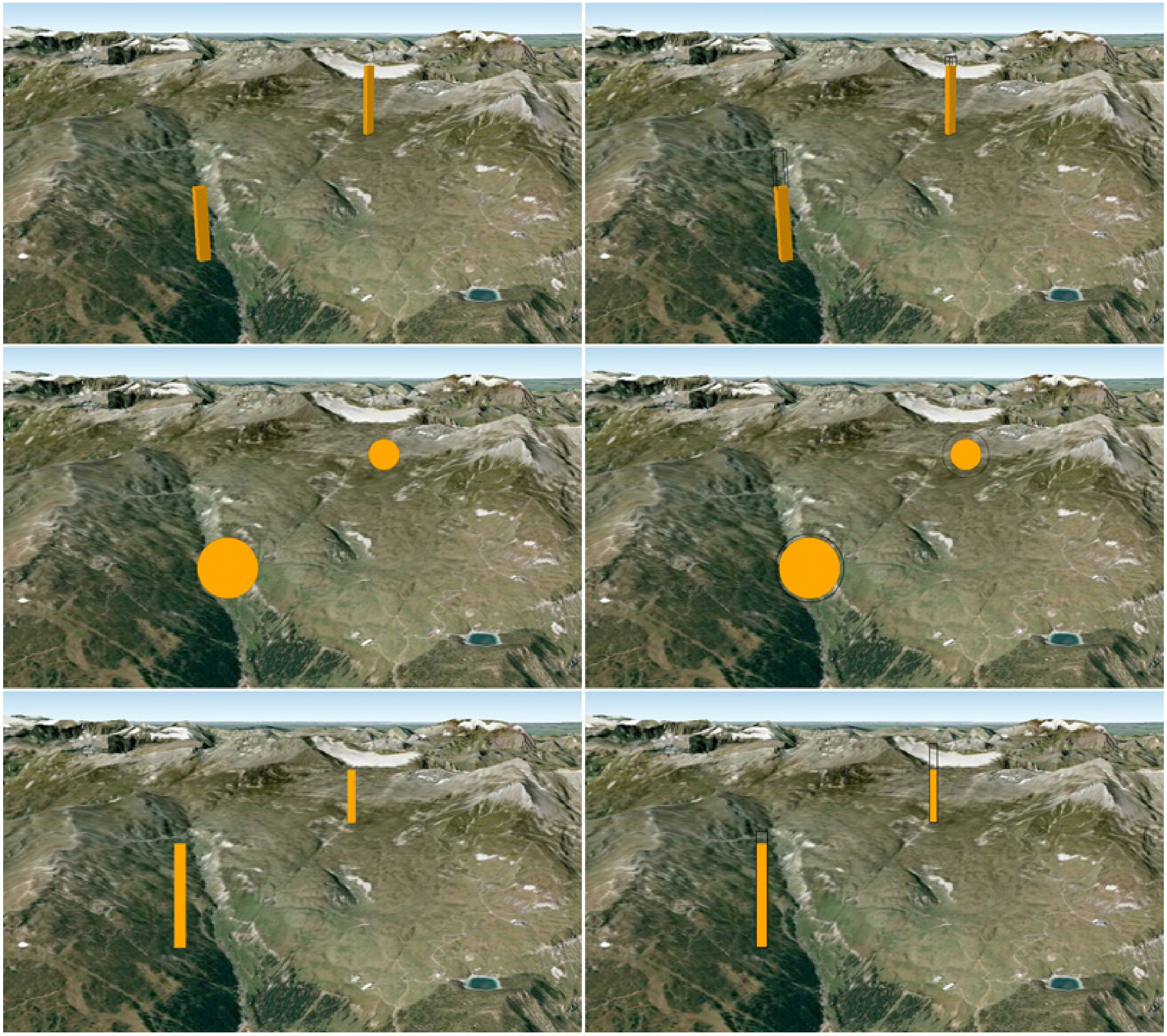

Figure 4. Experimental settings in Google Earth (Google 2011), displaying the same two data values with six different symbolizations (from top left to bottom right: 3D_b, 3D_bf, 2D_c, 2D_cf, 2D_b, and 2D_bf). Each display covered most of the computer screen, and symbols and frames were thus clearly visible.
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Experiment

IMPLEMENTATION AND PARTICIPANTS

The experiment designed to explore the defined hypotheses comprises 20 different displays, each representing two different values within the virtual environment Google Earth (Google 2011), which were prepared for each of the six symbol types (see Figure 4). The use of 20 different bar combinations ensures that there is some variation between the displays, but nevertheless each bar combination was analysed several times by different participants. Each of the 6×20 displays is available with either one or the other of the two values in the foreground (labelled A) or background (labelled B) respectively, for a total of $2 \times 6 \times 20$ experimental settings. Two elementary tasks (Andrienko and Andrienko 2006) were set for each setting. Participants were required to indicate the larger symbol (A, B, or equal) and to judge the size of the smaller symbol relative to the larger symbol (as a percentage value). The first task allows testing of whether symbol-size comparison is possible; the second task shows how accurately it can be done. In a balanced within-subject design, each participant worked through the two tasks in 40 of the 240 experimental settings, covering all six symbol types.

The settings and tasks were provided through online questionnaires, and the answers and task-performance times by setting and participant were managed in a relational database.

The 31 participants were university staff and students with either a geography or a geomatics background and/or were trained in information visualization. They were thus considered to form a group of informed users likely to undertake visual analysis of geospatial data sets. The sampling was intentionally biased, as the experimental results will lay the foundations for more specific evaluation of complex data-analysis tasks with data and domain experts. Further evaluations with a more diverse group of participants may be needed to apply the results to a wider group of lay and occasional users of data displays within virtual environments.

DATA COLLECTED

The data collected in each setting include records indicating which of the two symbols is larger (A, B, or equal); the estimated ratio of the size of the smaller symbol to the size of the larger symbol, expressed as a percentage; and the time in seconds needed to complete these two tasks. Accuracy of task completion is measured by the true ratio of symbol sizes minus the ratio estimated by the participant (e.g., if the size of the smaller symbol is 67% of the size of the larger symbol, and the participant estimated 65%, the accuracy is expressed by the difference, in this case +2). These differences are expected to be normally distributed around the mean of zero, which indicates a correct estimation. Participants tend to estimate the differences in multiples of 5 or 10, while the true differences can be any integer value. It can be assumed that under- and over-estimations are made with about equal frequency, which compensates for this slight bias.

The data set potentially comprises 1240 records (31 participants × 40 settings). However, 19 records are missing from the database because one questionnaire was not saved completely, and a further 14 records were deleted because they were empty. As a result, the data set consists of 1207 records of larger symbol indication, symbol comparison, and task-completion time. The exact numbers by symbol type are as follows: 3D_b, 198; 3D_bf, 198; 2D_c, 203; 2D_cf, 206; 2D_b, 201; and 2D_bf, 201. One participant reported that he was interrupted during the experiment. Three task-performance times over 600 seconds were deleted (the fourth-highest time being 296 seconds), as it was assumed that they were caused by interruptions.

DATA ANALYSIS

The quantitative data were analysed statistically to test the hypotheses (see "Research Aims" above). Participants' responses as to which bar is larger are categorical data, which are tested using chi-square tests. The task-completion times are log-normally distributed (Limpert, Stahel, and Abbt 2001), and the symbol-size comparison differences are normally distributed. These are evaluated using mean and standard deviation to show the central tendency and spread. The significance of deviation of the mean from the expected mean of zero is evaluated using Student's *t*-tests. In addition, the differences in results between the different symbol types were analysed using analysis of variance (ANOVA) and post-hoc Tukey tests (Zar 2010). All judgements of significance are based on a 95% level ($\alpha = 0.05$).

Results

EVALUATION OF CIRCULAR SYMBOLS

As mentioned above (see "Toward Appropriate Data Displays"), for this experiment the data values were mapped to the circle radii. This approach does not take into account that circles are judged mainly by area and that, furthermore, circle areas should be scaled perceptually instead of mathematically, as circle sizes are generally underestimated (Slocum and others 2005). In this experiment, therefore, the ratios of symbol sizes reported by the participants were compared to calculated differences in circle areas and perceptually scaled circle areas (using Flannery's exponent of 0.57; see Slocum and others 2005). Figure 5 shows the varying results for the means (standard deviation is not affected). The perceptually scaled circle areas yield the most accurate results. However, as Chang (1980) has noted, the exponent for the perceptual scaling of circle areas may vary depending on many other factors that influence judgements of size. Nevertheless, the results for perceptually scaled areas of circles were used for the hypotheses testing reported below. The large spread of reported size-comparison differences for circles relative to other symbol types (see Figure 10, symbols with frames) makes them the least effective, although another scaling exponent might improve the mean slightly.

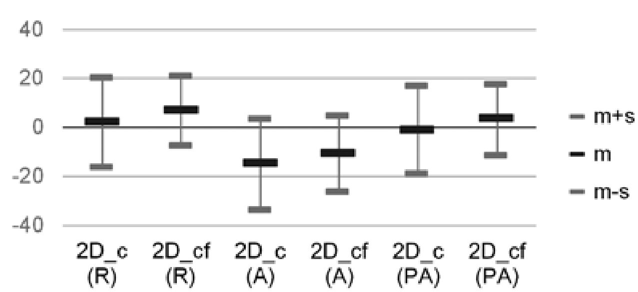

Figure 5. Unitless mean (m) and standard deviation (s) of quantitative symbol-size differences of circles with (2D_cf) and without (2D_c) frames, based on data values mapped to circle radius (R), circle area (A), and perceptually scaled circle area (PA).

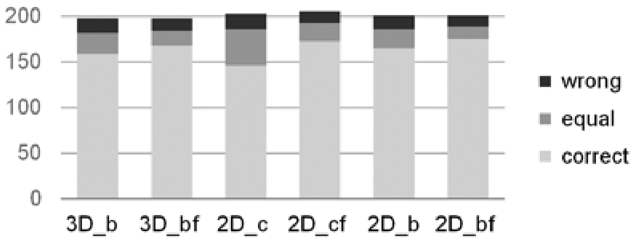

Figure 6. Number of correctly or wrongly identified larger symbols by symbol type (for differentiation of judgements that symbols are of equal size, see Figure 7).

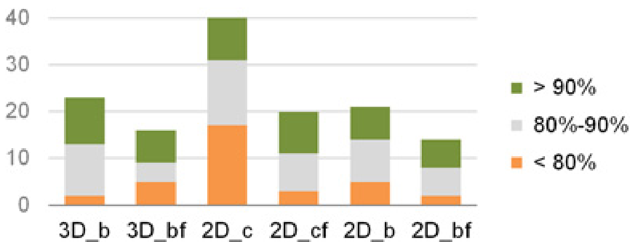

Figure 7. Number of settings judged to have two equally sized symbols (100%) by symbol type, with true ratio.

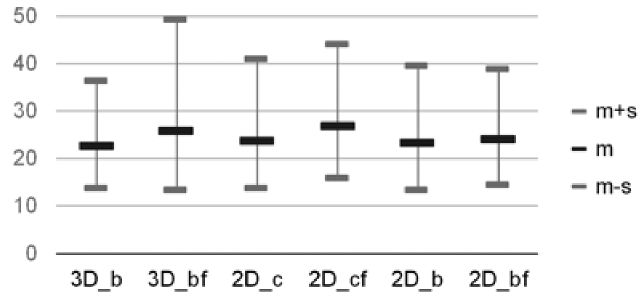

Figure 8. Mean (m) and standard deviation (s) of log-normally distributed task-performance times (seconds) by symbol type.

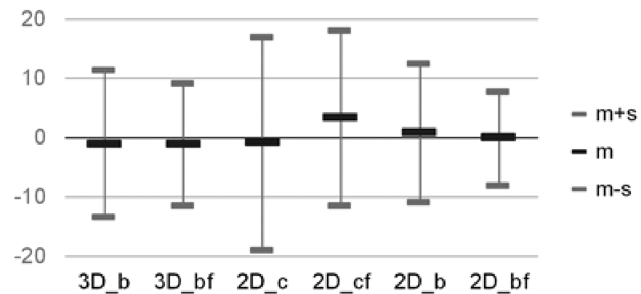

Figure 9. Unitless mean (m) and standard deviation (s) of normally distributed differences between true and estimated quantitative symbol-size differences by symbol type.

TESTING THE HYPOTHESES

H1: The bigger of two symbols representing quantitative data in 3D virtual environments can be reported independently of symbol type.

The variation in correctly or wrongly identifying the larger symbol is significant ($\chi^2 = 23.522$, df $= 10$, $p = 0.009$) between the different symbol types (see Figure 6). All symbol types (3D_b, 3D_bf, 2D_c, 2D_cf, 2D_b, and 2D_bf; see Figure 3) show about the same frequency of wrongly identified larger symbols. More variation is shown between the symbol types for those identified as being of equal size. This variation is detailed in Figure 7, which compares the number of symbols identified as being of equal size to the true ratio of symbol sizes. While two symbols of which the smaller is at least 90% of the size of the larger can be accepted as being of about equal size, this makes somewhat less sense for values between 80% and 89%, and it seems wrong to state that two symbols are of equal size if the smaller symbol is less than 79% of the size of the larger one. These judgements could be added to the wrongly identified larger symbols, while the other “equal” judgements (e.g., for values >90%) may be added to the correctly identified larger symbols. Symbol 2D_c (circles without frames) is the least effective for the elementary task of identifying the larger of two symbols.

H2: Task-performance time is lower for symbols with reference frames.

The variation between the means of task-performance times by symbol type is significant ($F = 2.798$, $p = 0.016$). The only two means that are not significantly different are 2D_c and 2D_bf. As Figure 8 shows, the variation is less between symbol types but more within symbol types when task-performance times are compared for symbols with and without reference frames. Mean task-performance times are significantly higher for symbols with reference frames than for those without reference frames. In addition, variation in task-performance times, indicated through the standard deviation, is higher for symbols with frames, especially for 3D_bf and 2D_cf.

H3: Task-performance time is lower for 2D bars than for 3D bars and lower for 3D bars than for 2D circles.

Ordering the means of task-performance times produces the following ranking (from lowest to highest): 3D_b, 2D_b, 2D_c, 2D_bf, 3D_bf, 2D_cf (see Figure 8). Thus,

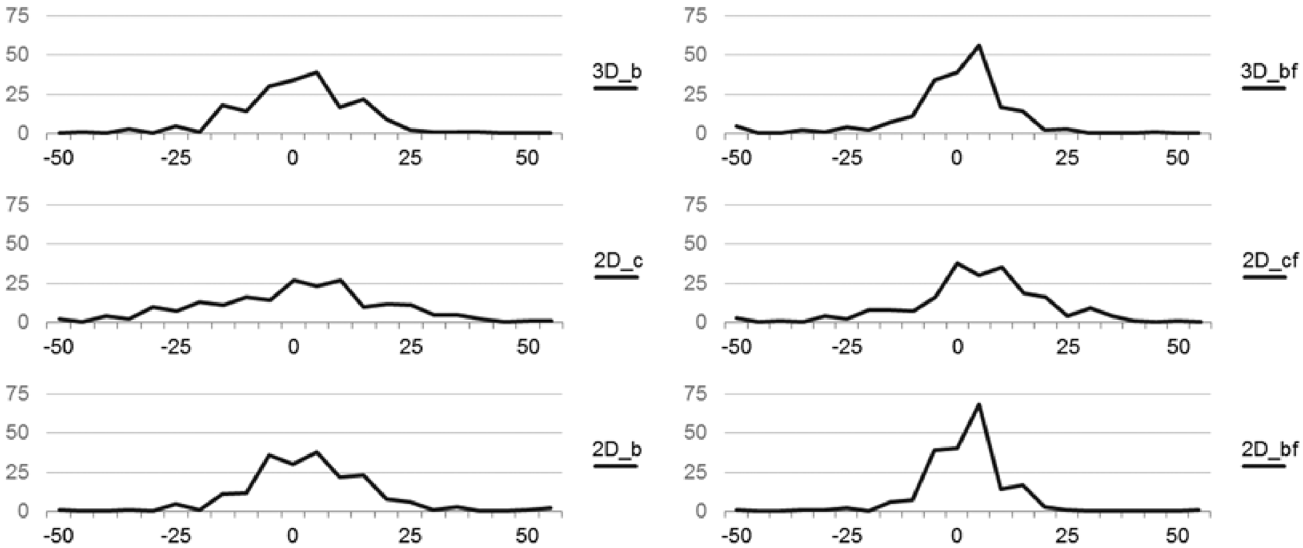

Figure 10. Histograms of numbers of symbol-size comparison differences for all symbol types.

3D bars without reference frames are processed fastest, while circles with frames take longest. The hypothesized ordering is true for symbols with reference frames but not for symbols without reference frames.

H4: Task accuracy is higher for symbols with reference frames.

The variation between the means of differences between estimated and true ratios of symbol sizes is significant ($F = 3.509$, $p = 0.004$). The means of symbols 3D_bf and 3D_b, and of symbols 3D_b and 2D_c, are not significantly different, whereas the differences between the means of all other pairs of symbol types are significantly different (see Figure 9). In addition, none of the means of differences between estimated and true ratios of symbol sizes are significantly different from zero, except for symbol type 2D_cf ($t = 3.220$, $t_{\text{crit}} = 1.978$). Looking at the standard deviation, and thus the variation in symbol-comparison differences, we find that 3D_bf, 2D_b, and especially 2D_bf have the smallest variation (see Figure 9).

H5: Task accuracy is higher for 2D bars than for 3D bars and higher for 3D bars than for 2D circles.

Based on the significance testing for H4, which shows that the means of symbol-size comparison differences are not significantly different from zero except for symbol 2D_cf, the rank-ordered amount of variation shown by the standard deviations is used to judge informally the ranking of symbol types. By ordering the standard deviations of symbol-size comparison differences, we arrive at the following ranking from most accurate to least accurate symbol type: 2D_bf, 3D_bf, 2D_b, 3D_b, 2D_cf, and 2D_c (see Figure 9 and Figure 8). This is also illustrated in the histograms of symbol-size comparison differences by symbol type in Figure 10.

Discussion and Implications

SUMMARY OF TESTED HYPOTHESES AND DISCUSSION

Hypothesis 1 (*The bigger of two symbols representing quantitative data in 3D virtual environments can be reported independently of symbol type*) is rejected, as there is significant variation between different symbol types (see Figure 6 and Figure 7). Ranking the symbol types according to the fraction of correct judgements (without equal or wrong judgements), we find the following order (fraction of correct judgements in parentheses): 2D_c (72%), 3D_b (80%), 2D_b (82%), 2D_cf (84%), 3D_bf (85%), and 2D_bf (87%). Thus, symbols with reference frames are generally better judged, and the order of appropriateness of symbols proposed in hypotheses H3 and H5 is supported.

Hypothesis 2 (*Task-performance time is lower for symbols with reference frames*) is also rejected, as the means of task-performance times are significantly higher for symbols with frames than for the same symbols without frames (see Figure 8).

Hypothesis 3 (*Task-performance time is lower for 2D bars than for 3D bars and lower for 3D bars than for 2D circles*) is accepted for symbols with reference frames but rejected for symbols without reference frames (see Figure 8). The ordering of symbols from lowest to highest task-performance times, based on ranked means, is as follows: 3D_b, 2D_b, 2D_c, 2D_bf, 3D_bf, 2D_cf.

Hypothesis 4 (*Task accuracy is higher for symbols with reference frames*) is accepted for 3D bars and 2D bars but

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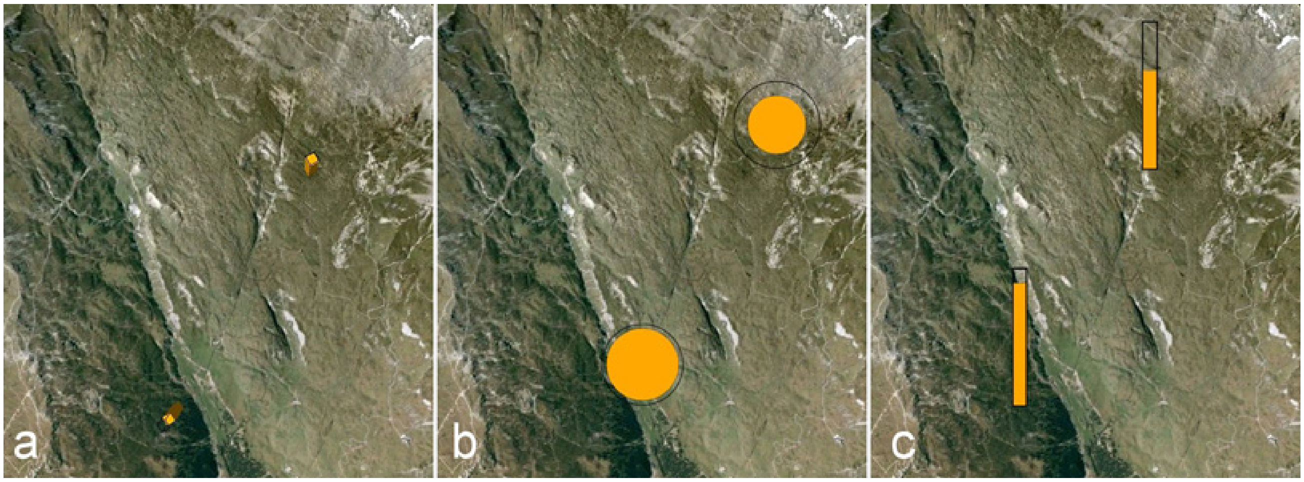

Figure 11. Top view of (a) 3D bars (3D_bf), (b) 2D circles (2D_cf), and (c) 2D bars (2D_bf), all in Google Earth (Google 2011).
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not for 2D circles (see Figure 9). Hypothesis 5 (*Task accuracy is higher for 2D bars than for 3D bars and higher for 3D bars than for 2D circles*) is accepted: 2D bars with frames yield more precise results than 3D bars with frames, and the same is true for 2D bars and 3D bars without frames, while circles with and without frames are least accurate and least precise (see Figure 10).

The least effective and least efficient symbol types are 2D circles without and with reference frames. A few participants reported that they felt the circles were the most difficult to judge and that for circles the tasks were more guessing than estimating. While reference frames improve effectiveness slightly, 2D circles are nevertheless much less effective and show a wider spread of answers than 3D bars or 2D bars. Comparing the last two leads to the conclusion that 2D bars are more effective and efficient (with reference frames) than 3D bars. While 2D bars with reference frames yield the fastest, most accurate, and most precise results of all the symbol types tested, 3D bars with reference frames are not much worse, and may thus be a valid option for displaying quantitative data in virtual environments, especially because they may integrate better with the landscape in which they are displayed. Such aesthetic considerations can affect the usability of visualizations (Cawthon and Vande Moere 2007).

Interestingly, hypothesis 2 is rejected, as symbol types with reference frames require more processing time on average. An earlier study (Bleisch, Dykes, and Nabiker 2008) found that reference frames improve efficiency when comparing 2D bars in virtual environments in an experimental setting using X3D (eXtensible 3D, Web3D 2011) as the virtual environment. The difference in results may be partially explained by the different experimental setting and instructions: in the earlier experiment, navigation within the virtual environment was more explicitly encouraged, and navigating to a potentially better view of the proportional symbols is more difficult for symbols without frames, as a reference is missing. Generally, the recorded task-performance times suggest that participants approached the tasks in an efficient way. The mean task-performance times indicate that they rarely navigated or explored different viewing angles, even though this was possible. In such a process, the existence of reference frames connotes the existence of additional information that needs evaluation, and thus warrants a longer task-performance time.

LIMITATIONS AND FURTHER RESEARCH

The virtual environments of the experimental settings were all displayed and, as participants do not seem to have navigated much, evaluated from the same viewpoint. Especially for the 2D bars and 2D circles, navigation to another viewpoint or even to the top view might have helped interpretation, while it would be more difficult to judge 3D bars using a top view (see Figure 11). Further research could evaluate a more dynamic use of these types of visualizations. In addition, the user interface of Google Earth (Google 2011) displays the 2D symbols in such a way that they are very small in the legend; as one participant suggested, this may have helped the interpretation of circle sizes (see Figure 12).

The empirical results presented here were produced via a somewhat psychophysical approach whereby reaction to different stimuli is measured. Such approaches were very popular in cartography and map design research some years ago (Montello 2002). However, as data displays in virtual environments are a newer form of visualization, and elementary tasks need evaluation before more com-

Figure 12. Small 2D symbols as displayed in Google Earth's legend (Google 2011).
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plex tasks – including cognitive reasoning – that potentially build on the basic tasks can be tested, the chosen approach is valid. Further research should test the 3D bars, however, especially with more complex data sets and tasks in more applied settings. Such evaluations are available for 2D bars and bar charts (Bleisch 2011), but evaluating with more complex data sets and various tasks may also be valuable for 3D bar displays. In addition, further symbol types may be thought of that will need evaluation, or at least theoretical validation, through discussion of 2D cartographic, information visualization, and perception knowledge. For example, Kumke (2009) has proposed the use of coloured cones to visualize thermal information in virtual environments. Future research could also evaluate how lay users perform with different quantitative data displays in virtual environments.

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