Geographic Data Visualization on Mobile Devices for User's Navigation and Decision Support Activities

Stefano Burigat and Luca Chittaro

HCI Lab, Dept. of Math and Computer Science, University of Udine
Via delle Scienze 206, 33100, Udine, Italy
burigat@dimi.uniud.it, chittaro@dimi.uniud.it

1 Introduction

Users who operate in the field (e.g., maintenance personnel, geologists, archaeologists, tourists, first responders) bring often with them paper sheets (e.g., city maps, forms, technical plans, object descriptions) containing data needed for their activities. Even when this data is available in digital form, the mobile condition of these users makes them prefer more portable and manageable solutions (such as paper) to potentially more powerful and flexible ones (such as laptop computers). For example, it is easier to handle and look at a paper map rather than a digital laptop map while on the move. However, the increasing availability of small and powerful mobile devices (PDAs and Smartphones) is opening new opportunities. At first devoted to manage user's personal information, these devices can now be employed to assist users in carrying out different tasks in the field.

Unfortunately, the design of effective applications for mobile scenarios cannot rely on the traditional techniques devised for desktop applications due to a number of issues:

- Data presentation and exploration on mobile devices are heavily affected by the small size and resolution of displays. For example, displaying a map in its entirety to assist users in navigating a geographic area typically provides only an overview without sufficient detail, while zoomed-in views provide more detail, but lose the global context. Thus, users are forced to perform panning and zooming operations, a process which is cognitively complex, disorienting and tedious.
- The limited processing power of mobile devices restricts the amount of data that can be managed locally and prevents the use of computationally expensive algorithms. For example, 3D representations of geographic data (e.g., virtual reproductions of terrain) are still uncommon on mobile devices, while they are widely used in some desktop scenarios.

- Input peripherals of mobile devices heavily constrain the set of possible interface designs. For example, keyboards (either physical or virtual) are limited in size and/or number of keys, making it difficult to manually insert data.
- User's mobility affects the design of applications: factors such as user's speed, different and changing activities, distractions, device autonomy and environmental conditions (e.g., weather, lighting, traffic) must be taken into consideration. Moreover, users are typically involved in other tasks in the field and cannot focus their attention primarily on the mobile device.
- Mobile phones are used by a larger population with respect to traditional computers. Therefore, usability, which has already proven to be an important factor for the acceptance of desktop applications by final users, becomes even more important in mobile applications.

However, the power of mobile graphics hardware is increasing and this makes it possible to provide users on the move with more sophisticated and flexible visualizations [11]. In the following sections, we will survey research that investigated the visualization of geographic data on mobile devices. Indeed, a wide range of user's activities in the field depends on obtaining and exploiting data on the geographic area where users are located. We will first deal with research on map visualization since maps are the most common and used means to provide users with geographic information on an area, thus representing a key building block for applications that aim at supporting users in the field. Then, we will focus on more specific topics, concerning navigation of a geographic area and the support of user's decisions in the field.

2 Map Visualization on Mobile Devices

In the latest years, research on geographic data visualization on mobile devices has mainly focused on how to best represent and interact with maps on small displays. Indeed, maps are the most efficient and effective means to communicate spatial information [23]. They simplify the localization of geographic objects, revealing spatial relations and patterns, and provide useful orientation information in the field.

As highlighted in Sect. 1, using maps on small displays differs from using paper maps in a mobile setting or viewing maps on a desktop computer. This motivated researchers to propose various solutions for the *adaptation* of map contents for mobile scenarios. In particular, since a map is always strongly related to the context of its use, various contextual elements (e.g, user, location, task, device) have been considered to perform the adaptation so that the user could get what is most suitable for her needs.

For example, Fig. 1 shows a detailed map of an area of the city of Munich (on the left) and the same map adapted for a specific mobile scenario (on the right). The adapted map provides the user with information on the route to follow to reach her hotel from her current position near a pub, passing nearby a shopping area she is interested in (identified with the shopping cart icon). Only relevant information along the route, such as street names and points of interest (POIs), is highlighted and the map has been rotated to be oriented in the main direction of the route.

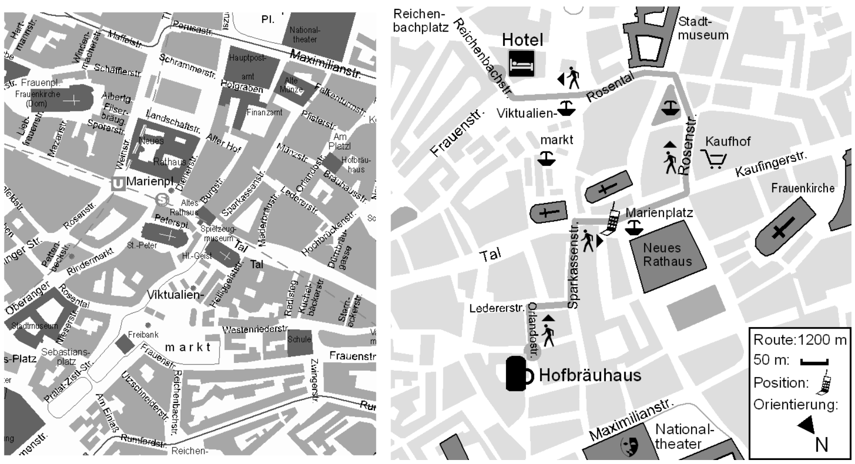

Fig. 1. Comparison between an original map (on the left) and the same map adapted for a specific mobile scenario [30]. Image courtesy Tumasch Reichenbacher, Technical University Munich, DE. Base data copyright: Städtisches Vermessungsamt München.

Reichenbacher [31] claims that the most important task in adapting maps is highlighting relevant map features. He proposes various graphical means to put visual emphasis or focus on a feature:

- Highlighting the feature using colors;
- Emphasizing the outline of the feature;
- Enhancing the contrast between the feature and the background;
- Increasing the opacity of the feature while decreasing the opacity of other map content;
- Focusing the feature while blurring other map content;
- Enhancing the level of detail of the feature with respect to other features;
- Animating the feature by means of blinking, shaking, rotating, increasing/decreasing size.

Nivala and Sarjakoski [27] employ some of these principles to adapt the symbols to use in a map according to the current usage situation and user preferences, so that more fluent map reading and interpretation processes could be obtained. Figure 2 illustrates an example of map symbol adaptation according to season and user's age. Map (a) on the top left is a summer map for the age group 46 and above, map (b) on the top right is a winter map for

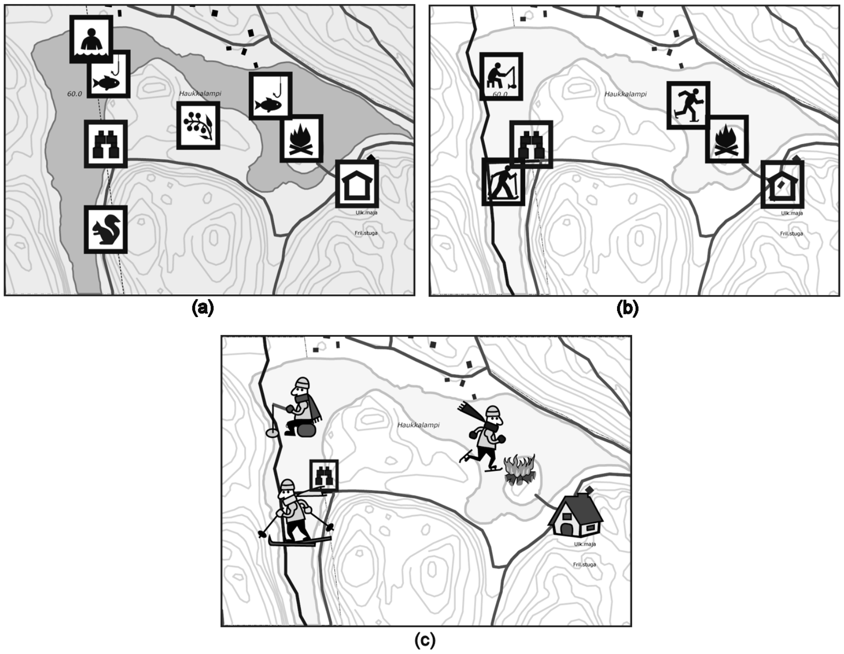

Fig. 2. Maps of the same area for different seasons and age groups [27]. Image courtesy Nivala, A.M. and Sarjakoski, L., Finnish Geodetic Institute, FI.

the age group 18-45 and map (c) on the bottom is a winter map for young people under 17 years old. The most obvious difference among the maps are the different symbols. The two maps on the top differ in information content: during the winter and summer different kinds of POIs are relevant for the user (for instance, swimming places in summer time and skiing tracks in winter time). There is another difference between the first two maps: pictograms with a white background are provided in map (a) to improve the contrast of the symbol for elderly people, while map (b) uses transparent symbols to prevent as much of the information as possible from being hidden, which is critical with small screens. Map (b) and map (c) also use different symbols for the same POIs for adults and for teenagers. Indeed, traditional map symbols may not be familiar to young people and more illustrative symbols were designed to more accurately reflect how they perceive the world.

Some authors propose general approaches for the adaptation of maps to mobile devices. For example, Chalmers et al. [10] studied how to enable map-based applications to adapt to variations in display specifications, network quality, and user's current task. Their approach is based on explicitly considering variants of the features represented on maps (for example, variants of a road may represent the road at different levels of detail) and on modeling user's preferences for each feature. Users specify their preference for features of a particular type by associating a weight to the type, for instance, to describe a preference for displaying roads rather than rivers. When performing the adaptation, the system determines the content to display according both to user's preferences and overall goals that must be met (for example, downloading all needed content within a predefined time). This approach was found to be useful in deriving adapted maps with reduced content for transmission with different bandwidths and with different map download time requirements, degrading the data presented while providing users with as much relevant detail as possible.

Zipf [38] provides a comprehensive overview of the design steps involved in adaptive map generation, considering a wide range of variables such as user preferences and interests, tasks, cultural aspects, communicative goals and current context and location. For example, the orientation of a map can be adapted so that the map is aligned in the direction the user is walking, thus simplifying navigation of an environment, while the meaning of colors can be taken into specific account when generating maps for different cultures.

One of the design steps identified by Zipf and investigated by different authors is shape simplification through *generalization*. Generalization is a graphic and content-based simplification of the data presented on a map that aims at abstracting irrelevant details to reduce the cognitive effort of the user, and at simplifying the process of creating a lower scale map from a detailed one. As reported in Chapters **??** and **??**, generalization techniques can also be used to support progressive transmission of vector data through wired or wireless networks, albeit studies in this direction for mobile scenarios are still at an early stage.

Agrawala and Stolte [1] developed some techniques for the generalization of cartographic data that improve the usability of maps for road navigation on mobile devices. Standard computer-generated maps are difficult to use because their large, constant scale factor hides short roads and because they are usually cluttered with extraneous details such as city names, parks, and roads that are far away from the route. The techniques proposed by Agrawala and Stolte are based on cognitive psychology research showing that an effective route map must clearly communicate all the turning points on the route and that precisely depicting the exact length, angle, and shape of each road is less important. By distorting road lengths and angles and simplifying road shape, it is possible to clearly and concisely present all the turning points along the route in less screen space. The generalized maps that are obtained exaggerate the length of short roads to ensure their visibility while maintaining a simple, clean design that emphasizes the most essential information for following the route. These generalized maps can fit to the display size of a PDA by rotating the entire route so that the largest extent of the map is aligned with the vertical axis of the page, thus providing extra space in the direction the route needs it most.

Generalizing map features is a useful approach to simplify the display of maps on the small screen of mobile devices but maps can be still too large to

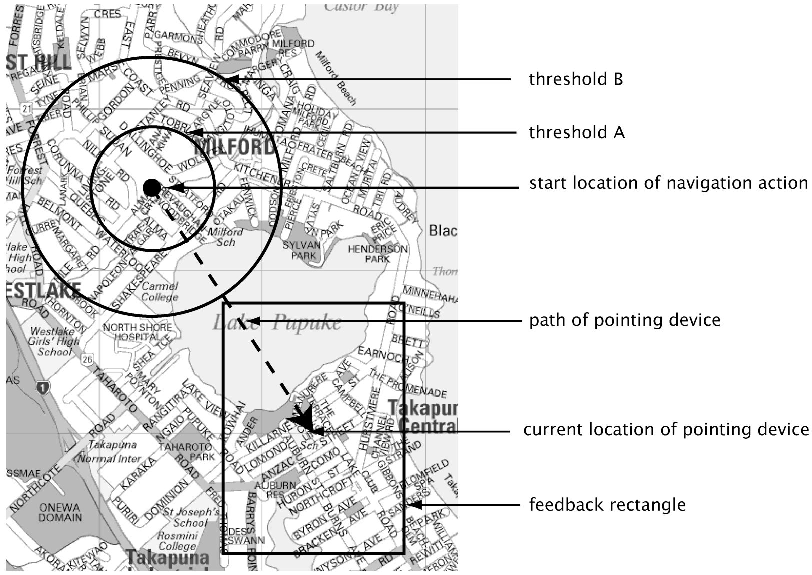

Fig. 3. Illustration of the system proposed by Jones et al. [19] to combine panning and zooming into a single operation, including control feedback cues (which are emphasized for clarity). Image courtesy Steve Jones, University of Waikato, NZ.

fit into the available screen space. Several techniques have thus been proposed in the literature to visualize large maps on mobile devices.

A basic approach is to display only a portion of the map and to let users control the portion shown by conceptually moving either a "viewport" on top of the map, or the map under the viewport. Scrollbars are typically used to support this interaction, providing separate vertical and horizontal viewport control. Another mechanism is *panning*, which allows users to drag the map in any direction without any constraint to the movement. It is also common to provide users with a *zooming* function that allows to increase or decrease the size of the visible portion of map [16]. Alternative interaction techniques have been developed to simplify these operations on mobile devices. Jones et al. [19], for example, present a technique that combines zooming and scrolling into a single operation, dependent on how much users drag the pointing device on the screen with respect to the starting position. Figure 3 illustrates the technique. When users start an action by tapping on the map with a pen, two concentric circles are drawn and their center is the location of the action. As the user drags the pointing device, a direction line is drawn between the starting position and its current location, indicating the direction of travel. If the pointer remains within the inner circle, the user is free to scroll within the map in any direction. As the pointer moves further away from the starting position, the scroll rate increases. When the pointer moves beyond the inner circle (threshold A in Fig. 3), both zooming and scrolling operations take place. As the user moves closer to the outer circle (threshold B in Fig. 3), the map progressively zooms out and the scroll speed is modified to maintain a consistent visual flow. When the pointer reaches the outer circle no further zooming occurs, while scrolling remains active. The rectangle indicates to the user the area of the map that will be displayed once the navigation operation is completed. Its size changes proportionally to the current zoom value. An experimental evaluation showed that the proposed technique reduces the physical navigational workload of users with respect to a standard technique based on the use of scrollbars, panning and zoom buttons.

Other techniques to display maps on small screens are based on combining panning and zooming with compression or distortion and can be classified into *Overview&Detail* and *Focus&Context* techniques.

Overview&Detail techniques provide one or multiple overviews (usually at a reduced scale) of the whole map, simultaneously with a detailed view of a specific portion of map. The Large Focus-Display [21] is an example of such a technique, where the overview is a downscaled version of a map that highlights the currently displayed region as a rectangular viewfinder (Fig. 4). Users can drag and resize the viewfinder to perform panning and zooming operations. By examining the size and position of the viewfinder, users are also able to derive useful information for the browsing process, such as the scale ratio between the displayed portion and the whole map. Despite these advantages, the overview covers parts of the detailed view and its content is hard to understand because of the scale that needs to be used for it on a small screen.

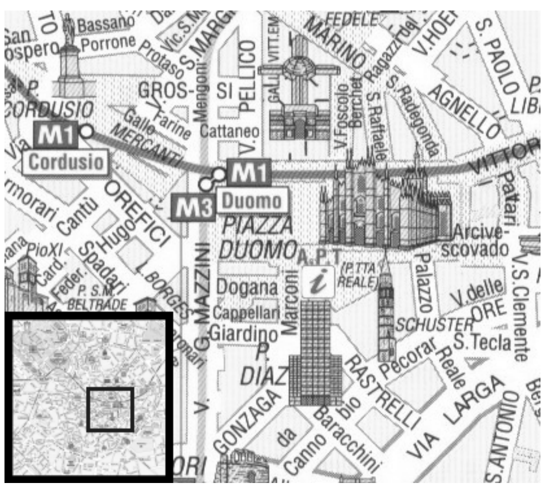

Fig. 4. Large Focus-Display: a detailed view of a map area is complemented by an overview of the whole map (displayed in the corner) that highlights the currently displayed portion as an interactive rectangular viewfinder.

Fig. 5. Variable-scale maps: a circular area (in the center) is shown in full detail while the remaining area is generalized and distorted to fit the available space [17]. Image courtesy Lars Harrie, Lund University, SWE.

As a possible alternative, Rosenbaum and Schuman [32] allow users to interact with a grid overlaid on the currently displayed map area to perform panning and zooming operations. The grid is proportional to the whole map and each grid cell can be tapped to display the corresponding portion of map. Cells can also be merged or splitted to provide users with different zoom levels.

Unlike Overview&Detail techniques, Focus&Context techniques are able to display a map at different levels of detail simultaneously without separating the different views. To achieve this result, only a specific area of a map, called focus area, is represented in full detail, embedded in surrounding context areas distorted to fit the available screen space. These techniques are generally based on the assumption that the interest of the user for a specific map region decreases with the distance from this region. A typical example of Focus&Context technique is given by by the Rectangular FishEye-View [29], where a rectangular focus is surrounded by one or more context belts, appropriately scaled to save screen space. The scaling factor for each context belt is usually chosen in such a way that less detail is displayed with increasing distance from the focus.

Variable-scale maps [17] apply the same principle used in the Rectangular FishEye-View but show in full detail a circular area surrounding a specific point (not necessarily the center of the map) while using a small scale and applying generalization and distortion operations to fit the remaining map area in the available space (Fig. 5).

Unlike variable-scale maps, focus maps [39] are not based on distortion but on subdividing a map into different regions of interest and displaying each region with a different amount of detail according to its degree of interest. This is achieved by using generalization and color. Map features lying inside regions with high degree of interest are less generalized than those inside regions with low degree of interest. Moreover, bright and shiny colors are used for the former regions, while softer and duller shades of the same colors are used for the latter. As an application example, regions of interest may comprise the region a user is currently in and, if the current task involves movement, the regions she is about to encounter. In this way, user's attention is directly drawn towards those regions that are currently most relevant, but the other regions can still be used, for example, to help the user locate and orient herself.

Despite their capability to improve map visualization on small screens, Focus&Context techniques are unsuitable for users who need to use large undistorted maps to perform spatial tasks involving distance measurements, such as first responders who need to identify locations of potential hazards in a building or view the real-time location of other team members. To better support these users, one can provide them with information to locate relevant objects even when they are off-screen. This is the approach followed by Baudisch and Rosenholtz [4], who propose Halo, a technique to visualize off-screen objects locations by surrounding them with circles that are just large enough to reach into the border region of the display window. From the portion of the circle visualized on-screen, users can derive the off-screen location of the object located in the circle center. A user study has shown that Halo enables users to complete map-based route planning tasks faster than a technique based on displaying arrows coupled with labels for distance indication. In a subsequent work [9], we compared Halo with two other techniques based on exploiting size and body length of arrows, respectively, to inform about the distance of objects. In our study, arrows allowed users to order off-screen objects faster and more accurately according to their distance, while Halo allowed users to better identify the correct location of off-screen objects.

3 Supporting User's Navigation in the Field

Navigation can be generally defined as the process whereby people determine where they are, where everything else is, and how to get to particular objects or places [20]. Helping users navigate the geographic area they are in is a typical goal of systems supporting activities in the field. For example, it is a key service of *mobile guides* [5], applications that exploit information such as user position, place, current time and task, to provide users with information and services related to a specific geographic area. A number of the proposed techniques is based on the visualization of 2D maps representing the considered geographic area but alternative solutions have also been investigated, especially to provide users with directions to reach specific objects or places.

3.1 2D Map-based Techniques

2D maps provide information about the geographic area users are in. By exploiting positioning technologies such as GPS (Global Positioning System), they can highlight the user's current position by means of a graphical symbol. Furthermore, the positions of objects and other people can be presented. Additionally, maps can show routes and *landmarks* (i.e., distinctive features of an environment, such as churches and squares, that can be used as reference points during navigation) for reaching specific objects or places in a geographic area.

Most of the research results presented in Sect. 2 are also significant in the design of maps for navigation. For example, by investigating the effect of map generalization on user's performance in route-following tasks in a geographic area, Dillemuth [13] found that a generalized map was more effective than an aerial photograph (Fig. 6). Indeed, users took less time to complete tasks and performed less zooming operations in the former rather than the latter condition. However, Dillemuth also points out that missing or erroneous information in a map cause confusion and errors in navigating an area, thus suggesting that an accurate aerial map with a lot of detail would be preferable to a generalized but outdated map.

Baus et al. [6] studied how to perform map adaptation for pedestrian navigation according to user's walking speed and accuracy of positional information. Figure 7(A) presents an example map for a slowly moving user and unprecise positional information, whereas Fig. 7(D) shows a map for exact positional information at higher speed. The precision of positional information is encoded in the size of the dot, which represents user's current position on the map. A decreasing positional information results in a bigger dot. In

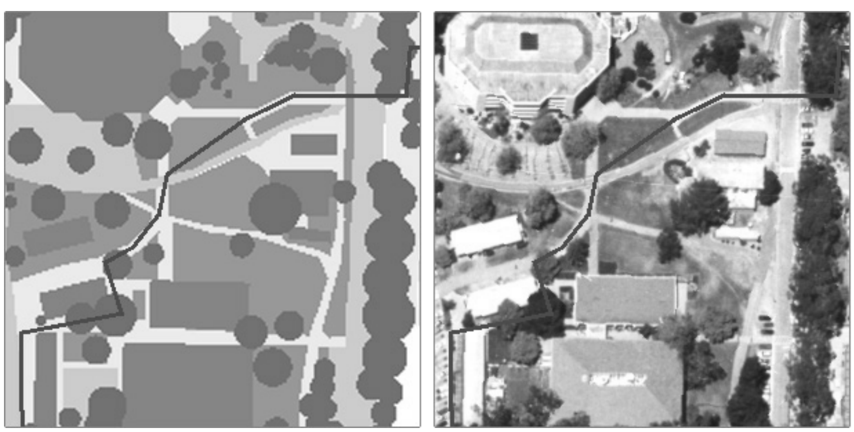

Fig. 6. Examples of generalized map (on the left) and aerial photograph (on the right) used in the route-following study by Dillemuth [13]. Image courtesy Julie Dillemuth, University of California, Santa Barbara, USA.

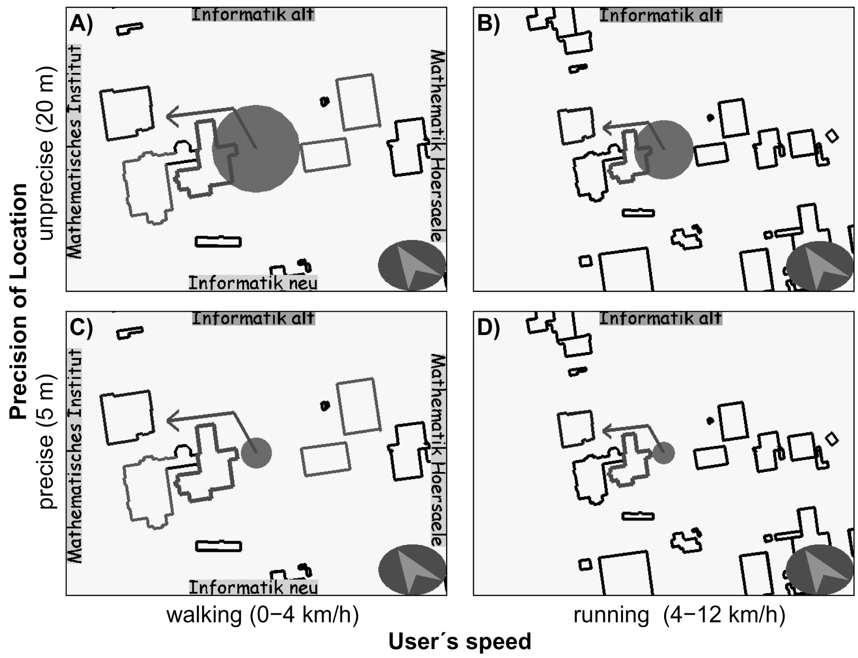

Fig. 7. Map adaptation according to user's moving speed and precision of location information [6]. Image courtesy Jörg Baus, Saarland University, DE and Antonio Krüger, University of Muenster, DE.

addition, if the user moves fast, a greater portion of the map is presented to help the user orient herself and the amount of information about buildings is reduced.

In general, using a map for orientation implies a mental effort to switch between the egocentric perspective of the viewer and the geocentric perspective of the map. The effort is smaller if the map is *forward-up* (the top of the map shows the environment in front of the viewer) rather than *north-up* (the top of the map always shows the northern part of the environment). Indeed, as shown by various studies (e.g., [18, 34]), the number of navigational errors is lower with a forward-up map compared to a north-up map. Moreover, forward-up maps allow the user to better understand her orientation and to reach targets faster [33]. A further investigation on the orientation of mobile maps has been carried out by Winter and Tomko [37] who argue that it is more intuitive for the user to find her actual position at the bottom of the map rather than at its center, where her position is typically shown. Indeed, by looking down at the device in her hand, the user perceives the bottom of the map as the closest part to her body, and the map as showing all features in the space ahead of her. This suggests a map design that moves the user's position to the bottom of the mobile map to reduce the cognitive workload of map reading.

3.2 Perspective Views and 3D Map-based Techniques

In recent years, some attempts have been made at exploring the use of perspective maps and 3D graphics to communicate geographic information on mobile devices for navigation purposes. Perspective views (Fig. 8) are based on showing maps with an inclination that should make it easier for users to match what they see in the display with their view in the real world.

Fig. 8. Perspective views: maps are inclined to make it easier for users to match what they see in the display with their view in the real world. Source: iGO Website.

Exploiting 3D graphics can add further possibilities of visual encoding, can significantly increase the quantity of data displayed on the same screen, and can take advantage of users' natural spatial abilities. However, 3D approaches often suffer from problems such as graphic occlusion and difficulties in comparing heights and sizes of graphical objects. Moreover, designing interfaces for visualizing and manipulating 3D data on mobile devices is much more complex than in desktop applications because of the limitations highlighted in Sect. 1.

One of the first investigations on using 3D graphics on mobile devices to support user's navigation has been carried out by Rakkolainen et al. [28] who proposed a system combining a 2D map of a urban environment with a 3D representation of what users see in the physical world (Fig. 9). By evaluating the system in the field with a mockup implementation on a laptop computer rather than a PDA, they found that 3D models help users to recognize landmarks and find routes in cities more easily than using a 2D map only.

Fig. 9. Combining a 2D map of a urban environment with a 3D representation of what users see in the physical world to support navigation [28]. Image courtesy Ismo Rakkolainen, Tampere University of Technology, FI.

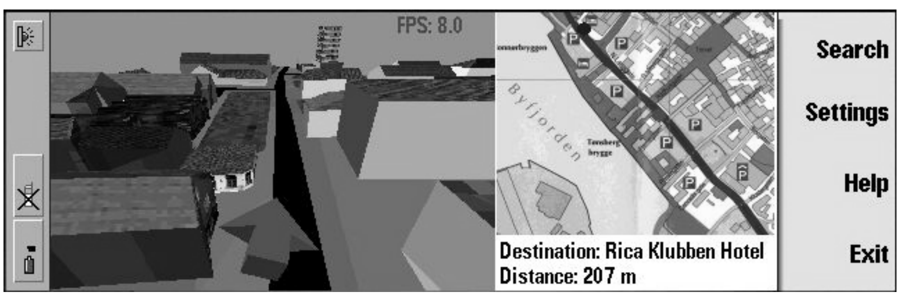

Fig. 10. The TellMarisGuide system combining 2D and 3D maps [25]. Image courtesy Katri Laakso, Nokia, FI.

However, user evaluation of mobile 3D maps is still in its infancy and the first results are not fully consistent. For example, Laakso et al. [25] reached different conclusions with respect to Rakkolainen et al. and found that 3D maps were slower to use both in initial orientation and route finding compared to 2D maps. Their evaluation concerned a system, called TellMarisGuide, that supports tourists when they are visiting harbors by visualizing 3D maps of the environment along with more classical 2D maps (Fig. 10). 3D maps are used to support navigation in a city and route finding to POIs such as city attractions or restaurants.

Fig. 11. In the LAMP3D system, the user selects objects with a stylus to obtain information on them [7].

Besides providing navigation support, 3D can also simplify the access to information related to a geographic area. For example, our LAMP3D system [7] is meant to support the location-aware presentation of 3D content on mobile devices. LAMP3D provides users with a 3D representation of a geographic area, synchronized with the physical world through the use of GPS data, and allows them to request information on the objects they see in the world by directly tapping on their virtual reproduction on the screen (see Fig. 11). Using this approach, content is filtered according to user's position and the information about the closest POIs is easier to get.

3.3 Alternative Approaches: Text, Audio, and Route Sketches

Besides 2D and 3D maps, other approaches can be used to provide users with information to navigate a geographic area. These approaches are mostly used to support route-following tasks, that is to provide users with instructions to correctly move along a route to reach some place or object. A very simple approach consists in providing users with textual instructions, which are usually easily understood by users and need few technical resources. However, long descriptions are often needed to give directions (because the context must be explicitly described) and this may quickly increase the cognitive load on the user, reducing the usefulness of the approach.

Another approach consists in providing audio directions. An important advantage of audio is that it does not require users to look at the screen of the mobile device to obtain navigation information, thus simplifying interaction. Unfortunately, audio instructions suffer from the same limitations of textual instructions when complex descriptions must be provided. In an experimental study, Goodman et al. [15] found that text, speech and text+speech are equally effective in presenting landmark information to people for navigation purposes. Audio can also be used to enable blind users to build a mental model of a geographic area. This can be obtained, for example, by representing important map features, such as POIs, with distinct and unique sounds, called *hearcons* [22]. With hearcons, a representation of the real world with various POIs is given by a virtual auditory environment around the user. The distance between the user's position and each POI is mapped directly onto the loudness of the hearcons. Moreover, by using different sound families for different types of information, the sources can be distinguished through the sense of hearing.

Finally, an additional approach to support navigation consists in the use of *route sketches*, i.e. graphical abstractions of a route that provide users with essential information about it. Arrows are a frequently used abstraction: they are familiar to users of car navigation systems and can be ideal for users with limited orientation and map-reading abilities. As reported in [24], the main advantage of route sketches is also their limitation since the high level of abstraction may also take away information that would help a user to find her way. Moreover, this approach is highly dependent on the accuracy of information on user's orientation. If this information is inaccurate, users may be provided with wrong directions, thus compromising their navigation effort.

3.4 Combining Audio and Visual Directions

In [12] we carried out a user study to compare different ways of improving users' navigation abilities by combining visual and audio directions on location-aware mobile guides.

We implemented three interfaces that provide the same audio directions but differ in the way they provide visual directions: the first interface adopts a traditional map-based solution, the second combines map indications with pictures of the environment, the third combines arrows indications and pictures.

As shown in Fig. 12(a), the first interface (Map Interface) visualizes the path the user has to follow as a (blue) line and the path the user has already completed as a (gray) bold line. With this interface, the user has to determine the direction by interpreting the map with respect to the physical environment. However, due to the rich information it usually provides, the map can be used even when GPS provides inaccurate data. The map is forward-up and includes street names, POIs (represented by red flags) along the path and its starting and ending points (represented by green flags). The user can pan and

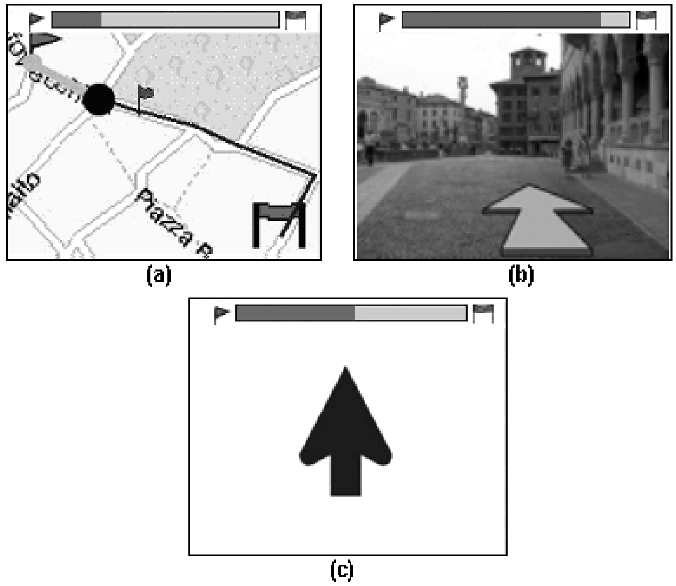

Fig. 12. The interfaces compared in the study by Burigat and Chittaro [12] to provide visual directions to users: map (a), pictures (b), arrows (c).

zoom the map to look at specific areas and a special button allows her to center the visualization on her current position.

The second interface (Map + Pictures) combines the Map interface shown in Fig. 12(a) with the visualization of pictures as shown in Fig. 12(b). The map is visualized while users are walking while the pictures appear when users are in proximity of relevant choice points such as crossroads. They provide specific views of the traveled geographic area and contain yellow 2.5D arrows that are meant to simplify the user's understanding of the direction to follow.

In the third interface (Arrows + Pictures), the map has been replaced by large black arrows (see Fig. 12(c)) that indicate the direction to follow. The behavior is similar to the Map + Pictures interface. To determine which direction the user is facing while moving we exploit the succession of position points provided by the GPS and present the appropriate arrows according to the path the user should follow.

The results of the evaluation (described in detail in [12]) show that combining a map with pictures that indicate the direction to follow or removing the map completely and replacing it with a combination of directional arrows and pictures, significantly improve user's navigation times with respect to the traditional map condition. This is likely due to the fact that it is more difficult to understand the correct direction to follow with a map (even if the map is forward-up) than with more explicit picture-based indications. Using pictures provides quite good navigational support because it simplifies the visual recognition of landmarks and has the additional advantage of depending only weakly on the actual direction of the user, thus being useful even when position and orientation information is inaccurate. This result is also confirmed by users' comments about the feeling of disorientation due sometimes to the use of the map. Moreover, while both approaches exploiting pictures allowed users to obtain a similar performance, the solution combining pictures and map was highly preferred because it provided an higher amount of information compared to the solution exploiting pictures and arrows.

4 Supporting User's Decisions in the Field through Geographic Data Visualization and Visual Queries

Navigation is only one, albeit important, of user's tasks in the field that can take advantage from the visualization of geographic data on mobile devices. In particular, up-to-date geographic data can be used by different categories of users to properly support their decisions. For example, firefighters and first-responders can use accurate geographic information while managing the impact of disasters to take decisions to evacuate residents, change management tactics, inform other crews by updating the set of available data on the disaster. Ecologists can employ geographic data to determine the best location to perform observations of animal or plant species and collect data about individuals. Utilities maintenance personnel may accurately locate equipment in the field and update information about its status.

All these activities require users to gain access to geographic data visualizations in the field as well as to manipulate them by modifying features, collect new data, take geo-referenced measurements. Specific mobile GIS (Geographic Information System) applications are usually devoted to this purpose.

With respect to geographic data visualization, mobile GIS applications are able to display both raster and vector data and manage different geographic features associated to a geographic area (e.g., roads, buildings, boundaries, trees) as separate layers so that users can display only the data they are interested in. Figure 13 shows the mobile version of a well-known GIS system (ESRI's ArcPad [14]). Users can navigate maps with standard tools such as pan and zoom, and can display map features and their associated attributes, including photographs, documents, video or sound recordings. Interactive functions allow users to measure distance, radius, and area on-screen and create, delete, and move point, line, and polygon features.

Mobile GIS applications are usually tailored to specific needs by creating custom forms for data entry and by integrating tools to solve specific field-based problems. In [36], for example, a mobile GIS is used to update maps of archaeological areas with the indication of interesting locations and to rapidly collect data about them and the artifacts found therein.

Geographic data can be characterized by an extraordinarily rich number of different attributes, and users operating in the field often need to explore such

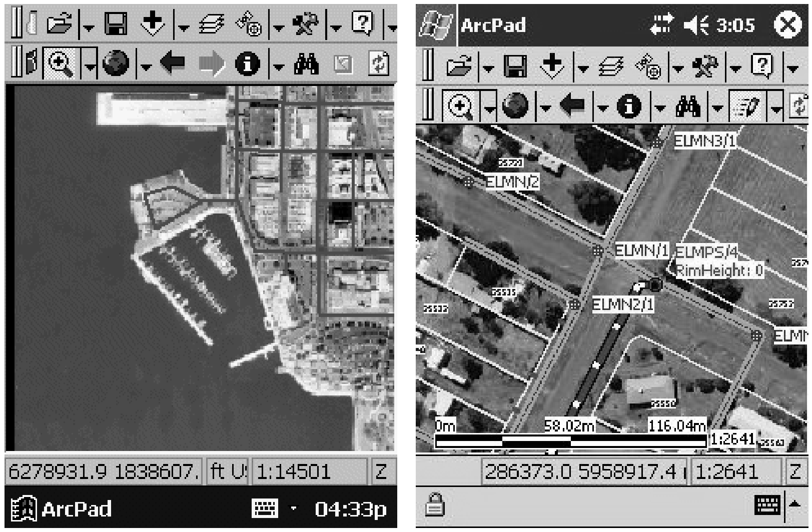

Fig. 13. ArcPad screenshots [14].

an information space to support their decisions. While mobile GIS is capable to collect, manipulate and display geographic data in the field, specific visual interfaces are still needed to provide users with complementary exploration and analysis tools. In particular, while mobile GIS allows users to display on a map only the data they are interested in by activating or deactivating specific layers, solutions that provide users with the capability to visually explore this data, for example by querying its attributes, are still uncommon.

An approach to support mobile users in visually accessing and querying GIS databases is presented by Lodha et al. [26]. They offer users a variety of queries (e.g., how far, where, closest) for many different types of geometric primitives (e.g., points, lines, polygons) and objects (e.g., buildings, metro stops). Users perform queries by directly interacting with the displayed geographic data. For example, a user can select a building on an aerial map, query for buildings in that area, and receive information such as the building's name in a schematic view. The user can paint points, lines, and arbitrary polygons on the display, and use these primitives as input to queries. For example, the user can draw two polygonal regions to find buildings contained within their intersection. User's location obtained from GPS can also be used as input to queries, for example to locate the nearest metro stop and telephone at the end of a path, highlighting buildings close to the user's path.

In [8], we have presented an application, called MAGDA (*M*obile *A*nalysis of *G*eographic *Da*ta), aimed at supporting users in the analysis of georeferenced data on PDAs. The approach we followed is based on exploiting *dynamic queries* [3, 35], which are typically used in desktop scenarios to explore large datasets, providing users with a fast and easy-to-use method to specify queries and visually analyze their results. The basic idea of dynamic queries is to combine input widgets (called "query devices" [2]), such as sliders or check buttons, with graphical representations of results, such as maps. By directly manipulating query devices, users can specify the desired values for the attributes of elements in a dataset and can easily get different subsets of the data. Visual results have to be rapidly updated to enable users to learn interesting properties of the dataset as they play with the query devices.

MAGDA allows users to select different categories of geographic objects (as with mobile GIS layers) and displays these objects as icons superimposed on the map of the considered geographic area (see Fig. 14), in their geo-referenced position.

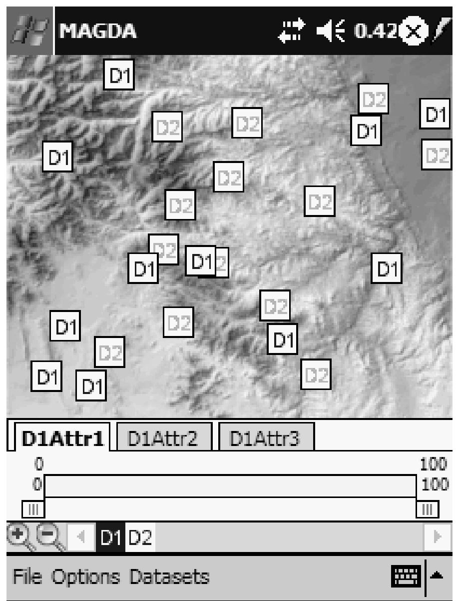

Fig. 14. The map displays all elements of the selected categories. A tabbed panel contains all query devices related to the currently explored category, which is highlighted in the toolbar at the bottom of the screen [8].

To define queries, users interact with query devices contained in a tabbed interface, where each tab allows users to specify values for a single attribute of the considered elements. Figure 14 shows an example where elements of categories called "D1" and "D2" are shown on the map, and it is possible to specify values for the attributes "D1Attr1", "D1Attr2" and "D1Attr3" of category "D1" by accessing the appropriate tabs. Elements belonging to the currently explored category are highlighted (by shading all other elements) to improve their visibility and reduce visual clutter.

As is typical of dynamic query systems, MAGDA can display all and only the elements that satisfy the current query (we call this *on-off visualization*). Thus, while users are manipulating query devices to specify attribute values, icons representing elements that satisfy (or not) the query are switched on (or off), providing a perceptual visual cue to make it easy for users to understand the effects of changes in the query (see Fig. 15).

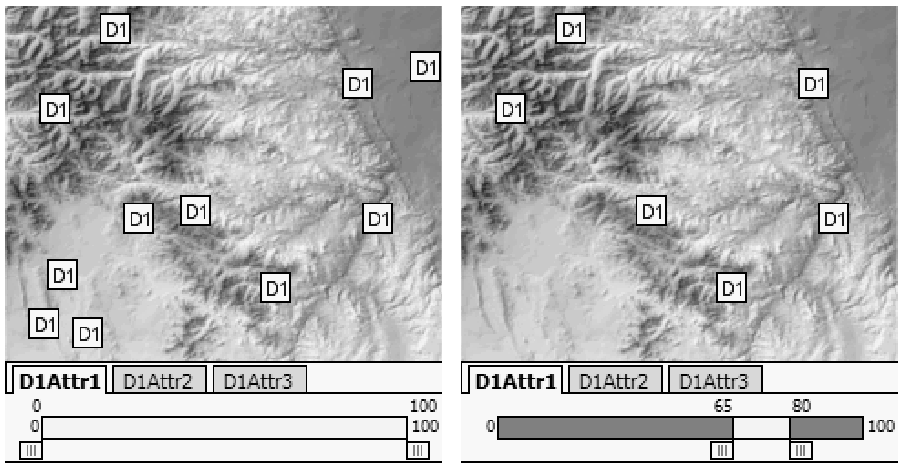

Fig. 15. On-off visualization of query results. On the left: no condition has been specified for attributes and all elements are visualized. On the right, a specific range of values has been specified for one attribute and only elements satisfying this condition are visualized [8].

However, the on-off visualization does not allow one to quickly determine how elements are distributed in an area according to how much they satisfy a query. This prevents users, for example, from easily identifying suboptimal results (which may be particularly important when a query produces no results) or finding out interesting patterns, trends or anomalies in the data that may prompt further investigations in the field (such as elements fully satisfying a query surrounded by elements that do not satisfy it at all).

A possible solution to this problem consists in exploiting graphical properties of icons to highlight the state of objects. Reichenbacher [31], for example, suggests to vary the opacity of icons to show qualitative or quantitative differences between objects. This method catches user's attention and directs it to the important and more relevant information without completely neglecting other information that could become important.

The solution we adopted in MAGDA, called *bar visualization*, augments all icons on the map with a vertical bar that is used to represent how much each element satisfies the user's query (Fig. 16). By default, we fill the bar associated with each element with a green area whose size is proportional to

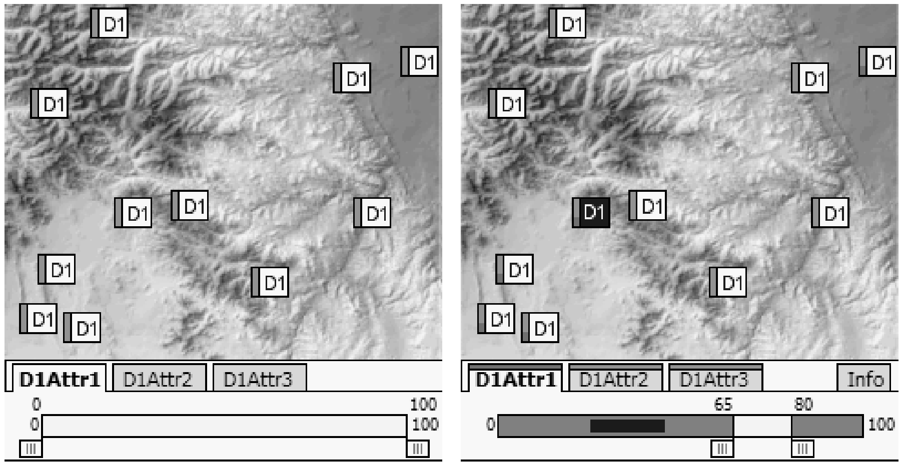

Fig. 16. Bar visualization of query results. Each icon is augmented by a vertical bar showing how much the corresponding element satisfies the user's query. Users can visually perceive the effects of their queries by observing changes in the color-filled areas of bars while manipulating query devices [8].

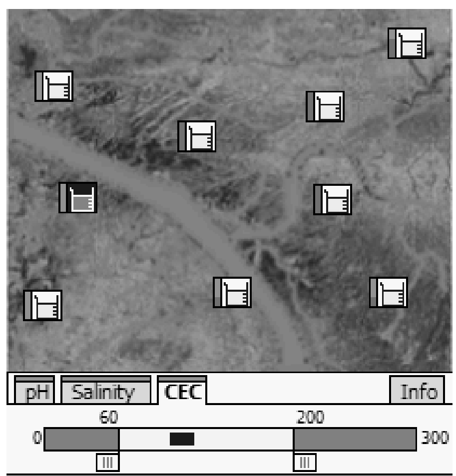

Fig. 17. Analyzing correlations between soil chemical properties and vegetation [8].

the number of satisfied conditions, while the remaining area gets filled in red. Using this visualization, it's easy for users to track elements that fully satisfy a query (i.e. those with a completely green bar) as well as to visually compare how much different elements satisfy the specified set of conditions (the less an element satisfies the query, the bigger the red area in the bar).

Figure 17 shows a scenario where MAGDA is used as a tool to analyze geo-referenced probes of soil, characterized by three continuous attributes:

pH, salinity and cation-exchange capacity (CEC). By properly manipulating query devices associated to these attributes and by looking at the results on the map of the considered geographic area, users are able to visually analyze the data to identify patterns, outliers and clusters. For example, by exploiting the correlation between soil chemical properties and vegetation it is possible to identify what probed areas are the most suitable for different plant species. In the figure, a 60-200 interval has been specified for the CEC property (these are typical CEC values for an organic soil type), a 5.5-7.5 interval for the pH property (optimal pH values for plant growth) and a 0-4 interval for the Salinity property (values above 4 may restrict the growth of many plants). As shown by the bar visualization, areas on the left are more suitable for most plants compared with areas on the right. However, while in the field, users may be interested in exploring areas that are only partially suitable for plants (for example to acquire data on plant species that are able to survive in those areas). Furthermore, if interesting phenomena are identified (for example, a fully unsatisfied result surrounded by fully satisfied ones, or a sudden variation in how much a query is satisfied between bordering areas), they may prompt researchers to perform more accurate investigations.

5 Conclusions

Mobile technologies have tremendous potential in supporting users in the field. In particular, various tasks, from searching for specific objects in an area to field data acquisition, can benefit from the possibility of exploiting devices such as PDAs and Smartphones to get and store geo-referenced data. Designing solutions for the visualization, exploration and use of geographic data on mobile devices is thus of fundamental importance.

This chapter has given an overview of research on geographic data visualization on mobile devices, with an emphasis on supporting user's navigation and user's decisions in the field. In the latest years, the first of these two topics received a lot of attention and various techniques have been proposed. However, there is still a need to compare these techniques and assess their effectiveness in different situations. For example, how much perspective and 3D-map based techniques are suitable to support navigation tasks is still unclear and further studies are necessary to identify the best presentation techniques for different classes of users.

The constant evolution of mobile technologies is also introducing the opportunity to use mobile devices as interactive tools to analyze geographic data and obtain the most appropriate information to support user's decisions where and when needed. However, current solutions, such as mobile GIS applications, while suitable to collect and display geographic data in the field, are still inadequate as mobile analysis tools and additional investigations are thus needed to provide users with more powerful and flexible tools.

In the near future, a growing demand for mobile solutions to support user's activities in the field is likely. As new needs and new issues emerge, research on geographic data visualization on mobile devices will remain crucial to produce applications that can be easily and effectively used while on the move.

6 Acknowledgments

This work has been partially supported by the Italian Ministry of Education, University and Research (MIUR) under the PRIN 2003 project "Web-based Management and Representation of Spatial and Geographical Data", subproject "User Interfaces for the Visualization of Geographical Data on Mobile Devices" and under the PRIN 2005 project "Adaptive, Context-aware, Multimedia Guides on Mobile Devices".

References

1. M. Agrawala and C. Stolte. Rendering Effective Route Maps: Improving Usability Through Generalization. In *Proc. Conference on Computer Graphics and Interactive Techniques (SIGGRAPH 2001)*, pages 241–249. ACM Press, 2001.
2. C. Ahlberg and S. Truvé. Exploring Terra Incognita in the Design Space of Query Devices. In *Proc. Working Conference on Engineering for Human Computer Interaction (EHCI 95)*, pages 305–321. Chapman & Hall, 1995.
3. C. Ahlberg, C. Williamson, and B. Shneiderman. Dynamic Queries for Information Exploration: an Implementation and Evaluation. In *Proc. Conference on Human Factors in Computing Systems (CHI 92)*, pages 619–626. ACM Press, 1992.
4. P. Baudisch and R. Rosenholtz. Halo: a Technique for Visualizing Off-screen Locations. In *Proc. Conference on Human Factors in Computing Systems (CHI 2003)*, pages 481–488. ACM Press, 2003.
5. J. Baus, K. Cheverst, and C. Kray. A Survey of Map-based Mobile Guides. In *Map-based mobile services - Theories, Methods, and Implementations*, pages 197–216. Springer-Verlag, 2005.
6. J. Baus, A. Kruger, and W. Wahlster. A Resource-adaptive Mobile Navigation System. In *Proc. Conference on Intelligent User Interfaces (IUI 2002)*, pages 15–22. ACM Press, 2002.
7. S. Burigat and L. Chittaro. Location-aware Visualization of VRML Models in GPS-based Mobile Guides. In *Proc. Conference on 3D Web Technology (WEB3D 2005)*, pages 57–64. ACM Press, 2005.
8. S. Burigat and L. Chittaro. Visualizing the Results of Interactive Queries for Geographic Data on Mobile Devices. In *Proc. Symposium on Advances in Geographic Information Systems (ACM GIS 2005)*, pages 277–284. ACM Press, 2005.
9. S. Burigat and L. Chittaro. Visualizing Locations of Off-screen Objects on Mobile Devices: a Comparative Evaluation of Three Approaches. In *Proc. Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI 2006)*. ACM Press, 2006, in press.

10. D. Chalmers, M. Sloman, and N. Dulay. Map Adaptation for Users of Mobile Systems. In *Proc. World Wide Web Conference (WWW 2001)*, pages 735–744. ACM Press, 2001.
11. L. Chittaro. Visualizing Information on Mobile Devices. *IEEE Computer*, 39(3):40–45, 2006.
12. L. Chittaro and S. Burigat. Augmenting Audio Messages with Visual Directions in Mobile Guides: an Evaluation of Three Approaches. In *Proc. Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI 2005)*, pages 107–114. ACM Press, 2005.
13. J. Dillemuth. Map Design Evaluation for Mobile Displays. *Cartography and Geographic Information Science*, 32(4):285–301, 2005.
14. ESRI. http://www.esri.com/software/arcgis/about/mobile.html.
15. J. Goodman, S. Brewster, and P. Gray. How Can We Best Use Landmarks to Support Older People in Navigation? *Behaviour & Information Technology*, 24(1):3–20, 2005.
16. C. Gutwin and C. Fedak. Interacting with Big Interfaces on Small Screens: a Comparison of Fisheye, Zoom, and Panning Techniques. In *Proc. Conference on Graphics interface (GI 2004)*, pages 145–152. Canadian Human-Computer Communications Society, 2004.
17. L. Harrie, L. T. Sarjakoski, and L. Lehto. A Mapping Function for Variable-scale Maps in Small-display Cartography. *Journal of Geospatial Engineering*, 2(3):111–123, 2002.
18. F. Hermann, G. Bieber, and A. Duesterhoeft. Egocentric Maps on Mobile Devices. In *Proc. International Workshop on Mobile Computing (IMC 2003)*, pages 32–37. IRB Verlag, 2003.
19. S. Jones, M. Jones, G. Marsden, D. Patel, and A. Cockburn. An Evaluation of Integrated Zooming and Scrolling on Small Screens. *International Journal of Human-Computer Studies*, 63(3):271–303, 2005.
20. S. Jul and G.W. Furnas. Navigation in Electronic Worlds. *SIGCHI Bulletin*, 29(4):44–49, 1997.
21. B. Karstens, R. Rosenbaum, and H. Schumann. Presenting Large and Complex Information Sets on Mobile Handhelds. In *E-Commerce and M-Commerce Technologies*, pages 32–56. IRM Press, Hershey, London, 2004.
22. P. Klante, J. Krosche, and S. Boll. AccesSights - a Multimodal Location-aware Mobile Tourist Information System. In *Proc. Conference on Computers Helping People with Special Needs (ICCHP 2004)*, pages 287–294. Springer-Verlag, 2004.
23. M.J. Kraak. Current Trends in Visualisation of Geospatial Data with Special Reference to Cartography. *Indian Cartographer*, 22:319–324, 2002.
24. C. Kray, K. Laakso, C. Elting, and V. Coors. Presenting Route Instructions on Mobile Devices. In *Proc. Conference on Intelligent User Interfaces (IUI 2003)*, pages 117–124. ACM Press, 2003.
25. K. Laakso, O. Gjesdal, and J.R. Sulebak. Tourist Information and Navigation Support by Using 3D Maps Displayed on Mobile Devices. In *Proc. Mobile HCI Workshop on HCI in Mobile Guides*, pages 34–39, 2003.
26. S.K. Lodha, N.M. Faaland, G. Wong, A.P. Charaniya, S. Ramalingam, and A.P. Keller. Consistent Visualization and Querying of GIS Databases by a Location-Aware Mobile Agent. In *Proc. Computer Graphics International (CGI 2003)*, pages 248–253. IEEE Press, 2003.
27. A-M. Nivala and L.T. Sarjakoski. Adapting Map Symbols for Mobile Users. In *Proc. International Cartographic Conference (ICC 2005)*, 2005.

28. I. Rakkolainen and T. Vainio. A 3D City Info for Mobile Users. *Computers & Graphics*, 25(4):619–625, 2001.
29. U. Rauschenbach, S. Jeschke, and H. Schumann. General Rectangular FishEye Views for 2D Graphics. *Computers and Graphics*, 25(4):609–617, 2001.
30. T. Reichenbacher. Adaptive Concepts for a Mobile Cartography. *Journal of Geographical Sciences*, 11:43–53, 2001.
31. T. Reichenbacher. *Mobile Cartography - Adaptive Visualisation of Geographic Information on Mobile Devices*. PhD thesis, Technischen Universitat Munchen, 2004.
32. R. Rosenbaum and H. Schumann. Grid-based Interaction for Effective Image Browsing on Mobile Devices. In *Proc. of the SPIE, Volume 5684*, pages 170–180. SPIE - The International Society for Optical Engineering, 2005.
33. C. Sas, M. O'Grady, and G. O'Hare. Electronic Navigation - Some Design Issues. In *Proc. Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI 2003)*, pages 471–475. Springer-Verlag, 2003.
34. A. Schilling and A. Zipf. Generation of VRML City Models for Focus Based Tour Animations Integration, Modeling and Presentation of Heterogeneous Geo-Data Sources. In *Proc. Conference on 3D Web Technology (WEB3D 2003)*, pages 39–47. ACM Press, 2003.
35. B. Shneiderman. Dynamic Queries for Visual Information Seeking. *IEEE Software*, 11(3):70–77, 1994.
36. N. Tripcevich. Flexibility by Design: How Mobile GIS Meets the Needs of Archaeological Survey. *Cartography and Geographic Information Science*, 31(3):137–151, 2004.
37. S. Winter and M. Tomko. Shifting the Focus in Mobile Maps. In *Proc. International Joint Workshop on Ubiquitous, Pervasive and Internet Mapping*, pages 153–165, 2004.
38. A. Zipf. User-adaptive Maps for Location-based Services (LBS) for Tourism. In *Proc. Conference for Information and Communication Technologies in Travel & Tourism (ENTER 2002)*, pages 329–338. Springer-Verlag, 2002.
39. A. Zipf and K.-F. Richter. Using Focus Maps to Ease Map Reading: Developing Smart Applications for Mobile Devices. *Kunstliche Intelligenz*, 4:35–37, 2002.