Lessons from the lighthouse: Collaboration in a shared mixed reality system

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ABSTRACT

Museums attract increasing numbers of online visitors along with their conventional physical visitors. This paper presents a study of a mixed reality system that allows web, virtual reality and physical visitors to share a museum visit together in real time. Our system allows visitors to share their location and orientation, communicate over a voice channel, and jointly navigate around a shared information space. Results from a study of 34 users of the system show that visiting with the system was highly interactive and retained many of the attractions of a traditional shared exhibition visit. Specifically, users could navigate together, collaborate around objects and discuss exhibits. These findings have implications for non-museum settings, in particular how location awareness is a powerful resource for collaboration, and how 'hybrid objects' can support collaboration at-a-distance.

Keywords

Virtual reality, WWW, museum visiting, mixed reality, location-awareness, context-awareness

INTRODUCTION

Mixed reality and augmented reality systems have increasingly broken down the barrier between the digital world of computers and the familiar physical world. In these systems, interaction with the digital is no longer limited to a single desktop display but extends into the physical world. For example, in systems such as the MagicBook [2], head-mounted displays are used to project computer–generated 3D objects onto users' views of the physical world. Users move and interact with 'virtual' objects as if they were real. Other mixed reality systems involve traversable boundaries between the virtual and the physical [10], or allow users to interact around physical objects that are connected to digital objects [17]. While the design of mixed reality is in its infancy, these systems show considerable potential for supporting new types of interaction, both co-present and at-a-distance.

In this paper we describe a mixed reality system that allows a group to share a museum visit. It allows visitors to a physical museum to co-visit with others using virtual reality (VR) and web versions of the same museum [11]. This shared experience is produced using a PDA, an ultrasonic tracking system, a 3D representation of the gallery, 2D maps, and mixed reality exhibits (physical and WWW). Drawing on our findings in studies of co-visiting in conventional museums [6], the system was built to provide three main resources for awareness and interaction: a shared audio channel, awareness of other's location and orientation, and a common information space. These are three of the interactional resources that are used in conventional museum visiting.

In an extensive user trial we found that the system effectively supported many, but not all, of the social aspects of a shared museum visit. Specifically, the shared resources that the system provided were effective in allowing users to navigate together, collaborate around objects, share their experiences and talk about the exhibition. Some participants even commented that the system was more sociable than a conventional museum visit. This shows both how mixed reality can be used to support interaction at a distance, but also which resources need to be provided to help users collaborate. From this we draw implications for mixed reality in museums and more widely.

We begin by reviewing the use of mixed reality systems in museums, and then we discuss our studies of conventional museum co–visiting. After describing the co-visiting system, we present results from the trial in three main sections covering the three resources the participants' used in their interactions. From this we identify three implications for the design of mixed reality systems: that collaboration at a distance can be supported using such systems; that location is a powerful resource for supporting awareness; and that better support for bodily orientation and gesture may solve some of the interactional problems associated with such systems.

AUGMENTING THE MUSEUM VISIT

Museums are a promising application area for mixed reality technologies. Driven by educational and cultural concerns to make collections accessible and understandable to the general public, museums have long experience with technologies for enhancing the visit, e.g. audio guides, video and interactive computer displays, as well as web and VR presentations accessible from afar. Museums are also open to experimentation with new technology, and allow researchers the opportunity to develop new systems in a real world setting.

Experimental museum systems have also made use of location-awareness and wireless network technologies to support automatic presentation of information to visitors.

For example, the HIPS project [13] used infrared technology to track visitors in the Museum Civico in Siena, offering them personalised audio messages on a hand-held. The Exploratorium in San Francisco also exploits location through the use of infrared and Cooltown technology [15] to control the presentation of audio and web pages to PDAs carried by the visitors.

These systems have been criticised for inhibiting interaction between groups of visitors [12]. This issue has been directly addressed in the *Sotto Voce* electronic guide system, which enables visitors to eavesdrop on their friends' audio commentaries. Trials of this system found that mutual eavesdropping provided "greater interactional cohesion" as most of the users treated the shared audio as a conversational resource [1].

However, this sort of technology has not often been used to enhance the experience of online visitors. One exception is the RHINO project [3], which combined mixed reality and robotics to guide both local and remote visitors. This suggests an opportunity for systems that explore more fully the sharing of museum visiting experiences by online and conventional visitors.

RESOURCES FOR MUSEUM VISITING

Our aim in developing our system was to support co–visiting in museums by users physically separated from each other, and also to support interactions across physical and digital media. These aims are similar to those of media space systems [4], although taken out of the work setting and into the mobile context of a museum visit. One lesson we took from media space systems was that simply supporting 'talking heads'—or video connections between users—is insufficient to support meaningful collaboration. Instead, support should be given for the actual resources used in collaboration, such as shared viewing of documents (in the case of media space systems).

Accordingly, we studied conventional visitors, using video and observation techniques, to look at the resources visitors use to share their visits [6]. This suggested four key resources used by co-present museum visitors that could be supported by technology. *Voice* is perhaps the most powerful resource of all, and is used both to discuss exhibits and negotiate the visit. *Location and orientation* are used to indicate what exhibit one is looking at, and what one is doing (such as moving to a new exhibit or examining an exhibit closely). The museum also provides a *common space* as the background to the visit, with exhibits and information that can be shared and discussed.

Figure 1. Moving between exhibits together

A short clip from our video recordings of museum visitors shows some of these resources in use (Figure 1). In this clip two visitors are navigating an exhibit together. By moving slightly back in frame two, the visitor on the right shows to their partner that they have finished looking at that part of the exhibit and moved on to the next. This physical movement creates a space for the second visitor to move to the exhibit, and also gives a lead in navigating the exhibit. In the third frame the second visitor follows her friend by moving closer to the exhibit and bending over to study it closely. This "following" was a common part of our observations of people navigating museums together. These are not just physical movements, but also subtle communications of navigation between visitors [18].

THE CO-VISITING SYSTEM

The co-visiting system was developed as part of an ongoing project set within the Equator Interdisciplinary Research Collaboration (www.equator.ac.uk). We designed the system for a specific exhibition: the Mackintosh Interpretation Centre in The Lighthouse, Scotland's Centre for Design, Architecture and the City. The Interpretation Centre is devoted to the life and work of Charles Rennie Mackintosh (1868-1928), Glasgow architect, designer and artist. The Centre is comprised of textual and graphical displays with authentic artefacts, and over 20 screens presenting video and interactive material to visitors.

The co-visiting system [11] allows three people to visit the Interpretation Centre simultaneously, one physically and two digitally. The various services that comprise the system were coordinated through the EQUIP infrastructure (http://www.crg.cs.nott.ac.uk/~cmg/Equator/).

The *physical* visitor is in the Interpretation Centre itself, equipped with wireless headphones and microphone, and a handheld PDA (Figure 2). The PDA (Figure 3) includes a sensor package that is part of an ultrasonic location system [14][1]. The location is calculated from the flight time of ultrasonic 'chirps' and a simple geometric model of the Centre. The sensor package also includes an electronic compass for orientation information. The location and orientation are displayed on a map of the Centre, along with the locations and orientations of the other two visitors.

The *virtual reality (VR)* visitor uses a first-person, 3D display with avatars representing the other visitors. Figure 4 shows the non–immersive display. The textured 3D model of the gallery was created from plans and photographs. Exhibits are modelled at a crude level showing form, but not fine detail. For example, text is unreadable within the 3D environment.

Lastly, the *web* visitor (Figure 5) uses a standard web browser displaying several Java applets, one of which is a variant of the physical visitor's map. Mouse clicks on the map are interpreted as movements around the Centre, with the direction from the old location to the new location treated as the new orientation. As with the physical visitor's map, the other visitors' locations are displayed on the map with differently coloured icons.

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[1] At a technical level we distinguish *positions* (points in 3D Cartesian space) from *locations* (named spatial extents) but in this paper we use *location* for both.

To support looking at exhibits as a group, the system supports 'hybrid exhibits' presented both physically and digitally. Each physical exhibit in the Centre has corresponding web pages, reproducing the artefact as text and 2D images to stand as a digital version of the physical exhibit. When a physical and a digital visitor are both at a particular location they see comparable versions of the exhibits associated with that location.

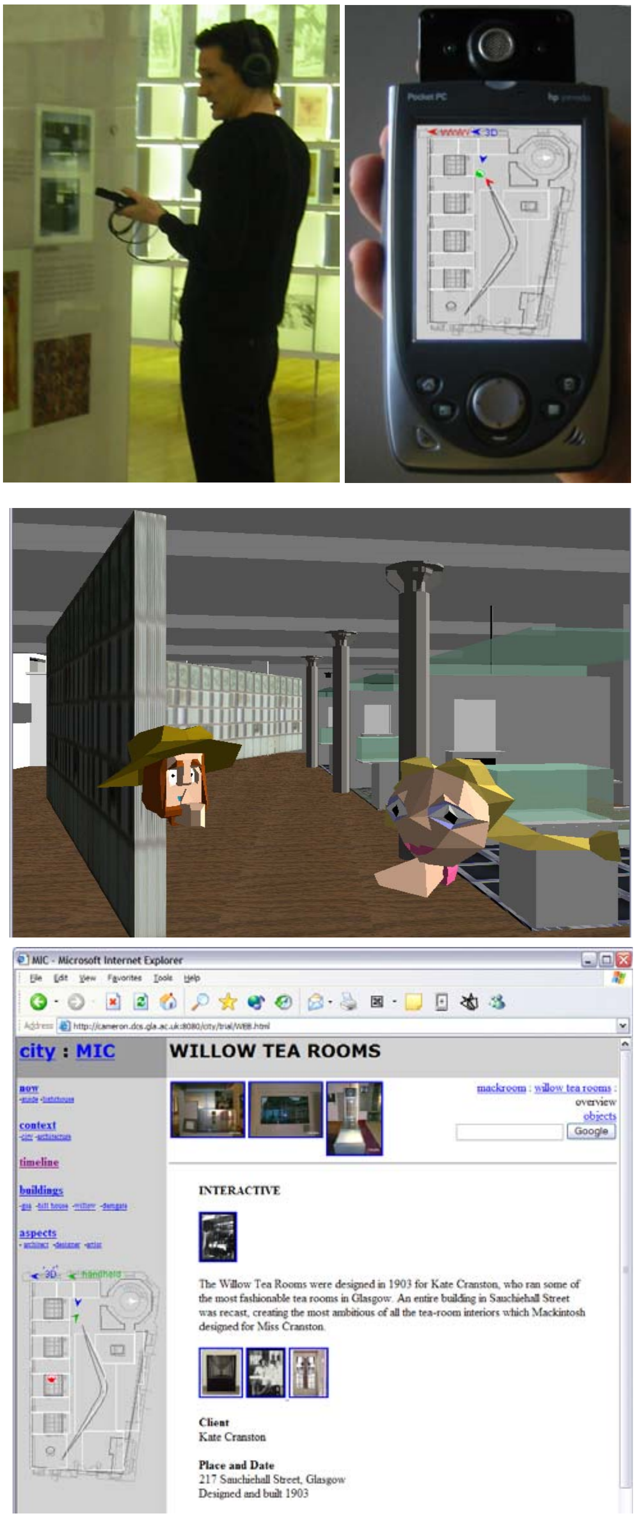

Figure 2, 3, 4 & 5: Physical, VR and Web views of the Mackintosh Interpretation Centre

For the digital visitors, an exhibit is presented as HTML pages in a web browser. The spatial location of each digital visitor is converted to a name that represents a spatial extent, or zone, in the Centre. A browser applet responds to a zone change by loading a new HTML page corresponding to main exhibit in the new zone. For a web visitor, this information is shown in the same window as the map, and includes a menu of hyperlinks as an alternative to map-based navigation. A VR visitor also uses a browser, separate to their 3D graphics display. Lastly, the visitors shared an audio channel, using an Internet voice conferencing system.

THE TRIAL

Our aim in trialling this system was not simply to evaluate it; measurements are difficult to make in settings where the aim is not utility but enjoyment [16]. Our focus was on lessons we could learn for the design of shared mixed reality systems, along with increasing our understanding of how these systems help or confuse users.

The trial involved 34 participants, organised into ten groups of three, and two groups of two. The groups of three consisted of a web visitor, a VR visitor and a physical visitor. The pairs explored different combinations: visiting without the physical visitor (one trial), and without the web visitor (one trial). Participants were recruited as groups of friends who were regular museum visitors, visiting a museum at least three times a year, with experience using the Internet. We recruited participants who were art school students (5), university students (15), and professionals connected with our university through friends or family (14). Ages ranged from 21 to 50, with 18 male participants and 16 female. Participants were paid for their time at the end of the visit.

Procedure

The groups were introduced to our system and told that they would each be visiting the exhibition in a different way. The physical visitor was taken to the Interpretation Centre, and the two digital visitors were taken to separate rooms on a different floor.

For the first half of the trial, participants were asked to explore the Centre together, to familiarise themselves with the technology and how they could co-visit. Since we were specifically interested in how the system supported social interaction, we introduced an artificial task for the second half of the trial. Each participant was given three questions, and the group was asked to answer these questions together. Some questions were designed to provoke open–ended discussion and interaction between the participants. For example, participants were asked "What is the group's favourite Mackintosh painting?" and "What contribution has Mackintosh made to Glasgow?" as well as more factual questions such as "What was Mackintosh's birthday?" This combination of open and task-centred behaviour allowed us to study behaviour that was typical of a museum visit, such as finding exhibits, and to observe how the system supported the shared aspects of visiting a museum. All the participants managed to answer the questions, with the exception of one group: non–native English speakers who appeared to have problems comprehending the questions. During the trial, the physical visitors were video taped, and all use of the system was logged. After the trial, the participants were interviewed as a group in a recorded semi–structured debriefing.

Analysis

For analysis we combined the map view used by participants, with the video and audio recordings. We also analysed transcripts of the post-trial debriefings, and observations of the digital visitors using the system.

We were interested in exploring how the system was used to inform our future designs. Accordingly, we choose a technique known as *interactional analysis* [1, 9], based on paying close attention to the details of how users interact with each other and with technology, usually through the analysis of video. Video is analysed to look for 'critical moments' where a system is used in a revealing way. These moments are then transcribed, and the transcript, along with the video, is used for analysis. This method has proven particularly successful for the analysis of collaborative technologies, in situations where the intricate details of interaction (such as small pauses) can have a large impact on the success of a system.

In analysis we paid special attention to where the participants used the resources such as location, provided by the system, and to interactions around the hybrid exhibits. Situations where participants got confused were also valuable since these show where the system can be improved to better support collaboration or understanding.

RESULTS

The quality of the exhibition contributed to what was obviously an enjoyable experience for the participants, although not without its frustrations. We present the results from the trial in three sections. In the first section we discuss the use of voice, and the interactions between participants. In the second section we discuss the use of location and orientation, and lastly we discuss the extent to which the system supported a "common information space" and a sense of shared presence for the participants.

Voice and interaction

Our system appeared to encourage much more talk and conversation between the co-visitors than we observed between conventional visitors. To an extent this was due to the artificial trial, and the use of an unfamiliar technology. However, a number of participants expressed the view that using the system encouraged more talk than a conventional museum visit:

> *Q: Is it different to a museum visit?*
> *A: Yeah, it's really talkative.*
> *B: You kind of go 'Mmmm, that's nice' [...] If you find something interesting, you go 'Look', and that's over here*

The technology therefore did not inhibit communication and even encouraged interaction. The shared audio channel, for example, encouraged the participants to talk to each other as if they were on a telephone. Moreover, since two of the participants were outside the exhibition, talk was not discouraged by the hushed reverence normally adopted inside museums.

Interaction around exhibits

By building hybrid exhibits we hoped to engage the participants with each other and with the exhibition. The trial suggests we succeeded: the participants engaged in rich collaboration around the hybrid virtual/physical exhibits. When participants found that the virtual objects corresponded to physical objects, they appeared to link together the virtual and the physical seamlessly. In this extract the participants discuss a set of Mackintosh pictures to decide which one they like the most:

```
P: Petunias is errm better for me than Rosemaries
V: Ok [pet]unias
W:    [hhh]          Petunias it is
P: Early work
V: Hey guys see: this other one it's really nice
its called Fort Melle hhh Fort Melle in nineteen
twenty seven
P: Nineteen twenty seven
V: Yeah, it's got the light
P: Yeah I know but I like[roses]
V: [Can you] see it?
W: Fort Melle?
V: Hmmmm
W: Yeah that's quite nice
P: I still prefer Roses
```

In the extracts, P (green arrow on the map) is the physical visitor, V (blue) is the virtual reality visitor, and W (red) is the web visitor. Square [brackets] show overlapping talk, underline shows speaker's emphasis, and numbers ***1*** show where in the talk images have been captured.

Figure 6: Focused interaction

Once the association has been established between the digital and the physical picture, the participants quickly move on to discussing the qualities of the object, and comparing it to the other digital/physical exhibits. However, interacting around these hybrid exhibits was not without its problems.

Sharing different perspectives

In ordinary face–to–face interaction we assume a reciprocity of perspectives between ourselves and others, but in our system each user had to build an understanding of the limited perspectives the other users had of the Centre. In the following extract the trial participants discover that the VR visitor does not have a map, and is at some disadvantage:

```
V: I cannot find the door.  And also. Ahh here we
are I'm at Mark. Hi Mark
W: Hi. Ciao.
V: So you're in front of the window just now?
P: What window? Ok, I'm going around.
V: you guys can have like aaa map of [movement]
P:                                   [Yeah]
V: and like on that map you always have the shape
that shape that says you where I am
P: Yes[Yes I can
W:    [humm hmmmm
P: Ahhh you don't have *1* it
V: Ahhh[mmhmm
P:     [Ohhhhh
P: that's a problem
V: that's why I have to go around wonderin cos I
don't have it
```

Figure 7: Understanding others' perspectives

It was through such questions and observations that participants learned about each other's perspectives. Indeed, participants put considerable effort into designing their interactions to take into account the limitations of others' views of the Centre. So, for example, in Figure 6 we see that the participants emphasise the year in which Fort Melle was painted ("nineteen twenty-seven"). The VR and web visitors only see information for a single year at a time for this exhibit, so they guide their co-visitors to the particular paintings by emphasising the year. Moreover, the web and physical visitors frequently assisted the VR visitor (who lacked a map) by guiding him or her to a specific exhibit. In turn, since the digital visitors could move much more quickly than the physical visitor, they frequently found information and then guided the physical visitor.

Interactional problems

While the participants did have some success interacting across the different media, this was not without its frustrations. In a face-to-face situation, interaction can be impeded for a number of reasons such as participants not giving enough attention to each other or giving excessive attention to objects—a phenomenon Goffman called "alienation from interaction" [7].

In the trial, interaction would often pause when participants found a difference between the physical and digital representations of the Centre. For example, the Centre's interactive displays were not available for the digital visitors. When the physical visitor started to use and talk about an interactive display that was not shared, the digital participants would refrain from interacting and move on to other exhibits. Yet these interactional troubles were not fatal for the sense of a shared space or for interaction. Participants showed skill in managing the differences between the digital and the physical worlds and exploiting shared features when possible.

A second form of detachment that the system produced was between the physical visitor and public museum visitors not participating in the trial, much like the detachment described as a negative feature of audio guides [12]. Engaged with interacting in the system, the physical visitor showed little or no attention to other people in the Centre—at times almost bumping into them as he or she moved around. This attracted glances from the other public visitors, although interestingly this did not appear to intimidate the physical visitor.

Location and orientation awareness

A second set of issues concerns how users made use of location, in the form of the maps and the 3D display, to manage their visit. Our system provided a simple sense of shared location and orientation using icons on an outline map for the physical and web visitors, and avatars in a 3D display for the VR visitor.

Using spatial movements in preference to hyperlinks

The digital visitors had a choice of ways to navigate the display information: clicking hyperlinks in the web pages or moving spatially around the Centre by clicking on the map or moving in the 3D display. The digital visitors used spatial movement in preference to the more conventional hyperlink navigation. Navigating this way supported collaboration in that, as users moved, their actions were visible to others. Participants also used their spatial memory of the Centre, as in Figure 8, by remembering that an exhibit was in one part of the Centre, and subsequently clicking on or moving to that area.

This presentation of location proved to be important for much of the collaboration in the system:

```
P: That was the one that we
looked at before the one with
the hanging baskets
V: Was that in Northampton?
P: Yeah in the very stripy
bedroom
V: *1* oh I'll go back
V: there then cos I know
where that was *2*

P: *3* Errrh that's the only

P: one I think *4*
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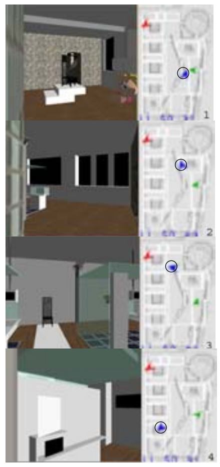

Figure 8: VR visitor (blue arrow, circled) moves to a part of the Centre she remembers

Using others to navigate

Shared awareness of location also allowed users to quickly move to their friends. Participants used this to quickly find what their friends were looking at and then move so as to look at the same thing. In the following clip we show frames from the overview map showing the movement of the web visitor (red arrow):

```
V: So I've got the *1* Derngate I've walked into
a display [Derngate Northampton]
W:        [Right Peter are you]
W: *2* blue or green
V: ahm you see me
V: I'm sorta moviing back
V: and *3* forth
W: Ok: *4* hold on. right got you
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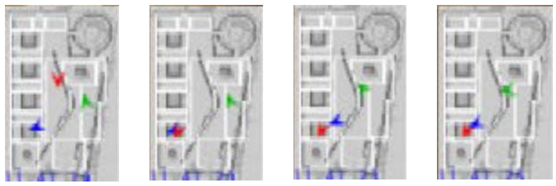

Figure 9: Web visitor (red arrow) moves to what their friend (blue arrow) is looking at

The web visitor (red arrow) is talking to the VR visitor (blue arrow) about the Derngate exhibit. As the VR visitor stops talking about this exhibit, the web visitor moves to the same location (frame two) and checks "are you blue or green?" The VR visitor, lacking a map and, so, not knowing the colour, 'wiggles' back and forth to confirm that the web visitor is now in the correct place. This gesture is something like the wave of a hand from a person in a crowd.

This extract shows how location is a resource that can be used to quickly find what exhibits are being discussed. Global location can be seen 'at a glance' by the web and physical visitors with this system, without the need to explicitly ask, and the VR visitor can see the location of others locally. This activity was observed across all the different media: the VR visitor would move to the web or physical visitor, the physical visitor would move to the VR or web visitor, and the web visitor would move to the VR or physical visitor. This extract also shows how participants used the fact that others could see their location in order to communicate; they moved with attention to what others could see ("I'm sorta moving back and forth”). The VR visitor here assumes that since they can see his or her location, a ‘wiggle’ will be visible to others. Having access to others’ locations was also used when giving responses to questions. In one extract a visitor asks what his or her friend is doing. The friend can clearly be seen looking at the map before responding with an answer taking into account others’ locations.

Problems with using location and orientation

While the map proved to be a powerful resource for our participants, its extensive use also highlighted a flaw in our system. If a digital visitor used hyperlinks to navigate to an exhibit, taking advantage of the digital aspect of the exhibit, his or her spatial location was not updated[2]. This led to confusion when the user referred to his or her location, to help others find the exhibit being viewed. Since the location was not updated, the others were led to the wrong exhibit.

Moreover, problems could still arise even when the map was updated and used, in particular when participants attempted to guide each other. Terms such as “to your left” and “behind you” not only had different meanings for each participant, but could also be ambiguous. With limited access to bodily orientation, and a lack of support for gesture, attempts to describe places in the Centre and how to get to them proved very difficult.

In the next extract, the web visitor is guiding a friend, apparently using “left” to mean the left hand side of the map, rather than the friend’s left side. The physical visitor ends up ignoring the web visitor, and walks to the right to get to the exhibit (using the map to find the friends and the exhibit). Participants would often attempt to guide their friends using ‘left’ and ‘right’ or ‘top’ and ‘bottom’ causing some confusion if the visitor did not have a map, or was using a different sense of left and right.

```
P: I think I’m lost I donnow if
I can find this street
W: You can… it’s no problem
right cu-come down come south
[...] *1*
Over to your left *2* to your
left Marigo to your left..

left no that’s right=left *3*
left keep going left left
P: hhhhhh=
W: [No]

V: [Right] right if you turn
round *4* behind you you should
see a paintings and drawings
display *5*
P: Auhhhhh
W: Right got it?

P: *6* Yeeah
```

Figure 10: Confusion over left and right

As studies have shown, navigation using voice alone is particularly difficult [5], and at times our provision of a map did not appear to help. In face-to-face interaction, reference to places and directions can be accomplished through the movement of our hands and body, e.g., by looking in a specific direction or pointing, and through awareness of others’ orientations. While the system monitored movement, we did not provide a mechanism for pointing or for more subtle movements of the body. This meant that large movements between exhibits were visible but subtle small movements were lost. This caused serious problems when navigating as well as inhibiting the subtle recommendation and sharing of exhibits that occurs when we visit with friends.

Common information space

The last resource we discuss is the shared information space provided by the system, and how this helped produce a sense of co-presence for the different visitors. As discussed above, the Centre was divided into spatial zones, and web pages were mapped to each of these zones, corresponding to each exhibit. When digital visitors entered a zone, a web page was displayed as a digital version of the main physical exhibit in that zone. In this way, the system attempted to provided a “common information space”, shared between the physical and digital visitors through these hybrid digital/physical exhibits. We hoped this would, when combined with the other resources, provide a shared space for users that they could experience together.

However, this shared common information space was only a pale imitation of the actual space of a museum. Although it supported interactions and discussion, the system could not support many of the subtle physical interactions that take place between visitors to a museum. This can clearly be seen in the way that participants viewed exhibits. When looking at an exhibit, the physical visitor would stand close to the exhibit and orient their body towards the exhibit. The VR visitor, however, needed to be *inside the zone* corresponding to that exhibit. Lastly, the web visitor would move to the exhibit by clicking in the zone on the map. These differences lead to considerable confusion. For example, two visitors could be spatially close and face the same way but be presented with different exhibits because they are in different zones (particularly problematic for the VR visitor who could not actually see the zone boundaries). They might then mistakenly assume they were both looking at the same exhibit.

Moreover, while the accuracy of the ultrasonic location system was sufficient to differentiate which zone a user was in, this did not help navigation *within* the zone. Without the ability to gesture, one could not easily refer to specific objects within a zone. Participants also could not see at a glance which part of an exhibit a co-visitor was viewing. As noted earlier, visitors to traditional museums orient their bodies as they look at exhibits, showing to others what part of an exhibit they are viewing, and which parts of an exhibit are not of interest. Our system could not support these rich interactions, so participants needed to use talk to smooth over these absences (Figure 6, above, offers an example of this).

These problems made the common information space very different from a truly shared physical space. Our system

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[2] This capability was implemented during the trial period but was not deployed to maintain consistency.

could not hope to support the rich experience of actually being in a place looking at a physical object (such as the texture of a painting), or experiencing the prolonged company of friends. Nevertheless the common information space did successfully support a shared experience for participants, and one with its own pleasures. Trial participants reported having a strong sense of a shared experience. For example, from one end of trial interview:

> *I quite enjoyed the social engagement […] being able to talk about everything more and not feeling that you are disturbing. Not thinking about other users in the gallery, you know it's kind of liberating*

The common information space successfully supported a shared experience by enabling users to talk, interact around, and discuss the shared exhibits. In this way the hybrid digital/physical exhibits enabled participants to share a world in common, and communicate using that world, if only partially.

Indeed, when compared to a solo visit through a web page, this use of a common information space (along with the other resources) adds depth to a digital visitor's experience. Interaction takes place across the digital and physical media, creating a socially engaging experience beyond that available to a conventional digital visitor. A sense of co-presence is achieved, even though the visitors are distant from each other.

DESIGN LESSONS AND IMPLICATIONS

We have learned a number of design lessons from developing our system. While we are optimistic about the opportunities for this type of system, we plan to make improvements and to address some of the problems mentioned above. In this section we discuss three main lessons from our work: how to support collaboration in a shared mixed reality, using shared location as a resource for interaction, and opportunities to better support gesture and orientation.

Supporting collaboration with mixed reality

While the participants in our trials were all in the same building, our system supports collaboration at a greater distance. The physical visitor's access to the rich content of the exhibition was maintained, while the hybrid exhibits enabled digital visitors to engage with the physical visitors (and with each other). The visitors interacted collaboratively around the exhibits.

Indeed, the success in enabling visitors to work around hybrid objects, and the use of location as a resource for interaction, suggests applications in other domains and settings reliant on the spatial layout of artefacts, such as shops, warehouses and city streets. Along with changing the setting, this technology may also be suitable for different activities, such as guided tours or online teaching, involving mixtures of local and remote participants. When transferring this work to different settings we expect that the specific resources for interaction used by individuals may also change. So, as with our studies of museums, these settings may repay prior investigation to examine which specific communicative resources are appropriate. In shopping, for example, the ability to share images of products or produce may be important, suggesting the use of portable cameras.

In our current work we are extending our system to the wider context of tourists on a city visit. Our own studies of city visitors suggest that an additional and more asynchronous form of interaction could be appropriate, associating particular city streets with web pages that can be referred to after a visit. New settings could also offer the chance to more reliably track artefacts, thanks to the greater size of the 'artefacts' in question, e.g., entire buildings.

In future designs we also intend that a greater proportion of the resources, such as video and hypermedia, will be available as resources for collaboration. For example, the physical visitor will also be able to interact with hypermedia, and able to guide others toward interesting parts of the web in a similar way to the current use of location as a resource for collaboration. In the current system the spatial structure of the exhibition and its artefacts was the primary shared resource for awareness and interaction amongst visitors. Interaction was occasionally hampered when participants found a difference between the physical and digital versions of the exhibition, as when the physical visitor referred to an interactive video display that neither digital visitor had access to. By offering more resources across this divide some of these problems may be avoided.

Location awareness as a resource

Location awareness allowed participants to talk about and use each other's context and navigation. This shared location depended on two features – an ultrasonic tracking system to find the location of the physical visitor, and a virtual location for the web and VR visitors. Through these features a visitor could, for example, tell the others to come to where he or she was in order to look at a particular exhibit. Awareness of location also meant that users could better understand what their co-visitors were looking at; each could simply look at the map or 3D display, and see which exhibits the others were viewing. Location awareness might be similarly useful for other collaborative settings where current activity can be inferred from location. Again, warehouses and department stores might be examples. This suggests that 'location-aware' devices such as 3G mobile phones might also be useful tools for location awareness, i.e., for making friends and others selectively aware of the user's location.

Additionally, maps have the potential to communicate more than current location and, so, to be an even richer resource. For example, in our ongoing work we are experimenting with representing the estimated inaccuracy of sensed locations to users, to reduce confusion when using systems such as ultrasonics and GPS. In a way that extends the notion of referential gesture, a visitor should be able to override the system's interpretation of his or her location and to choose what location to present him- or herself as being in—to the system and to other visitors.

Support for bodily orientation and gesture

Trial participants found it difficult to differentiate between individual artefacts that were part of the same exhibit, and encountered problems in talking about directions and locations. While the system used a compass to detect a physical visitor's orientation, this is a simplification of the more complex issue of how the visitor is standing and what they are viewing. Similarly, the system tracked the digital locations of the web and VR visitors (more accurately than the physical visitor), but only basic orientation was tracked. Details of bodily location, orientation and gesture are of considerable importance in museum interaction, but were poorly supported by our system. Participants partially compensated by talking, but better system support for orientation and gesture might serve in the more subtle presentation of attention and the management of transition between artefacts.

Many techniques might be used in supporting gesture toward locations and artefacts, and having those gestures made visible to others, e.g., using a digital wand or the PDA itself to point at exhibits, clicking on the map or selecting an object in the VR display (c.f. [8]). Video might be used to directly let each visitor be more visible to others, although there might be issues of mirror–like confusions over direction e.g. "Which left? My left or yours?" Video might be used indirectly too, for example using image analysis to map a visitor's gestures and stance onto those of an avatar in the VR. Annotation or telepointers could also be supported, allowing users to talk about different artefacts and locations using the shared representations.

There are also techniques that may reduce confusion resulting from interaction in the context of multiple spatial reference frames. For example, the web and physical visitors used similar maps, and misunderstandings arose when directions were given in terms of the map rather than the way the recipient of the directions was facing. Such misunderstandings might be reduced through the use of different spatial displays, such as radar-style presentations, or through the addition of individual viewpoint displays.

CONCLUSION

This paper has presented a study of a mixed reality system that allows web, virtual reality and physical visitor to share a museum visit together. A trial of this system in use uncovered how mixed reality systems, by providing key resources for interaction, can support social experiences at a distance. In particular, shared spatial location is a strong and intuitive resource for collaboration, giving users awareness of their co-visitors at a glance. The 'hybrid exhibits' which the system supported also allowed trial participants to interact around objects despite their differences in how they accessed the system.

To conclude, these findings have applications not only in museums, but to the many other contexts where collaboration takes place around objects. In our own future work we are taking this system out of the contained space of the museum into the broader context of tourism in the city. Our aims in doing this are not only to extend the technology, but to learn as much as we can about using mixed reality to create new types of social experience.

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REFERENCES

1. Aoki, P.M. *et al* Sotto Voce: Exploring the Interplay of Conversation and Mobile Audio Spaces. in Proceedings of CHI 2002, ACM Press, Minneapolis, Minnesota, 2002.
2. Billinghurst, M., Karo, H. and Poupyrev, I. The Magicbook: A Transitional AR Interface. Computer Graphics, 25. 745-753.
3. Burgard, W. The Interactive Museum Tour-Guide Robot. in American Association of Artificial Intelligence '98, Madison, Wisconsin, 1998.
4. Dourish, P. and Adler, A. Your Place or Mine? Learning from Long-Term Use of Audio-Video Communication. CSCW journal, 5 (1). 33-62.
5. Franklin, N. Language as a Means of Constructing and Conveying Cognitive Maps. in Portugali, J. ed. The Construction of Cognitive Maps, Kluwer Academic Press, Dordrecht, 1995, 275-295.
6. Galani, A. and Chalmers, M. Can You See Me? Exploring Co-Visiting between Physical and Virtual Visitors. in Proceedings of Museums and the Web 2002, Archives and museum infomatics, Boston, Mass., 2002.
7. Goffman, E. Alienation from Interaction. in Interaction Ritual: Essays on Face-to-Face Behavior, Doubleday, New York, 1967, 113-136.
8. Heath, C., Luff, P., Kuzuoka, H. and Yamazaki, K. Creating Coherent Environments for Collaboration. in Proceedings of CSCW 2001, Kluwer Academic Publishers, Dordrecht, 2001.
9. Jordan, B. and Henderson, A. Interaction Analysis: Foundations and Practice. The Journal of the Learning Sciences, 4 (1). 39-103.
10. Koleva, B., Schnadelbach, H., Benford, S. and Greenhalgh, C. Traversable Interfaces between Real and Virtual Worlds. in Proceedings of CHI 2000, 1-6 April 2000, ACM Press, 2000, 233-240.
11. MacColl, I., Millard, D., Randell, C. and Steed, A. Shared Visiting in Equator City. in Proceedings of CVE 2002, Bonn, Germany, 2002, In Press.
12. Martin, D. Audio Guides. Museum Practice, 5 (1). 71-81.
13. Not, E., Petrelli, D., Stock, O., Strapparava, C. and Zancanaro, M. Person-Oriented Guided Visits in a Physical Museum. in Ichim'97, Archives and Museum Informatics, Paris, 1997.
14. Randell, C. and Muller, H. Low Cost Indoor Positioning System. in Abowd, G.D. ed. Proceedings of Ubicomp 2001: Ubiquitous Computing, Springer-Verlag, Seattle, WA, 2001, 42-48.
15. Semper, R. and Spasojevic, M. The Electronic Guidebook: Using Portable Devices and a Wireless Web-Based Network to Extend the Museum Experience. in Museums and the Web, Archives and museum infomatics, 2002.
16. Serell, B. Using Behaviour to Define the Effectiveness of Exhibitions. in Bicknell, S., eds. Museum Visitors Studies in the 90s, Science Museum, London, 1993, 140-144.
17. University of Nottingham. Deliverable 1.1: Hybrid Physical-Digital Artefacts, SHAPE, Nottingham, UK, 2001.
18. vom Lehn, D., Heath, C. and Hindmarsh, J. Exhibiting Interaction: Conduct and Collaboration in Museums and Galleries. Symbolic Interaction, 24 (2). 189-216.