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ORIGINAL ARTICLE

Supporting device discovery and spontaneous interaction with spatial references

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Abstract The RELATE interaction model is designed to support spontaneous interaction of mobile users with devices and services in their environment. The model is based on *spatial references* that capture the spatial relationship of a user's device with other co-located devices. Spatial references are obtained by relative position sensing and integrated in the mobile user interface to spatially visualize the arrangement of discovered devices, and to provide direct access for interaction across devices. In this paper we discuss two prototype systems demonstrating the utility of the model in collaborative and mobile settings, and present a study on usability of spatial list and map representations for device selection.

Keywords Spontaneous interaction · Spatial user interface · Relative positioning

1 Introduction

Spontaneous interaction is a central characteristic associated with mobile and ubiquitous computing [10]. The principal idea of spontaneous interaction is to enable mobile users to associate their personal devices with devices encountered in their environment, in order to take advantage of serendipitous interaction opportunities [15]. Archetypal examples for spontaneous interaction include use of a printer in an unknown environment, interaction with public displays, and data exchange between mobile users. The chief concern in developing technologies that support spontaneous interaction is to minimize the effort for discovery of interaction opportunities, for establishing a connection to encountered devices, and for the actual interaction across devices.

Mobile devices are now routinely equipped with wireless networking capability, often supporting a variety of technologies to facilitate spontaneous connection with other devices, through widely deployed wireless infrastructures (e.g. WLAN, GPRS) as well as through direct peer-to-peer channels (e.g. Bluetooth, Infrared). Moreover, many discovery systems have been developed that let devices and services become aware of peers on the network, i.e. aware of their availability and their capability (Jini, UPnP, etc.) [6]. These advances address spontaneous interaction as an infrastructure challenge, however it is critical to recognise that discovery and interaction with encountered devices is also a significant user interface and interaction design challenge [11, 15]. Discovery systems help mobile devices find and access peer devices, but it remains difficult for their users to understand: what devices and services are available in their environment; how network entities found by their device relate to encountered physical entities; and how the intended interaction can be performed.

A central problem, from the perspective of a mobile user, is the identification of target devices for spontaneous interaction. A user will seek to engage in spontaneous

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interaction either by searching for a device that is able to provide a desired service (e.g., a printer), or by searching for a service representing a physically encountered device (e.g., the device of another user). In the first case, the problem is that devices found on the network will be identified in network terms, i.e. by a name and address geared toward their unique identification and localization in the network as opposed to in the real world. For a user it is not straightforward to map such devices names to actual devices in their environment, even if descriptive names are used ("Joe's Laptop", "Printer on D floor"). The second case poses the inverse problem: a device physically identified for interaction, such as a device in front of the user, does not readily give away how it is identified on the network, and how it can be accessed for interaction.

In this paper we present work on a spatial interaction model developed to address the problem of device identification for spontaneous interaction. The *RELATE* interaction model builds on the following principle, as illustrated in Fig. 1: from the perspective of a mobile device, the relative positions of potential target devices are determined, and reflected in the mobile user interface in the form of *spatial references*. Spatial references thus capture the spatial relationship of a client device (the user's device) with target devices in a visual presentation to the user, for matching what their device discovers on the network with what they see "in front of them." The spatial references are integrated on the user's device as user interface objects, to further facilitate the use of direct manipulation techniques for interaction with target devices.

The RELATE interaction model can be implemented with any location system that is sufficiently accurate to track spatial relationships of devices surrounding a mobile user. Many such systems have been proposed and developed, for instance based on computer vision [4] and ultrasonic tracking [1]. These systems require a deployed infrastructure

Fig. 1 The RELATE model for spatial interaction is based on relative positioning of potential target devices near a mobile user, and provision of corresponding spatial references in the user's device

in order to support device positioning. To overcome infrastructure-dependence, we have, in previously published work, introduced a system for relative positioning of devices in a peer-to-peer manner [9]. In prior work we have focussed on characterisation of relative positioning accuracy with RELATE [9], and introduced widgets for development of spatially aware user interfaces [13].

In this paper, we focus on the utility of spatial references for device discovery and spontaneous interaction, with three contributions:

- A review of earlier work in which we demonstrated RELATE in the context of collaboration support for co-located mobile users.
- Follow-on research introducing *Relate Gateways*, a user interface design in which interaction shortcuts to nearby devices are arranged as 'gateways' around the edge of a mobile user's device.
- A controlled study on usage of spatial information for selection of co-located devices.

2 Related work

Efforts in context-aware and ubiquitous computing over the last years have focused on making knowledge about the physical world available to mobile computer systems, and spatial knowledge has been of particular concern. As observed by Brumitt et al. [4], the addition of basic geometric knowledge has the potential to greatly increase the shared understanding between user and system. Use of geo-referenced data in conjunction with spatially aware handheld devices has become a widely investigated topic [7]. Mobile spatial interaction is explored for instance for navigation and wayfinding, access to place-specific information, and mobile augmented reality; the specific focus our work is the facilitation of spontaneous interaction across co-located devices.

Location-awareness for mobile devices has been investigated widely, with focus on development of infrastructures that track absolute positions of devices, or enable devices to directly compute their position on the basis of signals emitted by the infrastructure (e.g., [1, 20]). The RELATE work in contrast is focussed on *relative location* of devices surrounding a user: the rationale is that spatial relations rather than absolute positions help a user make sense of devices arranged around them. Spatial sensing is used for discovery of nearby devices and services (as opposed discovery based on network topology): in this respect our approach is related to physical discovery mechanisms; these include use of near-field communication for proximal interaction [18], and of beacons and tags for physical identification of interaction opportunities [12, 19].

In our interaction model, relative positions of nearby devices are presented to the user through a visualisation that exposes relative spatial arrangement. In related work, world-in-miniature visualisations have been used to show devices present in interactive spaces, to support interaction and relocation of applications [3, 16]. An interactive approach to obtain visual shortcuts to services embedded in an environment has been developed in the uPhoto system, in which users are provided with a "camera" to capture images that expose embedded hotlinks to services in the photographed scene [22]. Other user interfaces for user-centric discovery and association of services have integrated more coarse-grained location information (e.g. sorting device lists by proximity [20], and browsing services by room location [15]). Though not concerned with cross-device interaction, Halo is a visualisation technique closely related to our work, as it is concerned with indicating the location of off-screen targets [2]; in Halo this is achieved with drawing rings around the target and reaching into the visible screen area.

Spatial references in RELATE not only visualise potential target devices, but also support direct access across devices. Related techniques for cross-device interaction include: pick-and-drop, allowing users to pick up an object on one computer with a stylus and drop it on another nearby computer [17]; GesturePen, supporting selection of co-located devices as interaction target with pointing gestures [5]; eSquirt, a point and click technique for metaphorical squirting of data from one device onto another [12]; and Synchronous Gestures for dynamic device association, for instance bumping together of display devices to create a larger display [10].

3 RELATE interaction model and system

The RELATE interaction model is designed to support spontaneous interaction of mobile users within their immediate environment: the space a user can in principle oversee and interact with from their current position. The model is aimed to help users understand what devices and services are present, and to support association of the user's mobile device with any of the present devices in a seamless manner. The devices involved can be situated devices such as printers and public displays, as well as co-located mobile devices, including personal mobile devices of other users.

The interaction model involves the following steps:

1. A combination of network discovery and spatial sensing is used for spatially-bounded discovery of potential target devices around the user's mobile device.
2. The spatial relationships between the involved devices are tracked and modelled in real-time as spatial references.
3. Users are provided with a visualisation of available target devices in the user interface of their personal device, in a spatial layout that reflects device locations relative to the user's device.
4. Users initiate interaction and communication with a device by selection of the corresponding object in their user interface, using direct manipulation techniques.

The combination of network discovery and spatial sensing has two purposes: first, to limit discovery to devices that are ready to hand; and secondly, to associate network identities (device addresses) with spatial references. The association of network identity with a spatial reference is essential as it allows users to resolve the location of potential targets discovered by their device, and vice versa their devices to resolve the network address of a device physically selected by the user.

The spatial references involved are in terms of relative position, from an ego-centric perspective. The rationale is that relative positions, in contrast to absolute positions, support tasks such as: identifying an encountered device in front of the user; indicating where devices are from the user's perspective; distinguishing devices by spatial reference ("printer on the left vs. printer on the right").

RELATE-style interaction requires device positioning and tracking in real-time, at a level of accuracy that supports differentiation of devices co-located within an environment. The model is not tied to any specific location system, but the choice of system impacts on properties of the supported spatial interaction. We have developed a relative positioning system based on bi-directional ultrasonic ranging (synchronised over a dedicated RF channel) that has the following properties of relevance to our interaction model:

1. *Spatially-bounded discovery*: Ultrasonic ranging is limited to a few metres, and ultrasonic signals are contained within rooms. The sensing mechanism thus corresponds with our concept of limiting discovery to the immediate interaction range of the user.
2. *Location-limited channel:* The combination of RF and ultrasound in the sensing systems provides a location-limited channel that allows users to verify the authenticity of a device selected for interaction. In related work we have shown use of this property for securing spontaneous interactions against attacks on the wireless network [14].
3. *Infrastructure-less:* The sensing system operates in peer-to-peer mode and is not reliant on any infrastructure in the environment. It can support spontaneous

interaction between RELATE-enabled devices in any environment, indoors and outdoors.

4. *Fine-grained positioning in real-time:* The system provides accurate and up-to-date readings (performance in a setting with five devices in co-planar arrangement: 90th percentile accuracy of 7 cm for distances and 25° for angle-of-arrival; accurate updates within 1 s 70% of the time).

4 Supporting collaboration of co-located mobile users

The first application explored with the RELATE system was support for collaboration of co-located mobile users. The target scenario was to provide users who come with their mobile devices into a meeting with a spatial interface to more easily interact with the other meeting participants. The meeting support considered included awareness support to match names of participants with their relative position around the table, chat with spatially selected participants, file transfer by spatial reference, and virtual connection to a large shared display using a spatial metaphor.

4.1 System design and implementation

With the meeting support application in mind, RELATE sensing devices were packaged as USB add-ons (*Relate Dongles*) to be readily plugged into standard mobile computing devices (notebooks and PDAs). As dongle-equipped mobile devices become co-located, the dongles discover each other and form a wireless sensor network for collaborative measurement of their spatial arrangement. Each user's device acts as a client to the dongle sensor network, and translates measurements received into a visualization of the positions of the other devices. Figure 2 shows a notebook with sensor dongle, and a screen displaying the user's device surrounded by other discovered devices.

A two-dimensional map view was chosen for the visualization of co-located devices, using a relative coordinate system with the local device at the origin. Devices are represented by icons spatially arranged in a to-scale representation of the actual device arrangement, with the aim to allow a user to easily map between display and reality. The map view is implemented as a widget that also supports direct manipulation techniques: selection of one or more of the depicted devices, to specify the target of a command (e.g., pinging the device, or opening a pop-up window with more information on the device); and drag-and-drop of interface objects such as files onto device icons (e.g., to invoke file transfer to another device).

Figure 3 provides an illustration of the application, showing a meeting situation on the left, and the corresponding spatial user interface on the right. Note that the user interface provides an egocentric view of the meeting situation, with the user's own device highlighted for reference. The system supports collaboration by providing awareness of who the meeting participants are; this is done by annotating device icons with user names, to allow matching of faces with names. The system further supports initiation of communication (e.g. chat) and document exchange via the spatial references in the user interface. To transfer a document to another user's device, the corresponding file is selected in the user interface and moved with a drag-and-drop operation to the icon that spatially represents the target user. This means, that users do not have to concern themselves with computer names and IP addresses. Instead they can identify the desired target device on their screen by mapping the real arrangement of devices to the corresponding layout of icons in the interface, which significantly lowers the bar for spontaneous interaction.

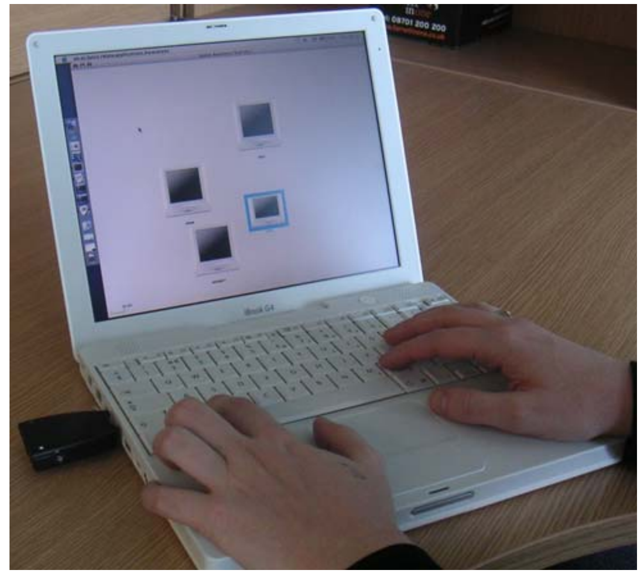

Fig. 2 Notebook augmented with a Relate sensor dongle for relative positioning of co-located devices. Discovered devices are visualized in a spatial layout in the user interface

4.2 Evaluation and observations

The application system has been tested and demonstrated in configurations involving between three and five mobile devices augmented with Relate dongles. A first set of experiments was conducted with five notebooks on a 2.4 × 1.6 m surface in an indoor office environment, with the primary aim of characterising relative positioning accuracy. For this purpose, each notebook was placed at randomly generated location and orientation on the surface for collection of measurements over several minutes. Over one hundred runs of the experiment were performed, each with a different randomly generated device arrangement. Half of the experiments involved device arrangements with

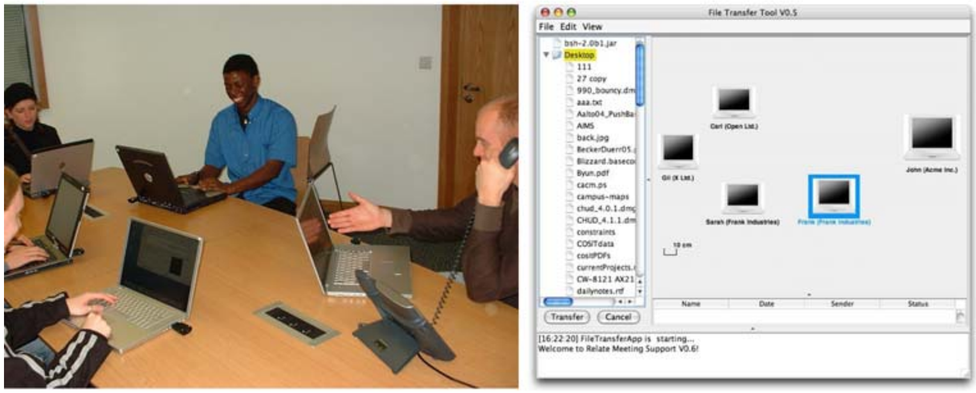

Fig. 3 Co-located mobile users are provided with an interface that provides spatial references to the devices brought into the meeting. The display shown on the *right* reflects the situation shown on the *left* (captured from the perspective of the user in the foreground). Note integration of the display with a file browser to support remote file transfer by drag and drop

limited line-of-sight between sensor dongles (with three of the possible ten lines-of-sight blocked). This was to test the systems ability to compensate for limited line-of-sight with collaborative sensing and sharing of measurements.

The sensor performance results are detailed in our prior published work [9]. For the purposes of this paper, we focus on impact of sensor performance on the user interface, observed alongside the above experiment and in a series of interactive demonstrations, in our lab environment and at the Mobisys '05 and EWSN '06 conferences (where smaller setups with three devices were used). We also review informal feedback received from demo participants on the spatial user interface design. The main insights gained in this respect are:

- Sensor data was pre-processed to filter noise prior to visual representation of relative device position (occasional outliers are typical in ultrasonic ranging) but the limited reliability of RF communication for sharing of measurements between sensor nodes still resulted in significant jitter in the visualisation. Users were clearly sensitive even to small amount of jitter, and found it very distracting when device icons moved although the corresponding real-world devices did not. Also problematic was that loss of measurements for a device over more than 10 s led the system to assume that the device had moved outside sensing range and left the meeting—causing further irritation in the user experience.
- Our demonstrations routinely involved dynamic addition and removal of devices to show discovery and automatic adaptation of the collaborative sensing protocol to changing numbers of nodes. The overall positioning accuracy of the system decreases when devices are removed as fewer measurements are available for producing position estimate: this appeared to be counterintuitive for users who expected that performance should increase in a less complex setup.
- Our concern had been to map device position as accurately as possible in a user-centred coordinate system, but we discovered that relative accuracy was much more important for usability than absolute accuracy. For example, when three devices were equally spaced in front of the user, then it was more important that the user interface reflected the equal spacing then the correct distance or angle between the devices. In all our demonstrations, it was apparent that users are very sensitive to proportionality. Small relative errors are perceived immediately and found confusing.
- The two-dimensional map representation, while aiming to provide detail on device arrangement at a glance, in many instances confused users. The mapping between the real-world and flat representation on the screen was not always clear to users, with many expecting a top view of the environment whereas our visualisation was based on front view. In response we have also considered perspective views in device icon size indicated depth.
- A general concern with the map representation was its large footprint on the screen. The demonstrated tasks in our application (awareness, file transfer) are typically not in the foreground of user activity in meetings but peripheral to activities such as note-taking or browsing of documents. This led us to consider visualisation of spatial references in a more peripheral manner, resulting in the RelateGateways design on which we report in the next section.

5 Spatial discovery and access to services

Building on the experience and insight gained with our initial application demonstrator, we have developed a second application based on the RELATE interaction model. The application setting in this case is mobile interaction with pervasive services in the environment of the user [8]. The targeted functionality is support for discovery of devices and services in the user's proximity, for identification and differentiation of devices ("which of the two printers does colour—the one on the left or the one the right?"), and for direct access to services from the user's mobile device.

5.1 System design and implementation

For this second application we used the dongle hardware from our initial development as plug-in for the mobile device in our scenario. In addition, we developed standalone sensor nodes (*Relate Dots*) for tagging of devices in the environment. The dots have no direct connection to the devices they augment but are pre-configured to identify 'their' device and the services it provides (with a URL for retrieval of a service description, transmitted to any dongle upon mutual discovery). The sensing protocol is modified as only the mobile device collects measurements from the sensor network.

The user interface design for this application takes account of the shortcomings observed with the map representation in our initial application, and the limited screen size on mobile devices. In this new design, discovered devices are represented by *Relate Gateways* which are arranged around the edge of the screen using a compass metaphor. Figure 4 illustrates the concept on the left, and shows a snapshot of the demonstrator on the right, with a mobile user device and public display as example for a service provided in the environment.

Figure 5 provides detail on the implementation of the Relate gateways interface. Gateways represent services in the environment and are arranged around the periphery of the mobile device's user interface. The position in the interface indicates the direction of the device providing the service. For example if the user is standing in front of a printer, they will see a printer gateway on the top of their screen. If the printer is on the left, the gateway will appear on the left. As the user moves around, or changes orientation, the positions of gateways are updated. In this way, gateways function as pointers to services. However, gateways are also access points to services, fully integrated with the user interface to support direct manipulation techniques. Users can use gateways in two ways: as target area for drag-and-drop operations that invoke default actions (e.g. dropping a file onto a printer gateway, to invoke it being printed); or as button that can be clicked to open a service menu (e.g. to select an action, or to set options).

The Relate gateway system supports operation in two different discovery modes. In the scanning mode all devices (and corresponding services) within visibility range (i.e. within line-of-sight, from a sensing perspective) are shown in the interface, to support general discovery and awareness of available services. In contrast, in the conditional mode, devices only become displayed as gateways when the user is in close enough proximity to directly use the device. For example a keyboard might be offered as service for text-entry on small mobile devices—in the scanning mode a user would be shown a corresponding gateway to find out that such as a service is available (and where in their environment), whereas in the conditional mode the gateway would only appear if the user places their mobile device in direct interaction range of the keyboard (which in our system design would be defined as a spatial condition by the service).

5.2 Formative study of the interface design

For assessment of the revised user interface design, we used a Wizard of Oz approach, in which displayed relative device positions were provided by a human operator. This approach was chosen to focus the study on the usability in principle of the gateway concept, factoring out influences caused by potentially fluctuating sensor performance (how to accommodate sensor noise and resulting uncertainty in the interface design is a separate concern necessitating

Fig. 4 The *Relate gateways* interface provides mobile users with a view of services available in the environment, arranged as gateways around the edge of the screen based on a compass metaphor. The photo on the *right* shows a public display as example of a service that is discovered and accessed through Relate gateways

Fig. 5 Implementation of *Relate gateways* as widgets arranged at the periphery of the user interface of a mobile device, and examples of gateways to a variety of services. Note that relative position of services is mapped to position around the user interface (orientation) and to a distance measure provided in the gateway representation

further study—informed for instance by work of others on mobile spatial interaction in the presence of uncertainty [21]).

Our study was set up in a larger meeting room extending into an adjacent hallway with an arrangement of three devices/services as shown in Fig. 6: a keyboard that users can select to have keyboard input redirected to their mobile device; a display supporting presentation of documents transferred from the mobile device; and a printer offering standard printing services. For exploration of spatial conditions we defined interaction zones around devices based on user distance, orientation and movement as illustrated in Fig. 6.

The study was conducted with 15 users recruited in one of the Universities participating in this research: all students between 21 and 25 years old, mostly male, and all with prior experience with mobile computers (but none had prior exposure to the RELATE system and concepts). Participants were given a short introduction and then asked to perform tasks that required interaction with all three deployed services, followed by invitation to more freely explore use of the system, and specifically use of scanning

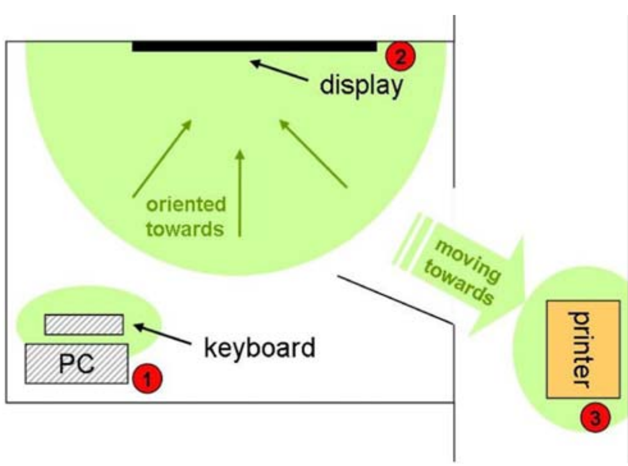

Fig. 6 Setup of devices and services with their respective interaction zones for exploration of the Relate gateways interface concept

versus conditional modes of discovery. The main insights gained from the study were as follows:

- The gateways interface appeared to be more easily understood than the map view in our prior application. The gateway interface abstracts relative positions to points around the edge of a screen and as a result was less confusing then the two-dimensional map representation.
- The arrangement of device-representing gateways around the edge of the screen was observed to be practical not only in terms of preserving screen real estate, but also facilitated drag-and-drop to discovered services very effectively; positioned around the screen perimeter, gateways were easier to locate then icons on a map, and also less susceptible to occlusion by other screen content. Users consistently rated drag-and-drop to a remote device via gateways as very intuitive.
- Following exploration of the alternative discovery modes, most participants suggested they would use the scanning mode when they enter an unknown environment, and conditional mode in familiar environment. This suggests that both should be supported but further thought needs to be given on how to expose clearly in which mode the interface is.
- The way in which the system facilitated seamless access to infrastructure devices led some of the users to perceive the mobile device effectively as universal remote control. While our motivation for the system had been facilitation of spontaneous interaction, it is apparent that the interaction model can also be effective for interaction over a distance with the devices in a familiar environment.

6 Controlled study of spatial interfaces for device selection

In addition to exploration of spatial references in the context of application demonstrators we have conducted a controlled study aimed to compare their use with a non-spatial condition for selection of co-located devices. As non-spatial condition we chose an alphabetically sorted listed as common for display of network-discovered services, and as spatial conditions a list sorted by device distance and a map view as used in our first demonstrator.

One key advantage of spatial references, as demonstrated, is that they enable device selection without prior knowledge of device names and addresses. However for this study we focused on a setting in which device names are available (as label on the device) in order to gain insight into user preference for spatial versus non-spatial interface. Our hypotheses for the study were:

(H1) Users prefer device selection with spatial references in comparison with device selection from an alphabetical list.

(H2) The mental demand is lower using spatial references when compared with an alphabetical list.

6.1 Experiment design and procedure

The experiment is a within-subject design with one independent variable, the level of spatial information provided in the interface: (1) no spatial information, (2) low spatial information (spatial list) and (3) detailed spatial information (iconic map). The order of interface presentation and the target devices were randomized for each configuration using Latin squares. User satisfaction, mental load and ranking of the three interfaces were the primary dependent variables.

The computer running the experiment was an OQO model 01, with a 5″ display and 800 × 480 pixel resolution. The three interfaces for the selection task, shown in Fig. 7, were implemented with HTML and named as follows: (a) alphabetical list (b) spatial list and (c) iconic map. We conducted the study in our department's library and used three notebooks, a projected screen and two printers to simulate a multifunctional meeting room. All devices were clearly labelled with their name to enable devices to be identified and selected without spatial hints.

Participants started the experiment on one of two predefined places in the room and one interface configuration (both places and interface configurations were counterbalanced among subjects). For each trial, the investigator touched one of the devices in the lab in order to show the participant which device to select. Participants then clicked ‘start’ to bring up the interface, and to select the indicated target. For each interface condition, a participant received six trials; the first two were for warm-up, followed by two each on the predefined participant positions. With the re-location of the participant from one position to the other, some devices were also re-arranged to modify the overall configuration. After all six trials, the participants filled in a questionnaire on satisfaction (based on the IBM computer usability satisfaction questionnaire) and mental load (using the NASA task load index). The procedure was then repeated for the other interface conditions, followed by a concluding interview in which users were asked to rank the three interfaces, and to provide general comments.

Nine male and nine female participants took part in the study. These were employees and students from different Departments in our University, with an average age of $M = 30.8$ ($SD = 7.9$). Participants rated themselves with $M = 3.8$ ($SD = 0.83$) for their experience with computers and $M = 3.4$ ($SD = 0.9$) for their experience with mobile devices (on a scale from 1 = none to 5 = expert).

6.2 Results

The user satisfaction scores showed higher satisfaction for iconic map ($M = 1.67$) and alphabetic list ($M = 1.69$) than for spatial list ($M = 2.11$). The perceived mental demand was higher for spatial list (3.3) than for iconic map (3.7) and alphabetic list. The frustration level was also rated higher for spatial list (3.6) than the other two conditions (4.3). Participants rated their performance toward task accomplishment higher for iconic map (1.6) and alphabetic list (1.6) than for spatial list (1.9). These results do not fully support our hypotheses as they do not show a significance preference for iconic map, and consistently lower rating for spatial list. Given that device names were clearly visible, list search was easier based on alphabetic sorting than distance sorting. Moreover, device distances do not vary much in co-located device settings: the direction at which a

Fig. 7 The three interfaces implemented on an OQO handheld for study of spatial references, from *left* to *right*: **a** alphabetical list, **b** spatial list, **c** iconic map

device is seen from the perspective of the user would appear to be much more significant for matching of interface to real world, than the distance.

The ranking results show a significant association between the amount of spatial information and whether it would be ranked as the most preferred one to use $\chi^2(4) = 14.67$, $P < 0.01$. Two-third of the participants chose iconic map as the most preferred interface for the selection task, as summarised in Fig. 8. As reasons for their preference of iconic map, participants mentioned for instance "I know where the devices are" but there were also a few participants who had problems to match the room with the iconic interface. Only two participants were in favour of spatial list; many participants commented on the order in which devices were shown in spatial list as confusing.

The study indicates that if device names are available spatial information still tends to be preferred by users but does not add to user satisfaction, and can be confusing if the abstraction is inappropriate. However it has to be noted that in practice device names are not as readily available as in our experimental setup. If device names are not displayed on the device, spatial hints can be expected to add significantly to usability: they can replace names if the spatial resolution is sufficient, or alternatively assist users in name-to-device matching.

7 Discussion

The two demonstrator systems we have built illustrate use of the RELATE interaction model and validate its support for spontaneous interaction in different application settings. The user benefits demonstrated are support for discovery and sense-making of interaction opportunities in the environment, and access to devices and services in abstraction from device names and addresses. Moreover we have presented a controlled study showing that spatial interfaces can perform as well as device lists also when device names are readily available.

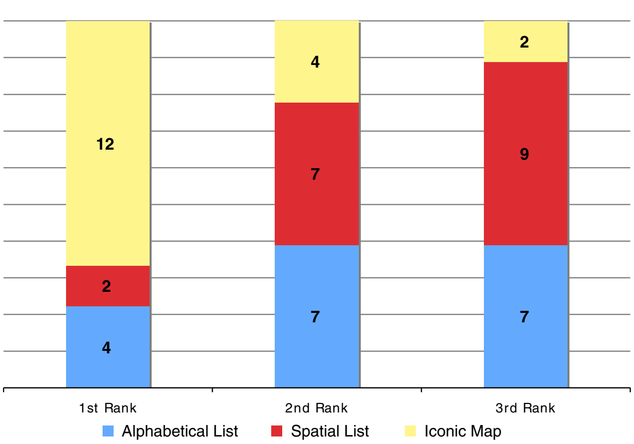

Fig. 8 Final ranking of the three interfaces

The interaction model demonstrated is generic and widely applicable to any situation in which users wish to dynamically associate devices. The two applications described emphasize interaction with devices that are a priori unknown to the mobile user, highlighting access without knowledge of device names; however the model may also useful for interaction across multiple devices of the same user, as spatial references can provide an efficient shortcut for tasks such as file transfer, relocation of applications, or migration of controls. A limitation to application of the model however is its dependence on relative positioning support; the model either requires a smart environment that tracks devices, or augmentation of devices with built-in sensors as demonstrated in the prototype systems we built.

The two applications have been demonstrated at relatively small scale, involving only a few devices around a mobile user. Scalability of the interaction model is a concern from a number of perspectives: space in the user interface to display spatial references (i.e. overall screen real estate, and resolution of devices that are close together); human perception of spatial representations (and ability to map entities between display and environment when numbers increase); and performance of the sensor system (e.g. longer delay of updates with growing number of devices). While this has not been tested, it is reasonable to expect that usability of the interface concept will decrease quickly with larger number of devices. Mechanisms to address this would include filtering (as already explored with the conditional mode in our second application study) and more advanced visualisation concepts, for instance based on grouping of devices.

User feedback obtained with both application systems support that users quickly understand the spatial mapping employed in the user interface. The gateways interface appeared to be more easily understood, whereas the map view involves a more complex mapping and potentially more confusing movement in the interface. An interesting insight is specifically the role of proportionality and relative accuracy in the representation of device position—less dominant though in a layout around the edge of the screen than in a two-dimensional map.

Finally, a general problem observed pertains to the inherent limitations of sensor systems, in particular their imprecision (precision refers to the quality of a sensor to produce the same or similar result with repeated measurement, not to be confused with accuracy). Whereas our initial system design sought to filter noise, an alternative approach is to use models that cope with uncertainty.

8 Conclusion

We have presented an interaction model designed to support interaction of mobile users with devices and services in their immediate environment. The model is based on relative positioning of devices and integration of spatial references in the mobile user interface. The contributions of the model are that it supports matching of network identity of devices with physical identity; visual discovery of interaction opportunities; and direct access to discovered devices. The model has been tried and validated in two application systems, demonstrating its versatility and support of very common tasks in mobile and ubiquitous computing, such as document transfer during an encounter of mobile users, and dynamic association of a mobile device with a device situated in the environment. A main advantage demonstrated is that spatial references support selection when device names are not available to the user. In a controlled study we have shown that spatial references can be as effective as name-based device selection also in less likely settings in which device names are readily available for identification of encountered devices.

The reported work exposes a number of challenges for further investigation. These include: development of further experimental data on the usability of spatial references and interface designs such as the Relate Gateways; assessment of scalability from both sensing and sense-making perspectives; and the investigation of spatial interaction and visualisation models that are more robust with respect to limitations of underlying sensing systems.

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