Visualizing Location Uncertainty on Mobile Devices: Cross-Cultural Differences in Perceptions and Preferences

CHAMPIKA RANASINGHE, JAKUB KRUKAR, and CHRISTIAN KRAY, University of Münster, Germany

Location uncertainty is often ignored but a key context parameter for location-based services. The standard way of visualizing location uncertainty on mobile devices is using a concentric circle. However, the impact of different visual variables (shape, size, boundary, middle dot, color) of this standard visualization on users is not well understood. There is a potential for misinterpretation, particularly across cultures. We ran a study that was previously conducted in Germany (N=32) in Sri Lanka (N=20) to investigate how users perceive different visualizations of location uncertainty on mobile devices. In particular, we investigated the impact of the four graphic dimensions, shape, boundary, middle dot and size. We identified consistencies and inconsistencies concerning perceptions of users regarding visualizations of location uncertainty across cultures. We also quantified the impact of different visualizations on the perception of users. Based on the consistencies between different visualizations and between the two cultures, we derived guidelines for visualizing location uncertainty that help developers in aligning location uncertainty with the perceptions of users. We also highlight the need for further research on cultural differences (and similarities) regarding how visualizations of location uncertainty impact the perceptions of users.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing theory, concepts and paradigms**; *Mobile devices*; *Empirical studies in ubiquitous and mobile computing*; **Geographic visualization**; *Empirical studies in visualization*;

Additional Key Words and Phrases: location uncertainty, cross-cultural differences, mobile geovisualization

ACM Reference Format:
Champika Ranasinghe, Jakub Krukar, and Christian Kray. 2018. Visualizing Location Uncertainty on Mobile Devices: Cross-Cultural Differences in Perceptions and Preferences. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 1, Article 30 (March 2018), 22 pages. https://doi.org/10.1145/3191762

1 INTRODUCTION

Smartphones are used globally to access context-aware applications, the majority of which relies on location information that is most frequently provided by global navigation satellite systems (GNSS) [2]. Alternative technologies for location sensing on smartphones include, for example, mobile networks [35] [36], wireless fidelity (WiFi) [23], inertial sensors [28], light, [6, 44] and sound [6]. Location information so obtained can sometimes be inaccurate, imprecise, incomplete, not up-to-date, delayed or unavailable due to many inescapable factors. These factors include multipath reflections, lack of line-of-sight, attenuation, clock errors, body shadowing, or environmental dynamics [9, 26]. As a result, the quality of the location information available to context-aware applications can vary greatly from being very accurate to no information being available at all. This can reduce the users' understanding of the system, cause frustration [43] and negatively affect decision-making [45]. It thus

Authors' address: Champika Ranasinghe; Jakub Krukar; Christian Kray, University of Münster, Institute for Geoinformatics, Heisenbergstraße 2, Münster, 48149, Germany, champika.manel@uni-muenster.de, krukar@uni-muenster.de, c.kray@uni-muenster.de.

2474-9567/2018/3-ART30 $15.00
https://doi.org/10.1145/3191762

makes sense to deal with uncertainty at the design level rather than ignoring it [7]. Visualizing uncertainty is one way to achieve this [5] though designers have to ensure this has no negative impact on users' trust in the system [29]. Currently, the standard way of visualizing location uncertainty on mobile devices is using a circle with a constant hue (blue). This circle represents location uncertainty usually with some level of confidence. On Android-based systems, for example, this level is set to 68% by default, which means that there is a 68% chance that the user's true location be inside the confidence region indicated by the circle [4]. The circle usually has a crisp boundary and a middle dot representing the last known location or the estimated location. The size of the circle changes based on the level of uncertainty (the higher the uncertainty, the larger the size). While this visualization is now ubiquitously used, it is not clear whether it is based on previous research and whether it benefits users, for example, with respect to understanding more clearly what the visualization means and where they are (not) located. The interpretation of visualizations, in general, can vary between cultures as well but has not been studied thoroughly for the visualization of location uncertainty. Gaining a deeper understanding of this aspect would thus contribute towards factoring cross-cultural and transnational aspects into the design of ubiquitous technologies [24, 40, 42].

In this paper, we therefore try to address this research gap. In particular, we investigate how users of two different cultural backgrounds (Germany and Sri Lanka) perceive visualizations of location uncertainty on mobile devices. Our previous study [39] with a group of 32 German participants had revealed that the type of visual representation has an impact on how people perceive location uncertainty. We have now repeated the same study with a group of 20 participants from Sri Lanka. The cultural backgrounds of these two groups were very different as was their familiarity with technology in general and smartphones in particular. In this paper, we present and contrast the results from both studies. The main contributions of the paper are: (a) we identified consistencies and inconsistencies in perceptions of users regarding visualizations of location uncertainty across cultures; (b) we also quantified the impact of different visualizations on the perception of users; and (c) we derived guidelines for visualizing location uncertainty.

2 RELATED WORK

Visualization of information uncertainty in general and specific to the domain of Geographic Information Science (GIScience) has been studied extensively, cf. e.g. [10], [32], [25]. Visual variables, a concept first introduced by Bertin [8] are graphic dimensions that can be used to encode information in a map or a visualization [41]. Visual variables used to represent geospatial data uncertainty are direct applications, variations or derivatives of the list of seven variables (position, size, shape, value, color, orientation, and texture) first introduced by Bertin. Some of the visual variables introduced as better representations of positional data uncertainty in this way are size, shape, texture, value, and color saturation [12]. MacEachren [30] suggested that color saturation and focus can be used to visualize uncertainty. According to the author [30], color saturation can be varied from pure hues (for very certain information) to unsaturated (gray) hues (for uncertain information) depicting the level of uncertainty. Focus can be set to "out of focus" for uncertain information in several different ways. These include, changing the crispness or fuzziness of the symbol edges (certain information: a sharp edge with a narrow line, uncertain information: broad fuzzy edge that fades from the center towards the background), changing the fill clarity (for example, using a sharp, distinct pattern to indicate certainty and a less defined pattern to indicate uncertainty), using fog (the thicker the fog, the higher the uncertainty) and changing the resolution [30]. Hengel [20] proposed a similar concept based on the hue saturation intensity (HSI) color model where whiteness (paleness) was used to represent the level of uncertainty (the paler the representation, the more uncertain the information are). Ehlschlaeger et al. [15] talks about using animations to visualize uncertainty. According to Gershon [16], variables such as boundary (thickness, texture, and color), blur, transparency, animation, extra dimensionality (eg. 3D); objects such as dials, thermometers, arrows, bars, objects of different shapes, and complex objects (eg. pie charts, graphs or bars, and error bars) could be used to represent imperfections in data. Furthermore, Gershon [16] points out that visual metaphors could be used to represent the degree of imperfection. These metaphors could be dashed lines instead of solid lines, a thick line representing location imperfection of a thin line, arrows attached to points and lines, blurred, fuzzy, or transparent image of a solid object, a schematic representation of an object instead of realistic and multiple images of one object [16]. Recently, Roth [41] identified 12 visual variables (general, not restricted for visualizing uncertainty) based on what had been proposed in literature, mainly based on the work by Bertin [8] and MacEachren [31][33]. The 12 visual variables are location, size, shape, orientation, color hue, color value, texture, color saturation, arrangement, crispness, resolution and transparency [41]. Detailed reviews of uncertainty visualizations are available in [30, 37, 41].

2.1 Visualization of Location Uncertainty on Mobile Devices

While visualizing uncertainty has been studied across a wide range of disciplines including the geospatial domain, our work focuses on the type of uncertainty commonly referred to as "positional accuracy" in the geospatial domain[12]. We use the term "location uncertainty" in our work due to two reasons. First, in the context of mobile devices, positional information has different facets such as orientation, viewing direction, body orientation, speed, acceleration, and location [27] whereas "location" just refers to the coordinates of the current location of the mobile device. Therefore, the term "positioning" has a broader meaning and using it in the mobile context to represent location could be misleading. Second, in addition to the accuracy, location information has different aspects of quality such as precision, granularity, coverage, conflicts, update rate and recency [19]. Therefore, to cover the uncertainty created by all these aspects, we use the word "uncertainty" instead of just accuracy. In our work, we focus on visualizing location uncertainty specifically on mobile devices. In this subsection, we review existing ways of visualizing location uncertainty with a focus on mobile devices.

Current applications use a circular shape to represent location uncertainty. The size of the circle represents the location error with some confidence level. This circular shape usually consists of visual representations such as a boundary, a middle dot, and transparency. The middle dot represents the last known location or the estimated location. Transparency is usually constant, with an evenly blue hue. The reason behind the use of a circular shape is to represent the error using the radius of the circle. Therefore the size changes according to the location error. It is unclear whether the use of the color and the sharp boundary were derived from the concepts of uncertainty visualization. Generally speaking, existing literature discourages the use of sharp boundaries for visualizing uncertainty [30]. The use of a boundary and the middle dot varies in different applications/ systems. For example, Google maps for Android uses a middle dot and a sharp boundary based on a 68% confidence that the user's current location is inside the circle [4]. Apple's Map app (used in iPhones and Apple watches [1]) uses a circle with a middle dot but no sharp boundary [22]. Heremaps used in Windows maps application also use a translucent circle with a middle dot but without a sharp boundary [21].

Early systems such as GUIDE [13] used a "Bar of Connectivity" to indicate the level reception of location information. This bar of connectivity can be considered as a blend of an object and animation metaphor. However, it is not known whether this representation was developed based on the uncertainty visualization concepts of adding objects by Gershon [16] or animation by Ehlschlaeger et al. [15] and Gershon [16]. Additionally, GUIDE also used a "Location Status Window" that displayed the last known location and the time in minutes that had elapsed since the last reading [13]. LOL@ [38] used a tooltip text attached to the location symbol to display the accuracy of the location. Adding text windows or tooltip texts also could be conceived of as adding objects as proposed by Gershon [16]. However, it is not clear whether GUIDE or LOL@ used them based on that concept of Gershon.

2.2 Evaluating Visualizations of Location Uncertainty on Mobile Devices

There exists a large body of user studies evaluating various aspects of uncertainty visualizations in the geospatial domain (a review of these studies is available in [25]). However, only a small number of studies focus on evaluating the impact of visualizations of location uncertainty on mobile devices on users. This section reviews these user studies, focusing on what they evaluated and the findings.

Dearman et al. [14] investigated the benefits and influences of providing a location error estimate to users. They communicated the error of the predicted location using four different visualizations and evaluated the impact of these visualizations on users in a location (poster) finding task. The four different visualizations of location error used were: (i) only the predicted location (a red dot and "Me" in the center) without any information on the location error. (ii) a circle (unfilled) of fixed size indicating the 95% confidence region around the predicted location, (iii) a circle (unfilled) of variable size indicating the N% confidence region around the predicted location where N is defined by the user, (iv) a circle (unfilled) of variable size whose size is determined by the optimal confidence calculated by the system around the predicted location. They used metrics such as the time taken to find a poster, perceived difficulty of finding a specific poster as well as the navigation strategies and the influence of each visualization on these strategies to evaluate and compare the effectiveness of the visualizations. They found that revealing the error of the predicted location using a visualization is beneficial to users over non-visualization. Aksenov et al. [3] varied the visual representation of the middle dot and the boundary in different ways to convey different aspects of location uncertainty and investigated their impact on the impressions of users. The four aspects of uncertainty used were: regular update is available with a known error, a location update is missing, location information in unavailable, location information is outdated. They also compared the commonly used visualization (last location update using a pulsating middle dot and a circle around that showing the associated uncertainty) to three other extended visualizations that visualize different uncertainty levels/the reasons for the uncertainty). The results indicate that visualization of the level of uncertainty (which in this case also conveys the reasons for such uncertainty) is helpful to users. For example, users indicated that when they saw the cross instead of a circle with pulsating middle dot, they knew that they should look for alternative strategies. Burigat and Chittaro [11] compared three types of uncertainty visualizations on mobile phones: basic visualization (a static non-pulsating grey dot), circle visualization (a concentric circle with a middle dot but without a crisp boundary) and street-coloring visualization (street segments on the map that the user might be in are colored in yellow, figure 1i) that was introduced by them. In a field-based user study, they assessed the accuracy error (difference between the location that the users think that they were when asked by the navigation system and their true location recorded on a paper map by the experimenter who followed the participant), position assessment time (time taken by the users to pinpoint their location on the on-screen map when asked by the navigation system), perceived accuracy (how accurate that the users thought that they are in estimating their position), perceived usefulness and the subjective mental workload (measured using the NASA-TLX [18]) of these three types of visualizations. Users perceived that the street-coloring visualization is more useful than the basic visualization. Also, users perceived the background map to be more useful than the basic visualization. Furthermore, the overall workload required for the basic visualization was higher than the street-coloring visualization. Mental demand required for the street-coloring visualization was lower than that is required for the basic visualization. The effort required was low both for circle and street-coloring visualizations compared to the basic visualization. There was no significant difference between the three approaches in the accuracy error, position assessment time and perceived accuracy. Users preferred the street-coloring visualization over basic visualization. In summary, the street-coloring visualization was well received by the users, despite it being completely different from what the users usually see in their mobile navigation applications. However, there is no evidence that the street-coloring visualization is better or worse than the traditional circle visualization. McKenzie et al. [34] investigated four visualizations of location uncertainty and their effectiveness in depicting positional uncertainty. The four visualizations were based on two glyph types (uniform blue circle with border and Gaussian fade) and the presence/non-presence of a middle dot (that they refer to as centroid). They investigated the effect of these visualizations on a position judgment task. In particular, they looked at the heuristics used for the judgment, effects of visualizations on the consistency of judgment with heuristics and the effects on performance. They discovered that the uniform blue circle without a centroid produces the most accurate responses. Therefore, although regarding visual representation, one might expect the Gaussian faded glyph to better represent uncertainty, the experiment revealed that the glyph (circle in this case) with a uniform opacity resulted in more accurate uncertainty judgments. Although not specific to visualization of location uncertainty on mobile devices, it is worthwhile to mention the recent work carried out by MacEachren et al. [33] to investigate the semiotics, and the intuitiveness of the different visual variables used to visualize uncertainty of spatial data. Results revealed that there are agreements and disagreements (on different levels) between the semiotics and intuition. While encouraging similar research on different contexts, they recommended further investigation of how these symbols could be used (for example scaled) on mobile devices and the impact of the background display on the accuracy and interpretation. In a previous study [39], we investigated the user preferences and perceptions of visualization of location uncertainty on mobile devices. We compared three glyphs: commonly used circle, cloud and the street- coloring visualization proposed by Burigat and Chittaro [11] as well as derivatives of those main visualizations by modifying the variables boundary (with a crisp boundary, without a crisp boundary), middle dot (with middle dot, without middle dot) and size (small, large). As the use of a boundary or a middle dot with street-coloring visualization is not meaningful, we did not use derivatives for the street-coloring visualization. We discovered that the boundary and the middle dot have an impact on the users' understanding of where they are located when they see a visualization. In the current paper, we extend this research by replicating the same study in a different cultural context and by carrying out further analysis to identify consistencies and inconsistencies between cultures and what they could mean.

2.3 Summary of Existing Work on Visualization of Uncertainty on Mobile Devices

Literature suggests many different ways to visualize uncertainty of geospatial data. However, the number of ways that have been applied for visualizing location uncertainty on mobile devices is very small. Besides, there is no experimental backing that the existing options of visualizing location uncertainty on mobile devices using a circle (and using other properties such as color, size, boundary and middle dot) are developed based on the common uncertainty visualization options proposed in the literature. According to the literature, shape, boundary (sharpness, fuzziness, width), color, transparency of an object, focus can be used to convey different levels of uncertainty (i.e., in the uncertainty visualization domain, they have a specific meaning, or they convey different levels of uncertainty). However, it is doubtful whether the visualizations used for communicating uncertainty on mobile devices, use them to mean the same things. For example, use of a middle dot is somewhat analogous to the focus metaphor proposed by MacEachren et al. [30]. Therefore, one could argue that the appearance of the middle dot resembles an "in-focus" metaphor which is usually used to communicate relatively certain information. Similarly, the removal of the middle dot could resemble an "out of focus" metaphor which is usually used to represent uncertain information. However, existing work uses the middle dot to indicate the approximate or the last known location. Therefore, there is a mismatch between what existing visualizations on mobile devices try to convey by (not) using a middle dot and what the literature says what they should convey. On the other hand, there is no experimental evidence regarding what users actually understand when they see a middle dot in a visualization on their mobile devices (i.e. whether it is what the developer wants to convey, or what the literature says that it could convey or something else). Another example along these lines is color saturation, which in the literature is used to represent the level of uncertainty. It can vary from pure hues (for very certain information) to unsaturated (gray) hues (for uncertain information) based on the level of uncertainty. However, most of the current uncertainty visualizations use a circle with a constant hue (light blue). Also, according to the uncertainty visualization literature, boundary crispness has a visual impact, and we do not know the impact of this visual variable on users. Furthermore, the popular blue circle changes only its size based on the level of uncertainty of location information. Current approaches have not specifically investigated the impact of different variations of the boundary and the middle dot on the perceptions of users regarding where they think they are located. In addition, the use of shapes other than the circle to represent location uncertainty is rare. Furthermore, how users from different cultures perceive them has not yet explored. Therefore, further investigations are required to find out what users understand when they see different visualization and whether there are cultural differences in these interpretations. Such research will be useful in developing uncertainty visualizations on mobile screens that better align with the intuitions of users.

The current study differs from existing studies evaluating visualizations of location uncertainty in several ways. First, we study the consistencies and inconsistencies in user perceptions with respect to where they think they are located when they see (a) different existing and novel visualization options (boundary and middle dot, boundary but no middle dot, only the middle dot without a boundary and no boundary no middle dot) (b) different shapes (existing and novel). Second, we investigate the perceived accuracy when they see visualization of different sizes. Third, we also focus on user preferences regarding existing and novel visualization options and shapes. Finally, we investigate whether there are consistencies and inconsistencies in perceptions and preferences between users of different cultural backgrounds.

3 STUDY

As discussed in the previous section, it is essential for users to fully understand the uncertainty attached to location information so that they know where they are (not) and can make informed decisions. At the same time, there are several open questions related to this issue and a need for further research, i.e., to improve the quality of navigation support systems and LBS in general. To gain a deeper understanding of how users interpret location uncertainty visualizations on mobile devices and their preferences, we carried out a user study focusing on three types of uncertainty visualizations. In addition to the widely used circle, we included the colored street segments (CSS) from Burigat and Chittaro [11] as well as a newly developed cloud shape [39]. We also varied certain aspects of the three visualizations to identify the impact of specific graphic measures (boundary, middle dot, size). Since cultural differences can play an important role in how people perceive visualizations and which ones they prefer, we ran our study with two groups that had different cultural backgrounds: one from Germany and one from Sri Lanka. In doing so, we aimed to find answers to the following three research questions:

- **RQ1 - Preferences of users:** *Is there a difference in preference between the three shapes (Circle, Cloud, and CSS), and is there a difference in preference between different visualization options?* This relates to the issue of whether users have a preference for a particular type of visualization and whether the way in which it is shown on the screen has an impact on their preferences. For example, we would like to gain insights into whether users prefer to have a center dot present for the circle visualization or not.
- **RQ2 - Perceptions of users:** *Is there an impact of different shapes and different visualization options on people's understanding of where they are likely to be located?* Specific sub-questions that we had under the umbrella of this core research question were: Is there an impact of the use of the three visual representations (border line, middle dot, size) on the users' perceptions of location uncertainty? Can the cloud shape successfully represent location uncertainty on mobile devices? Is the perception of uncertainty different when visualized with a cloud than with a circle? Do the user preferences regarding visualizations correspond to their perceptions?
- **RQ3 - Cultural background of users:** *What is the impact of users' cultural background on their preferences and perceptions regarding the different visualizations?* Here, we particularly wanted to find out whether results would be consistent across cultural backgrounds or whether there were any (systematic) differences.

Based on these questions and considerations, we designed and carried out a user study in two different countries (Germany and Sri Lanka). The following paragraphs describe the study in more detail.

(a) circle (BD: Border and Dot) (b) circle (ND:Dot only) (c) circle (BN: Border only)

(d) circle (NN: No border No dot) (e) cloud (BD: Border and Dot) (f) cloud (ND: Dot only)

(g) cloud (BN: Border only) (h) cloud (NN: No border No dot) (i) CSS

Fig. 1. (to be viewed in color) The three basic shapes considered in the study: circle, cloud, colored street segments (CSS); the circle and the cloud were tested with four visualization options: with border and dot (BD), dot only (ND: without border/with dot), border only (BN: with border/without dot) and no border no dot (NN).

3.1 Design

To minimize external influences and to ensure consistent conditions throughout the study, we followed a mixed design (within-subjects and between-subjects) for our lab-based study. Participants were shown a series of uncertainty visualizations on a mobile phone and asked a series of questions relating to those visualizations. In total, we used nine different visualizations in the study (see Figure 1), which were derived from three distinct shapes: a circle (Fig. 1(a)-(d)), a cloud (Fig. 1(e)-(h)) and the colored street segments (Fig. 1(i)). By using three distinctively different shapes, we hoped to be able to answer RQ1, and the four different variations for the circle and cloud visualizations were included to facilitate answering RQ2. As can be seen from Figure 1, we varied two graphical elements to arrive at the four variations, i.e., whether or not there was a dot present at the center of the visualization and whether or not there was a discrete border around the visualization.

These visualizations were shown on maps that we had extracted from [17] and then post-processed to remove icons, legends, and labels. The motivation behind this was to eliminate any interference resulting from people relying on this information when answering the questions. Throughout the study, we presented participants with a series of visualizations over the post-processed maps. Each screen also included a specific question at the top and a set of possible answers at the bottom. We used four different types of questions (as described below) to answer the research questions we had defined. Through this design, we intended to ensure the consistent delivery of questions and facilitated the recording of the participants' answers. To obtain initial insights into the impact of the cultural background, we ran the study in two different countries (Germany and Sri Lanka). Both countries differ substantially in terms of their cultural background, for example concerning their geography (continental vs. insular setting), climate, historical development, GDP, population and also regarding smartphone saturation (very high in Germany, much lower in Sri Lanka). Due to these large differences, we expected to be able to observe rather large effects if indeed they exist.

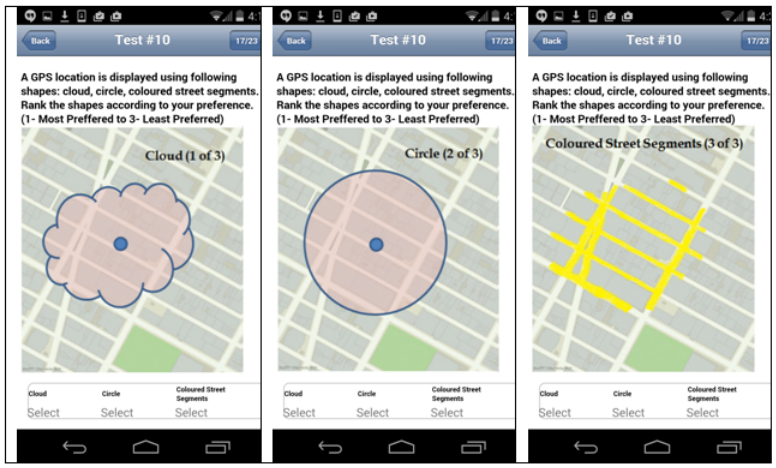


Fig. 2. (to be viewed in color) Example shape preference question asking participants to compare the three shapes (cloud - border and dot, circle - border and dot and CSS), which were presented in a repeating slideshow until the ranking question at the bottom of the screen was answered.

3.2 Participants

We recruited participants from around the two involved universities, using word-of-mouth, mailing lists, and other means to reach a large number of people. In Germany, 35 participants (27 male, eight female) took part in the study. Since the data gathered from three male participants turned out to be incomplete, we had to discard them. The remaining 32 participants were aged between 19 and 42 years (average: 23). All but two owned a smartphone, and 31 of them had also previously used it to navigate in unfamiliar environments (15 did so regularly, 11 occasionally and four rarely). Only one smartphone owner had never used their smartphone for this purpose. Since the study was carried out in English, we also asked participants to rate their English proficiency. Eleven people rated it as "very good," 13 as "good" and eight as "moderate."

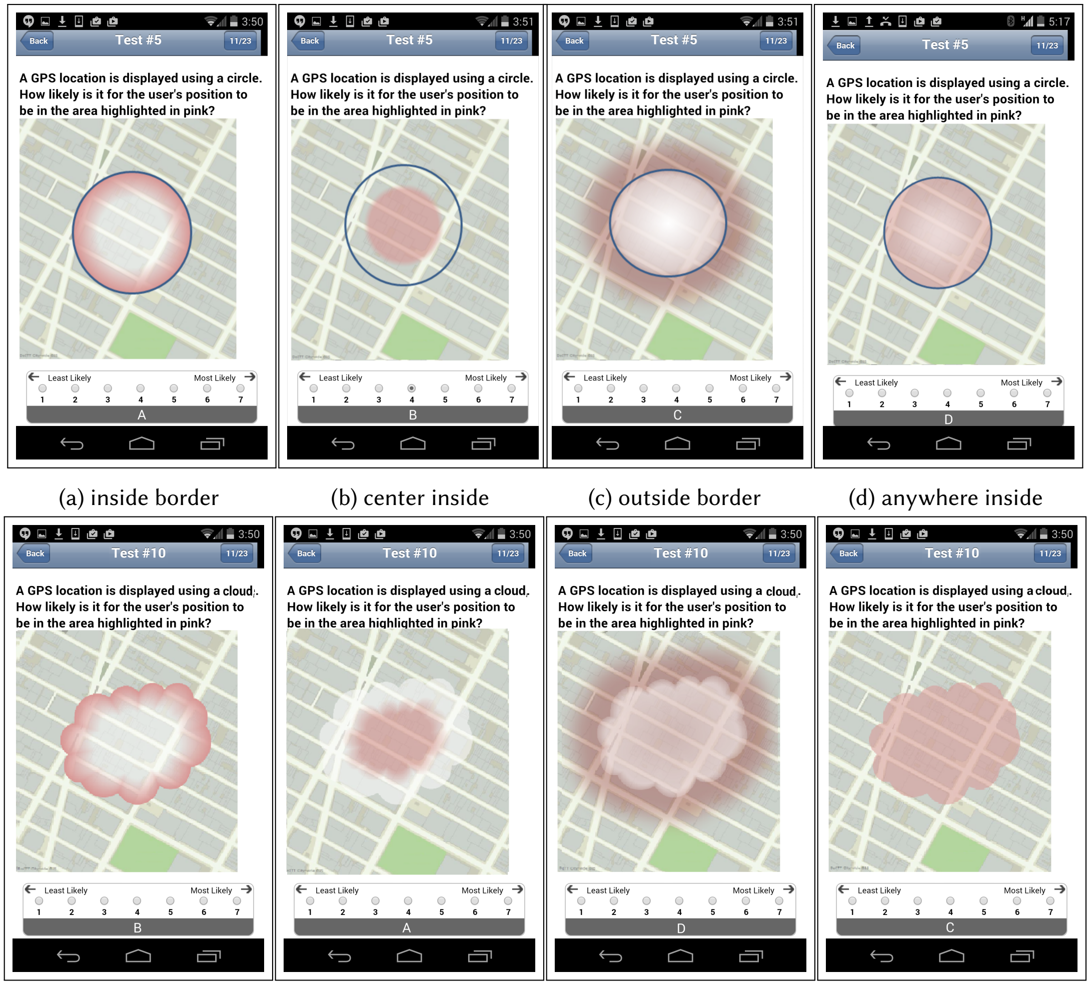
In Sri Lanka, we recruited 20 participants (8 male, 12 female), aged between 23 and 37 years (average: 30). No data had to be discarded. 14 of the participants owned a smartphone while six did not. All smartphone owners had used their device to navigate in unfamiliar areas (four did so regularly, six sometimes and another four rarely). When asked about their proficiency using the English language, six participants rated it as "good" while the other 14 ranked it as "moderate."

Fig. 3. (to be viewed in color) Example visualization option preference question asking participants for their preference amongst the four visualization options (BN:border only, BD:border and dot, ND:dot only, NN:no border no dot) for the cloud shape; these options are presented sequentially in a slide show that repeats until the question at the bottom of the screen is answered.

3.3 Materials

The entire study was carried out in the lab on a standard smartphone (Google Nexus 5 with a 4.95" HD screen) running a custom-built web-based application. The application first presented a simple questionnaire asking for demographic data (nationality, age, gender, English proficiency, smartphone ownership, use of the smartphone for navigation in unfamiliar environments). During the main part of the study, the application randomly and dynamically generated 23 questions for each participant. In total, there were four types of questions which were presented using the same layout: a textual question at the top of the screen, a limited set of options for selecting an answer at the bottom of the screen and uncertainty visualizations depicted in the center of the screen. This latter part took up about 80% of the overall screen. The four types of questions were designed as follows:

- **Shape preference:** people were asked to rank the three shapes (cloud, circle, CSS) that were shown in the center part of the screen (as a repeating slideshow) according to their preference. Four out of the 23 questions were of this type.
- **Visualization option preference:** participants were shown a repeating slideshow of four different visualization variations of either the circle or the cloud shape and then asked to rank them according to their preference. In total, there were two questions of this type.
- **Perceived location:** people were asked to indicate the likelihood to be in a highlighted region using a seven-point Likert scale. The center part showed either the circle or the cloud in one of the four variations (Border & Dot, Border only, Dot only, No border no dot) while one of four possible regions was highlighted (Anywhere Inside: entire shape highlighted, Center Inside: center of the shape highlighted, Inside Border: area just inside the border highlighted, Outside the Border: area just outside the border highlighted). Eight of the 23 questions were of this type.
- **Size-accuracy:** participants were shown a repeating slideshow of two different sizes of the same visualization (from among the nine we used - cf. Figure 1) and then asked to rank them according to which one they thought was more accurate. In total, there were nine questions of this type.



(a) inside border (b) center inside (c) outside border (d) anywhere inside

(e) inside border (f) center inside (g) outside border (h) anywhere inside

Fig. 4. (to be viewed in color) Two examples of a perceived location question (circle shape in the border only visualization option: BN, figures a-d; and the cloud shape with no border no dot:NN visualization option, figures e-h) asking participants to indicate the likelihood of being in the region highlighted in pink; only one image was shown at a time, when the user finishes entering the likelihood of being in the corresponding region, he can go to the next image by touching the screen.

Figures 2, 3, 4 and 5 show example screens generated by the application during the study for shape preference, visualization option preference, perceived location and size-accuracy questions respectively.

Except for the perceived location questions, the center part of the screen showed a repeating slideshow of several images while the top and the bottom part of the screen remained constant. Both the question and the possible answers thus always were visible to the participant. In the perceived location questions, for each question, users had to go through four different screens, one after one. Each of these four screens contained a question in the top part of the screen, a visualization of location uncertainty in the center part and a Likert scale in the bottom part. The visualization in the center part of the screen contained either a circle or a cloud in one of the

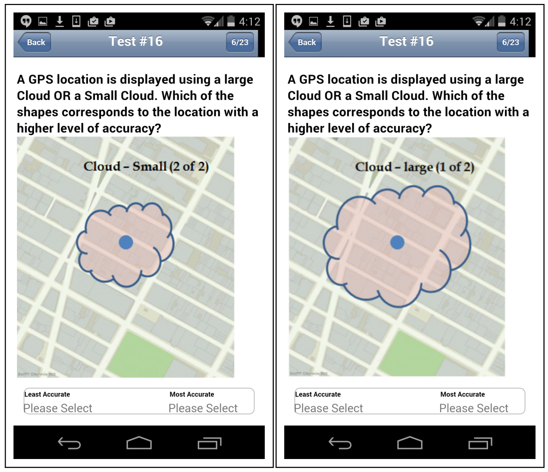


Fig. 5. Example size-accuracy question asking participants to rank a smaller and a larger version of the same visualization (cloud - border and dot(BD)) according to how accurate they are; both versions were shown alternatingely until a ranking was entered at the bottom of the screen.

four visualization options (for example, circle-border only). Also, one of the four regions (anywhere inside the shape, center inside, just inside the border, just outside the border) is highlighted. The question at the top asks the participant to enter the likelihood of being in the highlighted region. The participant can input the perceived likelihood using the Likert scale at the bottom of the screen. Once the participant enters the perceived likelihood for the highlighted region, she can go to the next screen of the same question by touching the screen. The next screen shows the same visualization (for example, circle-border only) but with a different region highlighted. The question at the top and the Likert scale at the bottom of the screen remain constant. In this way, the participant can input the perceived likelihood of being in the four regions using the four screens in a perceived location question. Participant also can go back using the back button (in the header part of the screen) or forward (by touching the middle part of the screen) to change what was entered or to compare the different regions. Figure 4 shows two of perceived location questions (circle border only: a-d; cloud no border no dot: e-h). We used gradients for highlighting the regions inside a visualization (i) to show the boundary of the shape more clearly and show the boundaries of regions intuitively without defining them using sharp boundaries; and (ii) to keep the way we highlight regions consistent across the different visualizations.

The questions, the visualization options inside questions (BD: Border and Dot, BN: Border only, ND:Dot only, NN: No border No dot) and the highlighted regions (Anywhere Inside, Center Inside, Inside Border, Outside Border) inside questions were randomized to minimize potential learning effects and bias.

3.4 Procedure

The study took place in a lab at one of the two involved universities. Each participant was welcomed by the experimenter, who carried out the study at both sites. No other person was present during the study besides the participant and the experimenter. After briefing the participant about the study and answering any questions they might have, they received the smartphone with the study app already open and set to a training mode so that participants could familiarize themselves with the app. Once they indicated that they were ready for the main study, the phone was configured accordingly and given back to the participant with the app already running. The participant then first had to answer a small number of demographic questions. After doing so, the app presented a summary view of the collected data and asked for confirmation while offering the option to correct any data that was incorrect. Once a participant confirmed the correctness, the main part of the study began. The app showed a series of 23 dynamically generated questions in random order as outlined above. The answers given by users were recorded using an online web server. After a participant had completed all questions, a completion screen was shown, and the phone was collected by the experimenter. During the following debriefing phase, participants could ask any further questions they had and also received a small payment in return for their time.

4 RESULTS

The data were analyzed under three main topics: (a) users' perception about where they are located when they see a visualization of location uncertainty (to find answers for the research questions 2 and 3); (b) perceived accuracy when they see visualizations of different sizes (also contributing towards answering research questions 2 and 3); and (c) users' preferences of different types of visualizations of location uncertainty (to find answers to research questions 1 and 3). The following sections describe these in more detail.

Table 1. Multivariate test results

Factor	**df_1**	**df_2**	**F**	**partial η^2**	**p**
culture	4	47	3.193	0.214	**0.021**
shape	4	47	5.509	0.319	**0.001**
visualization option	12	39	2.447	0.430	**0.017**
shape*culture	4	47	11.055	0.485	**0.000**
visualization option*culture	12	39	1.059	0.246	0.419
shape*visualization option	12	39	1.404	0.093	0.977

Table 2. Contrasts for the main effects of culture, shape and visualization option

Region	**Statistics**	**DE vs. SL**	**Circle vs. Cloud**	**Visualization options**		
				Border & Dot vs. Border only	**Border & Dot vs. Dot only**	**Border & Dot vs. No border No dot**
Anywhere inside	**F (1, 50)**	1.870	4.41	5.414	1.58	3.067
	partial η^2	0.036	0.081	0.098	0.023	0.058
	p	0.178	**0.041**	**0.024**	0.287	0.086
Center inside	**F (1, 50)**	2.326	2.64	4.823	0.069	5.422
	partial η^2	0.044	0.05	0.088	0.001	0.098
	p	0.133	0.111	**0.033**	0.793	**0.024**
Inside border	**F (1, 50)**	1.564	2.48	3.517	2.912	2.419
	partial η^2	0.030	0.047	0.066	0.055	0.046
	p	0.127	0.121	0.067	0.094	0.126
Outside border	**F (1, 50)**	3.592	19.92	0.632	2.991	.000
	partial η^2	0.067	0.29	0.012	0.056	0.000
	p	0.064	**0.000**	0.43	0.09	0.992

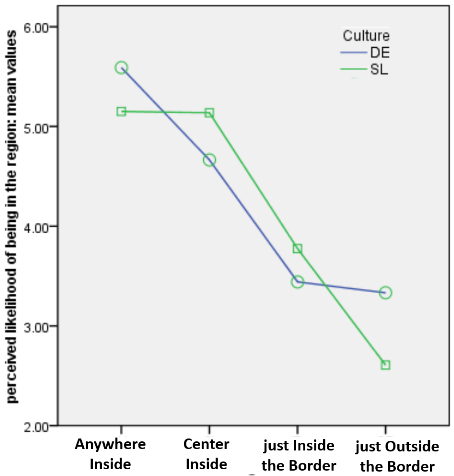
Table 3. Interaction shape*culture

Region	**DE vs. SL**
	Circle vs Cloud
Anywhere inside the shape	F(1, 50)=0.322, p=0.543, partial η^2 = 0.006
Center inside	F(1, 50)=0.060, p=0.808, partial η^2 = 0.001
just inside the border	F(1, 50)=0.163, p=0.688, partial η^2 = 0.003
just outside the border	F(1,50)=37.575, **p=0.000**, partial η^2 = 0.429

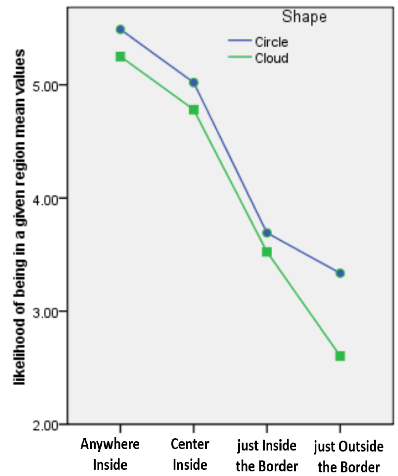
4.1 Users' Perception Regarding their Location when Seeing a Visualization of Location Uncertainty

The users' perception of being in a particular region was evaluated using perceived location questions (questions 1 to 8). Users indicated their perceived likelihood of being in four pre-defined regions (anywhere inside, center inside, just inside the border and just outside the border) for each type of visualization using a 7-point Likert scale (from 1 – least likely to 7 – most likely). Each visualization is characterized by its shape and the visualization option (border and dot, border only, dot only, no border no dot). Our objective was to determine whether there are any inconsistencies between the two cultures, German (DE) and Sri Lankan (SL), and if so, what they are. In order to investigate this, we considered the following factors in the data analysis: culture (DE vs SL), shape (circle, cloud) and visualization option (BD: border and dot, BN: border only, ND: dot only, NN: no border no dot), and four dependent variables: perceived likelihood of being anywhere inside the shape, perceived likelihood of being in the center of the shape, perceived likelihood of being just inside the border and the perceived likelihood of being just outside the border. We used SPSS to analyze the data (from perceived location questions) using repeated measures MANOVA using between-subject factor: culture, within-subject factors: shape, visualization option. We wanted to identify: (a) the impact of shape on the perceived likelihood of being a given region, (b) the impact of visualization option on the perceived likelihood of being in a given region, (c) the relationship between shape and culture on the perceived likelihood of being in a given region, (d) the relationship between the visualization option and culture on the perceived likelihood of being in a given region, (e) the relationship between the shape and visualization option on the perceived likelihood of being in a given region. Therefore, we analyzed the data for the main effects of culture, shape and the visualization option as well as interactions between shape and culture (shape*culture), visualization option and culture (visualization option*culture) as well as shape and visualization option (shape*visualization option). Table 1 provides an overview of the results. All effects are reported as significant at $p < 0.05$. We describe these results in detail in the remainder of this section.

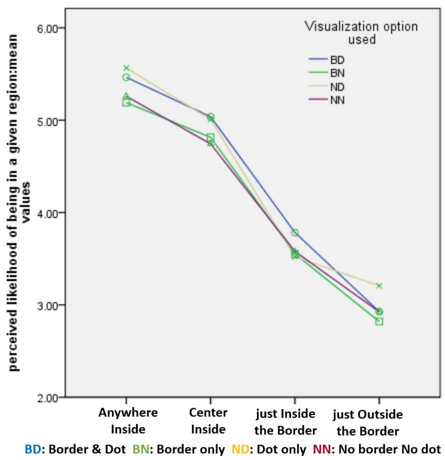
There was a significant effect of culture (Table 1). But none of the individual ANOVAs reached significance (Table 2). It can be seen that people from both cultures perceive a higher likelihood of being anywhere inside the shape and this likelihood decreases from the center to the outside (Figure 6a). We also found a significant effect of shape (Table 1): participants expressed a higher likelihood of being in a given region when visualized using a circle compared to when visualized using a cloud (Figure 6b). Contrasts reveal that people perceive a significantly higher likelihood of being anywhere inside the shape when visualized with a circle shape than with a cloud shape. The perceived likelihood of being just outside the border is also significantly higher when visualized with a circle shape than with a cloud shape (Table 2). There was also a significant main effect of the visualization option (Table 1). Contrasts revealed that the perceived likelihood of being anywhere inside the shape is significantly higher when visualized with a border and a dot (BD) compared to when visualized with a boundary only (BN) (Table 2). Also, the perceived likelihood of being in the center of the shape is significantly higher when visualized with a border and a dot (BD) compared to when visualized with only the border (BN), or when visualized with a border and a dot (BD) compared to when visualized without a border or a dot (NN). Border and dot (BD) and dot only (ND) options result in higher perceived likelihood anywhere inside and in the



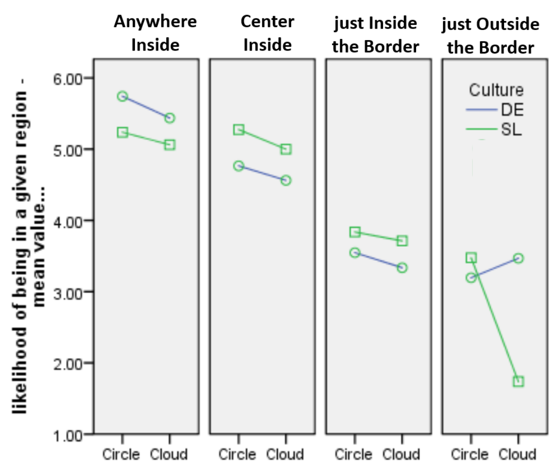
(a) Perceived likelihood of being in a particular region - mean results for the effect of culture: both groups were consistent in perceiving a higher likelihood of being anywhere inside the shape and believing that this likelihood decreases from the center of the shape to the outside.



(b) Mean results for the main effect of shape: There was a significant main effect of shape. Cloud received a low score compared to the circle. This difference is significant for the perceived likelihood of being anywhere inside the shape and for the perceived likelihood of being just outside the border.

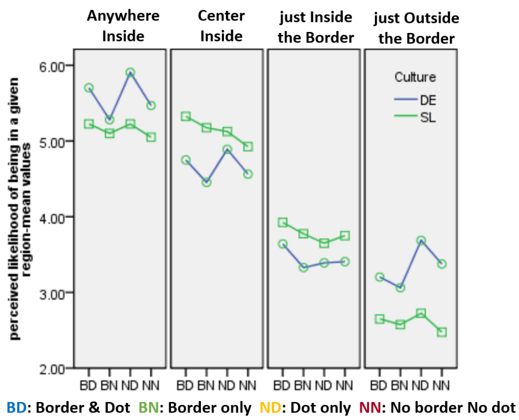


(c) Mean results for the main effect of visualization option: There was a significant main effect of visualization option. Perceived likelihood of being anywhere inside the shape was significantly higher when visualized with a border & a dot (BD) compared to visualizing it with only the border (BN). The perceived likelihood of being in the center of the shape was significantly higher when visualized with a border & a dot (BD) compared to visualizing it with only the border (BN) or when visualized with a border & a dot (BD) compared to visualizing it with neither a border nor a dot (NN).

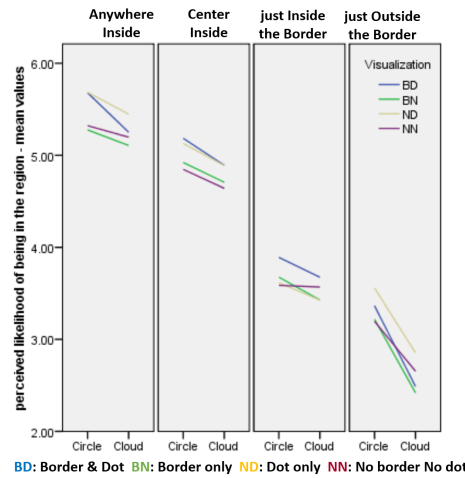


(d) Shape*culture interaction - mean values: There was a significant interaction between the shape and the culture. The relationship between the shape and the perceived likelihood of being anywhere inside the shape, center of the shape or just inside the border was consistent between the two cultures. However, this relationship is inconsistent between the two cultures in the just outside border region; there is a significant difference in the perceived likelihood of being just outside the border between circle and cloud, between Germans and Sri Lankans.

Fig. 6. (to be viewed in color) Mean results for the main effect of culture, main effect of shape, main effect of visualization option used, and the interaction between shape and culture (shape*culture interaction); all results generated at 95% confidence level.



(a) Interaction between visualization option and culture (visualization option*culture) - mean values: The interaction between visualization option and culture was not significant. i.e. the relationship between the perceived likelihood of being in a particular region and the visualization option used is not significantly different between Germans and Sri lankans.



(b) Interaction between shape and the visualization option (shape*visualization option) - mean values: The interaction between the shape and the visualization option was not significant. i.e. the relationship between the perceived likelihood of being in a particular region and the visualization option used is not significantly different between circle and cloud.

Fig. 7. (to be viewed in color) Interaction between visualization option and culture (visualization*culture) and between shape and visualization option (shape*visualization option): both are not significant at 95% confidence level.

center inside regions. Border and dot (BD) produced the highest perceived likelihood for just inside border and dot only (ND) produced the highest perceived likelihood in just outside the boundary region (Figure 6c).

We also found a significant interaction between the shape and the culture of the participant (Table 1). The relationship between the shape and the perceived likelihood of being anywhere inside, center inside and just inside the border of the shape is consistent between the two cultures, cf. Figure 6d. However, this relationship is inconsistent for just outside the border region. Contrasts also revealed that there is a significant difference in the perception between circle and cloud, between Germans and Sri Lankans for just outside the border region (Table 2). The interaction between visualization and culture is not significant (Table 1). This means that the relationship between the perceived likelihood of being in a particular region and the visualization option used is not significantly different between Germans and Sri Lankans. Table 4 in Appendix A summarizes the contrasts. Figure 7a shows the relationship between the mean perceived likelihood of being in a particular region and visualization options (compared between Germans and Sri Lankans). The interaction between shape and the visualization option is also not significant (Table 1). i.e., the relationship between the perceived likelihood of being in a particular region and the visualization option used is not significantly different between circle and cloud. Table 5 in Appendix A summarizes the contrasts and Figure 7b shows the relationship between the mean perceived likelihood of being in a particular region and visualization options (compared between circle and cloud shapes).

4.2 Users' Perception Regarding Size of the Visualization and the Level of Accuracy

Accuracy-size questions evaluated the perceived accuracy when users see location uncertainty visualizations of different sizes. Our data contained three categorical variables: culture (two levels: DE, SL), Accuracy (two levels: high, low), size (two levels: small, large). The data were analyzed using the log linear analysis on SPSS.

We were interested in finding out the relationship between the perceived accuracy and the size of the visualization, and whether this relationship is consistent between the two cultures.The three-way log linear analysis produced a final model that retained all effects. The likelihood ratio of this model was χ^2 (1) = 0, p = 1. The highest order interaction (culture*size*accuracy) was significant, χ^2 (1) = 193.85, p<0.001, showing a significant difference in the perceived accuracy between the two cultures. We then ran separate chi-square tests on size and accuracy variables for the two cultures separately. These tests revealed that there is a significant association between the size of the shape and the perceived accuracy in the German group χ^2 (1) = 306.25, p<0.001: the smaller shape was perceived as representing higher accuracy compared to the larger shape (See Figure 8). However, the association between the size of the shape and the perceived accuracy was not significant in the SL group χ^2 (1) = 5.441, p>0.001. (See Figure 8).

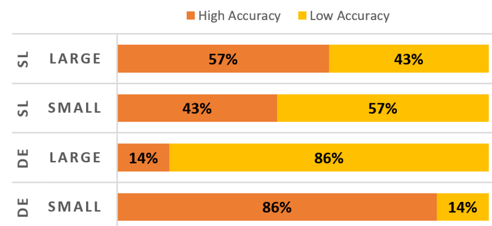


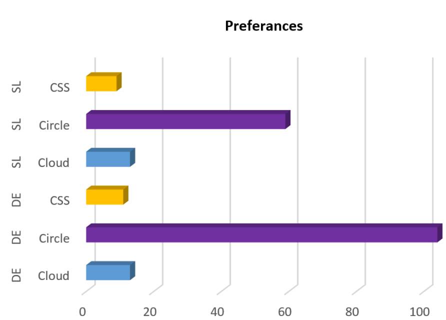
Fig. 8. Size of the shape vs. perceived accuracy - comparison between German and Sri Lankan groups

4.3 User Preferences

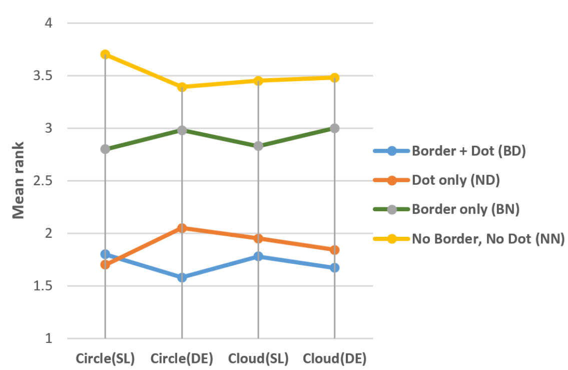
This section discusses the results of the analysis of shape preference and visualization option preference questions. These questions were aimed at evaluating user preferences to different shapes (circle, cloud and, CSS) and user preferences to the four visualization options (Border & Dot (BD), Dot only (ND), Border only (BN) and No border No dot (NN)).

4.3.1 *User Preferences Regarding Shapes: Circle, Cloud and CSS.*

Figure 9a depicts the user preference scores obtained for circle, cloud and CSS. It is evident that users in both groups preferred the circle followed by the cloud; CSS seemed to be the least preferred main visualization.



(a) User preferences to circle, cloud and CSS



(b) User preferences to the four visualizations: Border & Dot (BD), Dot only (ND), Border only (BN) and No border No dot (NN) - users prefer visualizations with a dot than visualizations with a border

Fig. 9. User preferences to different shapes and visualization options

4.3.2 *User Preferences Regarding Different Visualization Options (Border Dot (BD), Dot only (ND), Border only (BN) and No Border No Dot (NN)).*

This part presents the results from the analysis of visualization option preference questions that evaluated the user preferences to the four visualization options, Border & Dot (BD), Dot only (ND), Border only (BN) and No border No dot (NN).

Circle: Friedman's test revealed that there is a significant difference in preference between the four visualizations both in the SL group (($\chi = 31.92, p = 0.000 < \alpha = 0.05$)) and in the German group (($\chi = 40.245, p = 0.000 < \alpha = 0.05$)). Mean ranks for each visualization imply that the order of preference in SL group was Dot only>Border and Dot>Border only>No border No dot. There was no significant difference between dot only (ND) and border & dot(BD) according to the Wilcoxon Sign Rank text. In the German group, this order of preference was Border and Dot>Dot only>Border only>No border No dot.

Cloud: Friedman's test revealed that there is a significant difference in preference between the four visualizations, both in the SL group (($\chi = 22.258, p = 0.000 < \alpha = 0.05$)) and in the German group (($\chi = 45.123, p = 0.000 < \alpha = 0.05$)). Mean ranks for each visualization imply that the order of preference in both SL group and German group is Border and Dot>Dot only>Border only>No border No dot.

Figure 9b depicts the mean ranks for each visualization for circle and cloud, and for Germans and Sri Lankans. In summary, according to the analysis, users preferred visualizations with a dot or with a boundary (or both) over visualizations, which do not have a boundary or a middle dot (NN).

5 DISCUSSION

In this section, we discuss the essential findings, their possible implications and how they could be used to communicate location uncertainty on mobile devices effectively. We also briefly discuss what we did not evaluate as well as limitations of the study and future directions.

5.1 User Perceptions

The study revealed that there are consistencies and inconsistencies between cultures in the perception of where people are located when they see a visualization of location uncertainty. Both groups were consistent in perceiving a higher likelihood of being anywhere inside the shape and believing that this likelihood decreases from the center of the shape to the outside.

The circular uncertainty region in contemporary mobile devices assumes a normal distribution for the location error Android [4]. In a normal distribution, the probability decreases from the center to the outside. Therefore, according to the results of this experiment, what the visualizations of location uncertainty try to convey aligns with what people (regardless of the culture) perceived regarding the likelihood of being in different regions of these uncertainty visualizations. However, it is not always the case that the location error distribution follows a normal distribution. In principle, it could be any kind of distribution. For example, if it is a bi-modal distribution, we cannot assume a decreasing probability from the center towards the boundary, in which case what the user perceives does not correspond to the reality.

We found that shape has an impact on the people's perception of the likelihood of being in different regions of an uncertainty visualization. The perceived likelihood of being anywhere inside, center inside and immediately inside the border regions was consistent between the two cultures. Both cultures perceived a higher likelihood of being in these regions when visualized with a circle than when visualized with a cloud. However, the perception regarding the likelihood of being immediately outside the border was not consistent between the two cultures with respect to the shape. Germans perceived a higher likelihood of being immediately outside the border when visualized with a cloud than with a circle whereas Sri Lankans perceived a higher likelihood of being immediately outside the border when visualized with a circle compared to a cloud. This suggests that the interpretation of the cloud shape might be sensitive to cross cultural differences.

Visualization options also had an impact on people's perception of the likelihood of being in a particular region of an uncertainty visualization. The two cultures were generally consistent in the perceived likelihood of being in a given region with respect to the visualization option used. The perceived likelihood of being anywhere inside the shape was high for both cultures when visualized with border and dot (BD) or dot only (ND) options. Both cultures also see a higher likelihood of being in the center of the shape when visualized with border and dot (BD). Similarly, both cultures perceived a higher likelihood of being immediately inside the border when visualized using the border and dot (BD) compared to other options (border only: BN, dot only: ND and no border no dot: NN). Further, both cultures perceived a higher likelihood of being immediately outside the shape when visualized using the dot only (ND) option compared to other options (see figure 7a).

Our results also indicate that the perceived likelihood of being in a given region when visualized with a particular visualization option was not significantly different between the two shapes, circle and cloud (figure 7b). The perceived likelihood of being anywhere inside the shape was higher when visualized with border and dot (BD) or with dot only (ND) using a circle than when visualized with border and dot (BD) or with dot only (ND) using a cloud. The perceived likelihood of being in the center inside region was higher when visualized with border and dot (BD) using a circle than when visualized with border and dot (BD) using a cloud. The perceived likelihood of being just inside the border was higher when visualized with border and dot (BD) using a circle than when visualized with border and dot (BD) using a cloud. As the perceived likelihood of being just outside the border was inconsistent between the circle and cloud between the two cultures, we can only observe that in general, the perceived likelihood of being immediately outside the border seems to be high when visualized with dot only(ND) option.

Our results also identified the visual representations (shape, border, middle dot) as having an impact on the perceptions of users with respect to what they think where they are located. Therefore, the use of these visual properties such as shape, border and middle dot without properly understanding how people perceive them can result in misinterpretation (culture-specific or culture nonspecific). For example, using the border only (BN) visualization when uncertainty is low, and using border and dot (BD) when uncertainty is high could be misleading. On the other hand, this implies that we can modify people's perception by changing the visualization. The consistencies between cultures can be used to design better visualizations that align the level of uncertainty with the perceptions of users. Inconsistencies between cultures can be used to design culture-specific visualizations. For example, information about how people's perceived likelihood of being in a particular region changes between different visualization options can be used to select the appropriate visualization option for different levels of location uncertainty (use of dot only rather than border and dot when uncertainty is high). Information about the degree of differences in the perceived likelihood of being in a particular region between different visualizations can also be used to convey or encode other types of or additional uncertainty related information such as freshness of data, delay, confidence and source of location information (for example: GNSS only, GNSS combined with cell tower, Cell tower only, etc). For example, a system could change the shape from a circle to a cloud (keeping the same visualization option) when the updates are delayed beyond a threshold. Information about cultural differences in perceptions between cultures could be used to design/ propose visualizations appropriate for different cultures and encourages further research into cultural differences rather than setting global standards in location uncertainty visualizations. Our results also indicate that using shapes other than the conventional circle may be beneficial with respect to catering to cultural differences and to convey different aspects of location uncertainty.

The perceived accuracy concerning the size of the shape was inconsistent between the two cultures. The German group perceived a high location accuracy with the smaller shape compared to the large shape whereas the Sri Lankan group did not. This could be due to the experience of German users in using pedestrian navigation systems: in the contemporary circular visualization of location uncertainty, the size of the circle increases with the level of uncertainty and German users might have known this by experience. Consequently, it may make sense to adapt location uncertainty visualizations to different cultures as well as to the level of experience of users.

5.2 User Preferences

It is interesting to note that there were no cultural differences in preferences regarding different shapes and different visualizations. Both groups preferred the circle followed by the cloud. CSS was the least preferred. The order of preferred visualizations in both cultures was also the same (border and dot (BD)>dot only (ND) >border only (BN) >no border no dot (NN)). Both groups preferred border with a dot (BD) visualization the most (though in the SL group there was no difference between border with a dot (BD) and dot only (ND) visualizations.

5.3 Limitations

We ran the user study as a lab-based study. The reason for doing a lab-based study was to make the conditions constant for all participants. This was helpful to obtain information regarding only the visualization of location uncertainty displayed on the user's phone without the influence of other factors. Therefore, the results obtained in this study represent the users' pure perceptions and preferences regarding the visualizations, which is useful to understand what different visualizations and their variables convey. On the other hand, when users see these visualizations in real-world situations, their reasoning and judgments may be greatly influenced by the environment. For example, they might try to map what they see on the phone to the real environment around them to make decisions. Therefore, in such situations, their interpretations and perceptions could be influenced by the environment and other physical/mental factors. Hence, their interpretation and perceptions could be different in a real-world environment than what they are in a lab setting.

This study was focused solely on revealing users' perceptions and preferences regarding location uncertainty visualizations. We did not evaluate the impact of these visualizations on wayfinding performance, associated mental workload or other parameters used to evaluate different aspects of wayfinding efficiency. The visualizations that most correctly conveyed location uncertainty are not necessarily the ones that will lead to the highest navigation performance. Further research is required to investigate these aspects.

In perceived location questions, we used gradients for highlighting the regions inside a visualization for two reasons: (i) we wanted to show the border of the shape more clearly and show the boundary of the regions intuitively rather than to define them using sharp boundaries (ii) we wanted to keep the way we highlight regions consistent across the different visualizations. This can be better achieved by using gradients. However, the use of gradients also has the potential for misinterpretation of the perceived likelihood. Besides the fact that the participants were given a chance to practice the tests beforehand and ask questions before and during the tests from the experimenter, none of the participants asked a question regarding the highlighted regions.

Our study investigated only two cultures. The two cultures were selected based on their geographical and cultural background as well as on practicality (access to the users). Therefore, our results are not necessarily generalizable to all the cultures. It is also worthwhile to note the consistencies between the two cultures despite all cultural differences. The results of this study unearthed some interesting consistencies and inconsistencies between the two cultures under consideration. While the consistencies can help to generalize users' perceptions and preferences across cultures, inconsistencies do not necessarily mean things are different across cultures. Other factors such as the familiarity with smartphones, experience in using pedestrian navigation systems and personal factors might also have influenced these inconsistencies.

6 CONCLUSIONS

The work reported in this article investigated whether there are inconsistencies (or consistencies) between cultures with respect to perceptions and preferences regarding visualizations of location uncertainty. Our results imply that the visual representations have an impact on the perceptions of users and can thus be used to modify people's perception (by changing the visualization). Although the user preferences regarding different shapes and visualizations were very consistent across the two cultures, the perceptions varied between the two. There were consistencies as well as inconsistencies in how users perceived visualizations. For example, the perceived likelihood of being immediately outside a shape when visualized with a cloud was inconsistent between the two cultures. This deviates from the perceived likelihoods of being inside the visualization (anywhere inside the shape, center of the shape, immediately inside the border of the shape) between the circle visualization and cloud visualization, which were consistent between the two cultures. In addition, both cultures perceived that the likelihood of being in a particular region inside a visualization decreases from the center of the shape to the outside. We also identified the impact of different visualizations on the perception of users. Our results imply that the cloud could be a suitable option to visualize location uncertainty, especially to convey higher levels of uncertainty or to encode further details about the uncertainty (freshness, source).

Based on the consistencies and how different visualization impacted the perceptions of users, we derived guidelines on how to better visualize location uncertainty: (a) we recommend the use of the boundary and middle dot option (BD) when the location information is more accurate (i.e. when there is a strong tendency that the user is located either in the center or immediately inside the shape) and a middle dot only (ND) when the location error is high (i.e. when there is a tendency that the user could be located even outside of the shape); (b) we suggest to use a circle shape when the location uncertainty is very high (i.e. when there is a tendency that the user could also be outside of the shape) if the goal is to establish a global standard for visualizing uncertainty (since the likelihood of being outside of the shape is very inconsistent between the two cultures when the cloud shape was used); (c) the shape of the visualization could be varied (from circle to cloud) to encode other types of uncertainty-related information. For example, when the location error stays the same but the location information is outdated (exceeds a maximum temporal threshold), the shape of the visualization could be changed from a circle to a cloud visualization (for regions: center of the shape and immediately inside the border regions only).

Based on our work, we also identified a number of promising future research directions. Replicating our study with other cultures would help to deepen our understanding regarding what specific cultural factors affect uncertainty perception and visualization preferences. In addition, it makes sense to investigate further types of location uncertainty visualizations (e.g. new shapes, different representations such as dotted lines, color hue) to understand how they are perceived and what they can convey to users of mobile location-based services.

A SUPPLEMENTARY MATERIALS

Table 4. Interaction visualization option*culture

	DE vs. SL		
	Border & Dot (BD) vs Border only (BN)	**Border & Dot (BD) vs. Dot only (ND)**	**Border & Dot (BD) vs. No border No dot (NN)**
Anywhere inside	F(1, 50)=1.596, p=0.212, partial η^2 = 0.031	F(1, 50)=1.158, p=0.287, partial η^2 = 0.023	F(1, 50)=0.065, p=0.801, partial η^2 = 0.001
Center inside	(F1,50) = 0.521, p=0.474, partial η^2 = 0.010	(F1, 50)=2.28, p=0.137, partial η^2 = 0.044	(F1, 50)=0.709, p=0.404, partial η^2 = 0.014
Inside the border	F(1,50) = 0.434, p=0.513, partial η^2 = 0.009	F(1,50) = 0.007, p=0.936, partial η^2 = 0.000	F(1, 50)=0.051, p=0.822, partial η^2 = 0.001
Outside the border	F(1,50) = 0.059, p=0.810, partial η^2 = 0.001	F(1, 50)=1.602, p=0.211, partial η^2 = 0.031	F(1, 50)=1.149, p=0.289, partial η^2 = 0.022

Table 5. Interaction shape*visualization option

	Circle vs. Cloud		
	Border & Dot (BD) vs Border only (BN)	**Border & Dot (BD) vs. Dot only (ND)**	**Border & Dot (BD) vs. No border No dot (NN)**
Anywhere inside	F(1, 50)=2.022, p=0.161, partial $\eta^2 = 0.039$	F(1, 50)=1.273, p=0.265, partial $\eta^2 = 0.025$	F(1, 50)=2.110, p=0.153, partial $\eta^2 = 0.041$
Center inside	F(1, 50)=0.127, p=0.723, partial $\eta^2 = 0.003$	F(1, 50)=0.067, p=0.797, partial $\eta^2 = 0.001$	F(1, 50)=0.151, p=0.699, partial $\eta^2 = 0.003$
Inside the borde	F(1, 50)=0.021, p=0.886, partial $\eta^2 = 0.000$	F(1, 50)=0.019, p=0.890, partial $\eta^2 = 0.000$	F(1, 50)=1.134, p=0.292, partial $\eta^2 = 0.022$
Outside the border	F(1, 50)=.069, p=0.794, partial $\eta^2 = 0.001$	F(1, 50)=.309, p=0.581, partial $\eta^2 = 0.006$	F(1, 50)=1.278, p=0.264, partial $\eta^2 = 0.025$

REFERENCES

[1] 9To5Mac. 2015. Current location via Maps on Apple Watch. (2015). Retrieved November 12, 2017 from https://9to5mac.com/2015/08/20/how-to-use-maps-on-apple-watch/2015-06-13-21-45-40/

[2] European GNSS Agency. 2017. GNSS Market Report. pdf. (10 May 2017). Retrieved May 10, 2017 from https://www.gsa.europa.eu/system/files/reports/gnss_mr_2017.pdf

[3] Petr Aksenov, Kris Luyten, and Karin Coninx. 2012. O brother, where art thou located?: raising awareness of variability in location tracking for users of location-based pervasive applications. *Journal of Location Based Services* 6, 4 (2012), 211–233.

[4] Android. 2017. Location. (2017). Retrieved May 06, 2017 from https://developer.android.com/reference/android/location/Location.html#getAccuracy%28%29

[5] Stavros Antifakos, Adrian Schwaninger, and Bernt Schiele. 2004. Evaluating the effects of displaying uncertainty in context-aware applications. In *International Conference on Ubiquitous Computing*. Springer, 54–69.

[6] Martin Azizyan, Ionut Constandache, and Romit Roy Choudhury. 2009. SurroundSense: mobile phone localization via ambience fingerprinting. In *Proceedings of the 15th annual international conference on Mobile computing and networking*. ACM, 261–272.

[7] Steve Benford, Andy Crabtree, Martin Flintham, Adam Drozd, Rob Anastasi, Mark Paxton, Nick Tandavanitj, Matt Adams, and Ju Row-Farr. 2006. Can you see me now? *ACM Transactions on Computer-Human Interaction (TOCHI)* 13, 1 (2006), 100–133.

[8] Jacques Bertin. 1983. Semiology of graphics: diagrams, networks, maps. (1983).

[9] Henrik Blunck, Mikkel Baun Kjærgaard, and Thomas Skjødeberg Toftegaard. 2011. Sensing and classifying impairments of GPS reception on mobile devices. In *International Conference on Pervasive Computing*. Springer, 350–367.

[10] Ken Brodlie, Rodolfo Allendes Osorio, and Adriano Lopes. 2012. A review of uncertainty in data visualization. In *Expanding the frontiers of visual analytics and visualization*. Springer, 81–109.

[11] Stefano Burigat and Luca Chittaro. 2011. Pedestrian navigation with degraded GPS signal: investigating the effects of visualizing position uncertainty. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI 2011)*. ACM, 221–230.

[12] BP Buttenfield and R Weibel. 1988. Visualizing the quality of cartographic data. In *Third International Geographic Information Systems Symposium (GIS/LIS 88), San Antonio, Texas*.

[13] Keith Cheverst, Nigel Davies, Keith Mitchell, Adrian Friday, and Christos Efstratiou. 2000. Developing a context-aware electronic tourist guide: some issues and experiences. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 17–24.

[14] David Dearman, Alex Varshavsky, Eyal De Lara, and Khai Truong. 2007. An exploration of location error estimation. *UbiComp 2007: Ubiquitous Computing* (2007), 181–198.

[15] Charles R Ehlschlaeger, Ashton M Shortridge, and Michael F Goodchild. 1997. Visualizing spatial data uncertainty using animation. *Computers & Geosciences* 23, 4 (1997), 387–395.

[16] Nahum Gershon. 1998. Visualization of an imperfect world. *IEEE Computer Graphics and Applications* 18, 4 (1998), 43–45.

[17] Google. 2011. Google Maps for Mobile. http://www.google.com/mobile/maps (last accessed February 14, 2011. (2011). http://www.google.com/mobile/maps

[18] Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in psychology* 52 (1988), 139–183.

[19] Sven Heitmann. 2016. *Providing a way to evaluate location based systems under varying levels of location and orientation quality.* Master's thesis. Institute for Geoinformatics (ifgi).
[20] Tomislav Hengl. 2003. Visualisation of uncertainty using the HSI colour model: computations with colours. In *7th International Conference on GeoComputation.*
[21] HERE. 2017. Basic Positioning. (2017). Retrieved November 12, 2017 from https://developer.here.com/documentation/ios-starter/topics/map-positioning.html
[22] iMore. 2017. Maps App: The Ultimate Guide. (2017). Retrieved November 12, 2017 from https://www.imore.com/maps
[23] Yifei Jiang, Xin Pan, Kun Li, Qin Lv, Robert P Dick, Michael Hannigan, and Li Shang. 2012. Ariel: Automatic wi-fi based room fingerprinting for indoor localization. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing.* ACM, 441–450.
[24] Matt Jones, Simon Robinson, Jennifer Pearson, Manjiri Joshi, Dani Raju, Charity Chao Mbogo, Sharon Wangari, Anirudha Joshi, Edward Cutrell, and Richard Harper. 2017. Beyond "yesterday's tomorrow": future-focused mobile interaction design by and for emergent users. *Personal and Ubiquitous Computing* 21, 1 (2017), 157–171.
[25] Christoph Kinkeldey, Alan M MacEachren, and Jochen Schiewe. 2014. How to assess visual communication of uncertainty? A systematic review of geospatial uncertainty visualisation user studies. *The Cartographic Journal* 51, 4 (2014), 372–386.
[26] Mikkel Baun Kjærgaard and Kay Weckemann. 2010. Posq: Unsupervised fingerprinting and visualization of GPS positioning quality. In *International Conference on Mobile Computing, Applications, and Services.* Springer, 176–194.
[27] Christian Kray. 2003. *Situated interaction on spatial topics.* Ph.D. Dissertation. Universitätsbibliothek.
[28] Fan Li, Chunshui Zhao, Guanzhong Ding, Jian Gong, Chenxing Liu, and Feng Zhao. 2012. A reliable and accurate indoor localization method using phone inertial sensors. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing.* ACM, 421–430.
[29] Brian Y Lim and Anind K Dey. 2011. Investigating intelligibility for uncertain context-aware applications. In *Proceedings of the 13th international conference on Ubiquitous computing.* ACM, 415–424.
[30] Alan M MacEachren. 1992. Visualizing uncertain information. *Cartographic Perspectives* 13 (1992), 10–19.
[31] Alan M MacEachren. 1995. *How maps work: representation, visualization, and design.* Guilford Press.
[32] Alan M MacEachren, Anthony Robinson, Susan Hopper, Steven Gardner, Robert Murray, Mark Gahegan, and Elisabeth Hetzler. 2005. Visualizing geospatial information uncertainty: What we know and what we need to know. *Cartography and Geographic Information Science* 32, 3 (2005), 139–160.
[33] Alan M MacEachren, Robert E Roth, James O'Brien, Bonan Li, Derek Swingley, and Mark Gahegan. 2012. Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (2012), 2496–2505.
[34] Grant McKenzie, Mary Hegarty, Trevor Barrett, and Michael Goodchild. 2016. Assessing the effectiveness of different visualizations for judgments of positional uncertainty. *International Journal of Geographical Information Science* 30, 2 (2016), 221–239.
[35] Petteri Nurmi, Sourav Bhattacharya, and Joonas Kukkonen. 2010. A grid-based algorithm for on-device GSM positioning. In *Proceedings of the 12th ACM international conference on Ubiquitous computing.* ACM, 227–236.
[36] Veljo Otsason, Alex Varshavsky, Anthony LaMarca, and Eyal De Lara. 2005. Accurate GSM indoor localization. *UbiComp 2005: Ubiquitous Computing* (2005), 903–903.
[37] Alex T Pang, Craig M Wittenbrink, and Suresh K Lodha. 1997. Approaches to uncertainty visualization. *The Visual Computer* 13, 8 (1997), 370–390.
[38] Günther Pospischil, Martina Umlauft, and Elke Michlmayr. 2002. Designing LoL@, a mobile tourist guide for UMTS. In *Human computer interaction with mobile devices.* Springer, 140–154.
[39] Champika Manel Ranasinghe and Christian Kray. 2016. Visualizing Location Uncertainty on Mobile Devices: Assessing Users' Perception and Preferences. In *Geospatial Data in a Changing World.* Springer, 315–333.
[40] Jose Rojas. 2007. The cultural construction of ubiquitous computing. In *Culture and Collaborative Technologies Workshop (CHI 2007).*
[41] Robert E Roth. 2015. Visual variables. *The International Encyclopedia of Geography* (2015).
[42] Irina Shklovski, Silvia Lindtner, Janet Vertesi, and Paul Dourish. 2010. Transnational times: locality, globality and mobility in technology design and use. In *Proceedings of the 12th ACM international conference adjunct papers on Ubiquitous computing-Adjunct.* ACM, 515–518.
[43] Jo Vermeulen. 2010. Improving intelligibility and control in ubicomp. In *Proceedings of the 12th ACM international conference adjunct papers on Ubiquitous computing-Adjunct.* ACM, 485–488.
[44] Qiang Xu, Rong Zheng, and Steve Hranilovic. 2015. IDyLL: Indoor localization using inertial and light sensors on smartphones. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing.* ACM, 307–318.
[45] Jingxiong Zhang and Michael F Goodchild. 2002. *Uncertainty in geographical information.* CRC press.

Received August 2017; revised November 2017; accepted January 2018