The Spatial Character of Sensor Technology

Stuart Reeves, Tony Pridmore, Andy Crabtree, Jonathan Green, Steve Benford
School of Computer Science & Information Technology, Mixed Reality Lab,
University of Nottingham, Jubilee Campus,
Wollaton Road, Nottingham NG8 1BB, UK.
{str,tpp,axc,jzg,sdb}@cs.nott.ac.uk

Claire O'Malley
School of Psychology, University of Nottingham, University Park, Nottingham,
NG7 2RD, UK.
com@psychology.nottingham.ac.uk

ABSTRACT
By considering the spatial character of sensor-based interactive systems, this paper investigates how discussions of seams and seamlessness in ubiquitous computing neglect the complex spatial character that is constructed as a side-effect of deploying sensor technology within a space. Through a study of a torch (aka 'flashlight') based interface, we develop a framework for analysing this spatial character generated by sensor technology. This framework is then used to analyse and compare a range of other systems in which sensor technology is used, in order to develop a design spectrum that contrasts the revealing and hiding of a system's structure to users. Finally, we discuss the implications for interfaces situated in public spaces and consider the benefits of hiding structure from users.

Author Keywords
Sensor technology, space, ubiquitous computing, seams

ACM Classification Keywords
H.5.2 Information interfaces and presentation: User Interfaces.

INTRODUCTION
The research program of ubiquitous computing has often been centred around Weiser's well-known description of its goals, namely, to "[make] many computers available throughout the physical environment, but [make] them effectively invisible to the user" [11]. This notion of 'invisibility' of the device and seamlessness between devices has been the subject of several critiques. Tolmie et al., for example, suggest that invisibility has been cast as a "perceptual invisibility" rather than developing technology that may well be perceptually visible yet is "unremarkable technology." Such unremarkable technology becomes invisible *in use* as part of a daily routine [10]. Chalmers et al. also suggest that the notion of 'seamlessness' has been misused [4], suggesting that such seamlessness has been targeted at integration of components instead of or as well as interactions between those components. The result is systems that make "everything the same" rather than "letting everything be itself, with other things" [12]. As a result, Chalmers et al. posit a "seamful" form of design that exposes seams as resources for users to draw on. With this strategy, what may be a 'bug' or 'glitch,' or even the natural limits of technology can be transformed by systems into an active resource made available to users for reasoning about breakdown.

This paper is primarily concerned with the way in which seams between devices create a particular spatial character for the location in which they are deployed. This spatial character of seams derives from the use of spatially-embedded sensor technologies (e.g., GPS, Wifi, etc.) which are particularly prevalent in ubiquitous computing. Sensor technology plays a fundamental part in the creation of seams, and thus the character of the space in which such technology is deployed. The main issue, then, is how interactive and ubiquitous system design may appropriately address this essential spatiality.

SENSOR TECHNOLOGY IN ACTION
In this section we present a relatively simple example of a sensor space, and analyse how breakdown of the system exposes the essentially spatial character of sensor-based environments. In particular, we examine an instance of collaborative storytelling within a space in which a sensor technology has been deployed in order to inform the subsequent analysis and discussion.

Interactive Torch Technology
The sensor technology we shall examine is a torch-based (aka 'flashlight') system that plays audio based on the torch beam's location, which is visually tracked across physical surfaces [7]. A video camera detects and tracks the movement of the beam and image-processing software extracts key features of the beam's projection as it hits the surface (e.g., its position and the area or object it illuminates). The tracking of the beam in turn drives interaction with an

application. A number of torches can be calibrated to function with the system in order for multiple torch beams to be detected at once and their identities recognised.

The torch technology has been used previously for interacting with graphical objects projected onto an immersive Storytent interface for young children [8]. It has also been used for an interactive exhibit in the caves underneath Nottingham Castle, in which visitors could shine their torches at points on the walls of a cave in order to retrieve information about the many inscriptions and marks on the walls [7]. A further use of this interface was its deployment as a digging tool for a virtual "sandpit" [6], in which users could uncover artefacts by 'digging' with their

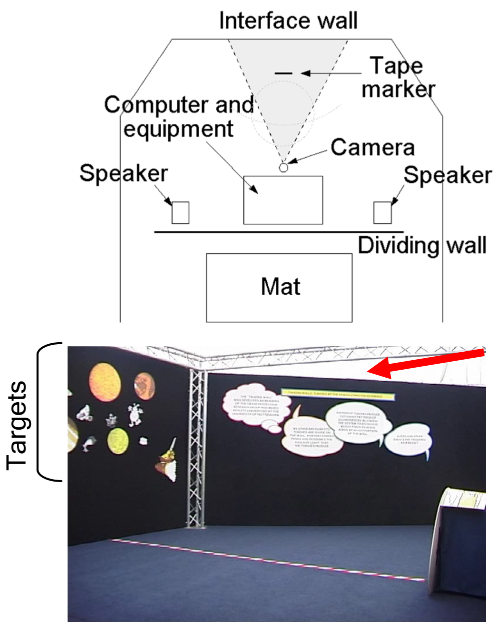

Figure 1. Layout of the space (top), photo of the main area (bottom)

torch beams pointed at a projected display.

The Journey into Space

The "Journey into Space" was a storytelling event that took place at the Newark and Nottinghamshire county show over two days in May 2004, during which small groups (2-10) of young children aged approximately between 5 and 11 years were led by professional storyteller Rachel Feneley[1] on an imaginary trip into outer space. The event took place in a large, hexagonal, metal-framed marquee. The walls were covered with dark cloth to set the scene, with various images of planets, spaceships, and aliens that had been printed onto paper (and thus moveable). During this storytelling, the torch interface was used to trigger sounds that had been recorded by the children, which would play when the beam was pointed at targets on the wall (the images of planets and so forth are shown on the left side of Figure 1, bottom). The top of Figure 1 shows a floorplan, and the bottom is a photo of the space (the red arrow indicates the orientation of the video camera performing torch recognition in the space, which was mounted on a horizontal section of the marquee frame just above head height). The area of the space was approximately nine by four meters.

The story that Rachel told began with the children training to be astronauts, and then embarking on a trip into outer space in a spaceship. With this ship, they landed on and explored a planet, and then returning home as heroes to adoring crowds. This sequence of story elements evolved as the story was told again and again, however the basic structure stayed the same. Here we shall briefly discuss in more depth some relevant segments of the story.

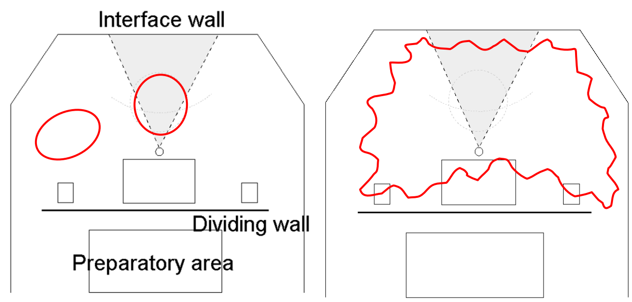

Figure 2. Spaceship circle formations when sitting inside the ship and travelling through space (left), exploring the planet used the entire space (right)

Boarding the Spaceship and Blastoff

At a point during the story, the Rachel and the children commenced their trip into outer space. By way of 'boarding' the spaceship, the children and Rachel assumed a circular formation that became the 'ship.' The left diagram of Figure 2 shows two of these; the formation's position closer to the wall occurred at the start of the two-day event, and after a short time, Rachel began to instead form the circle in the centre of the space, the reasons for which shall be discussed later. At this point Rachel introduced the torch for the first time (characterising it as a "magic torch"), and, handing it over to a single child[2], instructed them to initiate the countdown and blastoff sound that the children themselves had previously recorded with Rachel. Use of the interface was practically accomplished by pointing the torch at the wall, and in this instance, typically the blastoff sound was tagged to an image of the Earth.

Travelling Through Space

After the blastoff, children remained in the circle (again, two shown in Figure 2, left), and the torch was passed around in order to explore the "view out the window" (i.e., the interface

[1] Of the Lakeside Arts Centre at Nottingham University.

[2] Although parents and other onlookers sometimes formed a small audience on the edge of the space, the torches were used only by Rachel and children involved in the story.

wall), during which various other (often) pre-recorded sounds were triggered.

Landing On and Exploring a Planet

When the children landed on a planet, they left via an imaginary "chute" in the spaceship circle and began to explore the planet, and thus, in turn, the space (Figure 2, right). During this time the torches were used to explore the space, as children pointed them at targets on the wall (thus triggering sounds), people, or other objects in the space.

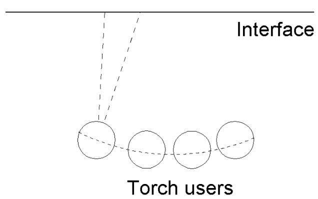

Figure 3. A 'vanilla' arrangement

ANALYSIS

We shall begin the analysis by considering the ways in which each part of the system may fail, and in parallel provide a series of ethnographic vignettes from the Journey into Space that typify a portion of these failures. The analysis we present here is chiefly concerned with three aspects of the event that emerged from a detailed study of this data: breakdown of the technology, its repair and temporal adaptation to breakdown. During this we shall also consider a spatial perspective on the interaction, in which these breakdowns, repairs and adaptations are thought of as occurring in interaction and interference spaces. This spatial model will also have implications for other interactive systems that we shall discuss later.

As mentioned previously, the torch technology has been through several iterations. This particular iteration of the technology was intended as a deployment 'in the wild' that stretched the technology beyond its use previously. At other events this use had typically been restricted to a kind of 'vanilla' (or 'standard,' 'default') arrangement of the technology and participants, in which a set of targets were attached to a smooth surface with users operating the torches directly in front of the wall and some distance away from its surface (see Figure 3). The Journey into Space event by contrast was quite different from these more 'vanilla' deployments, and, as can be seen by the red annotations in Figure 2, the use of space was varied instead of relatively static. Movements to and from the main area, and circular and freeform distributions of participants formed the core uses of space at the event. Further complicating matters was the fact that the marquee environment, with its translucent ceiling and fabric walls, stretched a number of the assumptions relied upon in previous experiences.

It was primarily this frequent and flexible reconfiguring of space and the varied modes of torch use that helped to initiate breakdown or failure of the interface. It is worth noting here that the authors are aware of well-known 'standard' failures that computer vision systems can succumb to, such as occlusion, noise and spurious data in the image [9]. Our intention here, however, is not to simply exhibit these problems, but to illustrate how sensor technology, its operation and such standard failures may be thought of more generally in spatial terms. This is especially relevant for public settings where users are navigating such a space during their interaction with the interface.

Over the course of the two days, ethnographic data (video recordings and field notes) was recorded for each group that took part in the storytelling (there were over twelve separate groups of children in all). This data was then analysed qualitatively, from a video-analytic perspective, in order to explicate the way in which the torch technology featured in the collaborative action of the storytelling.

Interference and Interaction space

We can start by considering in which space interaction is in any way possible. The following vignette exhibits some basic interaction with the interface, but also reveals how the calibrated shape of the space impacts this.

Rachel is conducting one of the first groups of children to go on the Journey into Space (Figure 4). The (three) children

Figure 4. R gestures to J to move away from the wall (left), J gets the sound working (right)

and Rachel are sitting in a circle towards the left side of the space, and are about to blastoff from the alien planet, heading back to the Earth. The torch has been passed to a girl, Jenny, who Rachel instructs. The countdown sound (simply a recording of the children counting down from ten to one) has been associated with a spaceship target on the wall.

R: You see the craft over there? (Points) Get up close and point the magic torch at the craft.

J: (Pointing the beam at the wall, but she has not pointed it at the right target.)

R: Yeah that one there. Can you see?

J: (Directs torch beam to the spaceship. There is no sound.)

R: That one there. You need to get a bit closer

J: (Walks towards wall.)

R: Keep going. (The countdown sound is triggered for a fraction of a second and then halts.)

J: (Gets closer and closer to wall, arriving within centimetres of it.)

R: Too close! Bit further back, bit further back.

J: (Slowly steps back from the wall, keeping the beam trained on the spaceship target. The countdown triggers, J glances back towards R and the group.)

Even though the torches were initially calibrated with the vision system, the nature of the fluctuating light within the space was at times a source of problems. The initial lack of sound triggering in this vignette as Jenny shines the beam at the wall was due to a combination of light levels, obliqueness of the beam as it was projected onto the wall and the group being situated generally outside of the area in which the torches were calibrated for the system. If the beam becomes too oblique or too weak here, the expectations of the vision system configured by this previous calibration will be compromised. When Jenny moved towards the wall the sound still failed to trigger. Rachel's instruction to move closer to meant that the target then became obscured from the camera when Jenny got "too close," resulting in further positions away from the wall being successively tested until the sound triggered. The trouble was resolved only after this kind of experimentation.

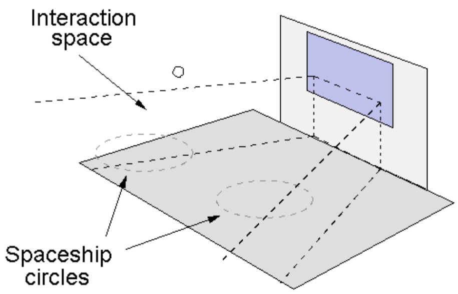

Figure 6. (Static) interaction space

From this we can begin to map out an approximate volume in which users may interact with the interface, as suggested in Figure 5. This space itself is largely defined by the initial calibration of the torch, thus it is derived as an approximation from the positions and orientations of the torch captured during this calibration. The constraints of obliqueness modify this space, as do the ambient light levels, albeit in a less predictable way. Each of these aspects came into play as Jenny used the torch. The combination of each of these factors generates the shape of the interaction space that is experienced by the group. Training data and obliqueness create a relatively static space, however this character is then less predictably altered by levels of light as they fluctuate during the day. Furthermore, it follows that within this interaction space there may be particular 'sweet spots' in which interaction with the interface is most smoothly conducted (i.e., is optimal). For the Journey into Space, this spot was usually the main area in front of the wall (where the torch was calibrated) that provided consistently less problematic interaction. We shall see later how this information featured in adaptation.

Our second vignette will help us to examine breakdown of the system, and the contingencies presented by the camera and the torch.

Another group of four children and a helper – Alice – are about to take off from the Earth (Figure 6). They are sitting in a circle in between the left side and the centre of the space.

Figure 5. The group are hearing the sound (left), P gets in the way and A gestures (right)

After asking who would like to trigger the blastoff, Rachel passes a torch to Helen, seated to Rachel's right. A boy, Paul, is sitting to Rachel's left.

R: Who wants to have the magic torch first? (Torch is passed to H.) Ok, so when you're brave enough, point it at Earth and we're ready to take off.

Helen points the torch at the Earth target, and the countdown sound begins to play, "Ten, nine, eight, seven, si…," at which point it breaks off and no "five" and so forth is heard. At the time when the break in sound was heard, Paul had leaned forward. This is then noticed by Alice who gestures for Paul to move his body back. The sound then retriggers and begins from ten again, this time completing.

This simple example involves Paul obscuring the beam, Alice rapidly noticing this and gesturing to Paul, and a subsequent repair of this breakdown that took at most a second. Again, the group were situated in a less opportune place in the space, however by good fortune (perhaps better light levels and reduced obliqueness), the sounds triggered correctly.

This example demonstrates one form of occlusion, namely occlusion of the torch. (This is illustrated in Figure 7, left.) Occlusion of the field of view of the camera was another form of occlusion (Figure 7, right). This second form was exhibited in the first vignette when Jenny got too close to the interface wall, obscuring the target that was to be triggered.

We can call these two forms instances of 'interference' with the interface. A map of the possible 'interference space' can be created, i.e., in the space which obstruction to the camera or the beam may in any way occur. The largest interference space is created by the camera that is trained at the wall; its position and field of view define a (relatively) static interference space (Figure 8, top). The torch itself, on the other hand, also defines an interference space, although it is smaller and mobile (Figure 8, bottom).

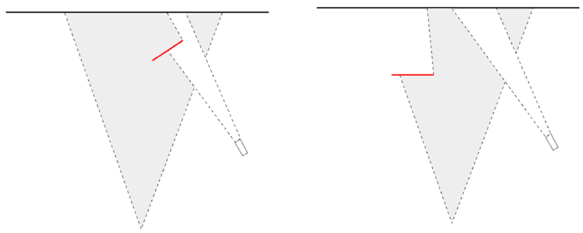

Figure 7. Two forms of occlusion

There is a fundamental asymmetricity between the beam and the camera, rather simplistically since obscuring the torch beam is an 'observable' event for both the camera and the participants as the beam may inspectably be partial on the wall or absent altogether, whereas obscuring the camera is not (it is only available to the system). As such, disruption of the camera image is internal to the system with no exposure to torch users.

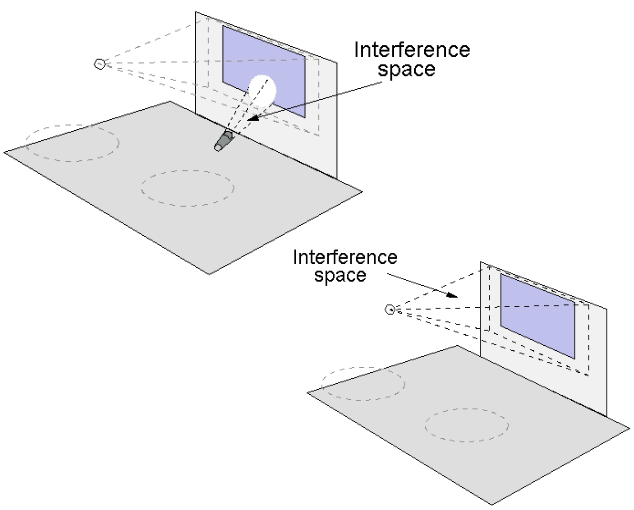

Figure 8. Interference spaces

The vignettes thus far highlight this difference between the interaction and interference spaces of both the torch and the camera. Jenny, for example, had to move back from the wall successively with Rachel's instructions ("bit further back, bit further back") experimentally until the interference space was vacated. Paul's obstruction of the torch, on the other hand, was quickly noticed and then rapidly managed by Alice. There is, then, an inequality between interferences with the camera and interferences with the torch. To illustrate its absurdity, we can consider, as a direct comparison to the camera, a torch that emitted infrared (or some other invisible emission) such that only the system could 'see' it. Compounding this is the fact that the torch produces a controllable interference space and is inspectably so, thanks to its beam and the social cues involved in its use (i.e., a kind of pointing).

We can begin to discuss these issues of breakdown and repair as illustrated briefly in the vignettes in terms of the basic legibility of the spatial character of the system to the participants involved in interaction. The torch provides greater and more legible resources to the users in order to repair breakdown. In contrast, the nature of the camera can cause problems simply because occluding the camera view is somewhat illegible.

There were, of course, other reasons for and effects of breakdown that have not been shown in the two vignettes. The aural results of breakdown were various: sounds sometimes stuttered if they had been triggered already, halted halfway through playing or even failed to play at all; sounds started anomalously even though a torch was not trained on the wall; a sound successfully played might be a different sound altogether to the sound that was recorded and attached to the target. As we have seen, sounds may also be triggered accidentally.

We can summarise the causes of the majority of breakdown into a short list, covering those already seen in the vignettes as well as others that were observed in the data. Breakdowns varied in terms of the speed with which resolution was possible; typically those involving the camera were more prevalent and more difficult to resolve than those with the torch.

- **Obscuring a target:** someone standing in front of a target on the wall being pointed at by a torch such that the target is no longer visible from the camera's perspective. Any sound playing will halt.
- **A person or a thing in front of the torch:** the beam is partially or fully obscured by someone standing between the torch and the wall.
- **Making the torch beam too oblique or using the torch outside the area within which the torch was trained:** the beam of the torch, when projected from an angle onto the wall, will be less and less detectable as a beam for the vision system. There are also recognition issues. If the system has been calibrated to recognise a torch being shone on the wall from a particular area of the space the range of angles it is expected to present will be coded into the recognition system. If it is shone onto the wall from an angle outside that set it might not be recognised or might be misclassified.
- **Other objects being detected by the camera as a beam/object to track:** originally there was a bug in the vision system that caused it to detect white, torch-beam-sized objects (e.g., white hats) as being beams. Thus spurious triggerings of sounds sometimes occurred.
- **Changes in background illumination:** since the event was held in a tent, light coming through the ceiling fabric varied, meaning that that the representations of torches built during training differed significantly from the descriptions extracted from the image sequence. This caused recognition errors and so inappropriate audio responses.

- **Unknowingly triggering sound:** sound is triggered by the torch in some way but either without the intention or knowledge of the user.
- **Inexplicable:** breakdowns that were difficult to tie causally to other events.

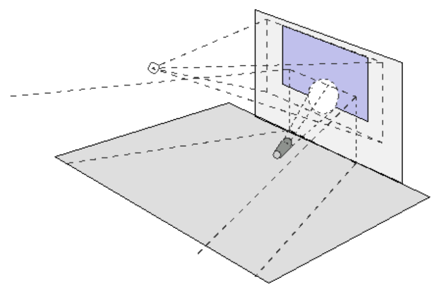

Figure 10. Mapping the spatial character

Finally in this section we can consider what happens when these two spaces – 'interference' and 'interaction' – exist as part of the same system. The resulting superposition of these different spaces creates a complex spatial identity, circumscribed by the varied tolerances of the vision system, environment and the torch. We can see an approximation in Figure 9 and a plan view in 10, which perhaps go some way to visualizing the interaction between these spaces. Obviously these diagrams cannot easily convey the sophisticated reality of the space's character, and at this point we should consider the rather nontrivial job faced by users of this space, particularly exemplified by Jenny's difficulties with the torch in the first vignette. The static space shown in Figure 9 alone would be a job of work for users to navigate and succeed in interacting successfully with the interface without cues, however the reality is that the exact boundaries of the interference and interaction space shift with the factors we have examined thus far. So, the user must manage this shifting character and the contingencies it produces in order to succeed with their interaction: e.g., ensuring they use the torch approximately 'here,' that no-one is obstructing the torch over 'here' in front of you, and that no-one is obscuring the camera 'here,' and so forth. As such, the design of the space places these concerns in the hands of the user (namely, Rachel) to manage. (We will consider a design of space that places these concerns in the environment later on in this paper.)

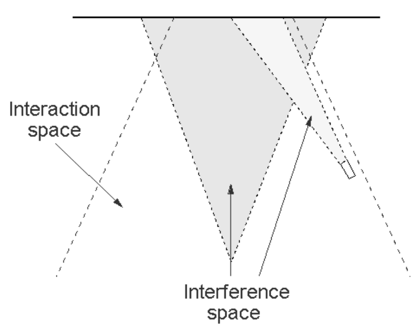

Figure 9. Mapping the spatial character (plan view)

The breakdowns and repairs we have discussed were contingent upon the configuration of the interface and the flexible and dynamic use of space during the storytelling. Studying breakdown and repair has made visible certain attributes of this spatial configuration and its relationship to interface design, when combined with the social interaction that takes place within this setting.

Adaptation

We have briefly examined breakdown and repair, and their relationship to the spatial character of the sensor system, however, we have not thus far addressed how this spatial character was adapted to. Some forms of breakdown were relatively simple to link to a cause and therefore avoidable, whereas others of a less obviously causal nature were harder to avoid. A particular set of strategies developed as a result of both repeated experience and through Rachel's knowledge about the system. This section will examine these in detail, retaining particular focus upon Rachel's adaptation.[3]

For the final vignette, we now join a group with three children that are about to return to their spaceship after exploring the planet (Figure 11). Peter, Tom and Rachel along with Jenny from the first vignette have started to congregate near to the wall, having just found the "gold" they were looking for in their exploration.

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T: (Walks across the space, shining his torch on the wall.)

R: Okay what we need to do is, if we speak really nicely (Walks over to gold.) and we wish it off okay? Come close. Okay what we need to do is we need to wish the gold off.

T: I wish I wish the gold was here.

R: Okay let's do that sounds good ready do we have to close our eyes Tom how do we do it?

T: <indecipherable>

R: Okay ready one two three all close our eyes I wish I wish the gold was here ahh (Takes gold from the wall.) woow! Okay, Alice I'm going to keep you in control of the gold.

T: (Has the torch beam pointed at the alien planet, and the sound of the aliens is triggered.)

P: (Darts his head around.)

R: What we need to do before the aliens come we need to get back into the ship (Points at ship) Everybody back to the ship!
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[3] The children's adaptation to the technology is an issue we note, but our analysis will focus upon Rachel's experience.

Figure 11. Finding the gold (left), running back to the ship (right)

Here the sound is triggered accidentally by Tom, the result of which (i.e., the alien sound being heard) is reconfigured by Rachel as part of the story, indicating that they need to "get back to the ship" before aliens arrive. Rather than marking the unexpected sound as a breakdown, Rachel transforms it into a resource for the story. The interesting point shown here is the way in which breakdown was sometimes deftly and rapidly managed and adapted to rather than disrupting the story completely. This sequence also illustrates that breakdown may not always be the result of technical failure such as light levels, obscuring the targets or getting in the way of the torch beam.

Breakdown was at times very difficult to predict, as shown in this sequence. This was usually due to both the difficulties in controlling all children in the space and the anomalous nature of some breakdowns. Rachel was often able to weave the glitches into the story, as seen with her reaction to Tom's accidental triggering of the alien sound. Anomalously triggered sounds were repurposed and transformed, folded back into the ongoing story, and sometimes provided a sense of spontaneity and excitement. Such misplaced sounds became resources for further actions, and were recontextualised with respect to the orientation of the group. Rachel also sought to verbally complete those sounds that were interrupted halfway or stuttered to a halt. On the other hand, there were breakdowns that were too disruptive or 'unweavable' to fold back into the story. As a result these breakdowns caused the story itself to come to a halt, or at least slow down. Subsequently, further attempts to correct the problem might be made with the torch, as exhibited by Rachel's instructing of Jenny to move progressively away from the wall. However, at other times the breakdown was directly followed by some very rapid consultation between Rachel and the team in order to decide whether the failure was terminal, or whether another attempt should be made with the torch. Another strategy employed here in the case of seemingly unmanageable breakdown, was to simply ignore the breakdown and continue with the next part of the story.

We must also consider that some other strategies were employed to pre-emptively avoid or manage breakdown altogether. For example, breakdown could be repaired by completely avoiding interference space, or avoiding certain forms of interaction with the interface. Knowledge about this came through information reported to Rachel about the interface's workings from the research team at the event. This measure was an avoidance strategy that involved restricting the space in which children sat or walked around in (i.e., interaction space). Figure 2 (left) shows two circle placements for the spaceship formation; initially Rachel seated groups in circles on the edge of the interaction space (as in the vignettes), meaning that the beam of the torch became oblique and distanced, thus affecting the vision system by both the distortion of the beam and the potential problems with high light levels. Through discussion with the research team at the event, it became clear that Rachel needed to conduct the spaceship circle in a more central location in order to overcome at least the obliqueness problem and so the groupings migrated towards a particular spot in the centre of the space.

A further problem was caused by children entering into the space of interference. Typically this would occur when children stood up and moved close to the wall, obscuring the targets or perhaps flagging themselves up as a false beam. This was overcome to some extent by the team informing Rachel about the issue of obscuring the camera's view, and so children could be directed to maintain a reasonable distance from the wall. A piece of tape was also placed on the floor in front of the wall (see Figure 1, top, labelled 'tape marker') as a kind of guide to the boundaries of interference; its placement was based on the closest distance a child of average height could stand from the wall without obscuring any targets. This mark provided further resources beyond directions such as "don't stand too close to the wall," and instructions to move back. As such the action could be planned around these markers pre-emptively rather than reflexively dealing with interference.

There were other ways in which adaptations took place over the course of the two days. We stress that these adaptations developed over time, constructed into an effective working body of knowledge about the torch technology in situ. These adaptations developed the telling of the story around the contingencies of the technology and the experiences of repair, just as the technology in use was shaped to fit the contingencies of the storytelling. This resulted in some of the following essential elements:

- **Managing interaction on boundaries:** avoiding situating the spaceship circle near the edges of the space; making sure torch users were not standing too far away, too close or at too oblique an angle. All of these have been seen in Jenny's troubles at the wall.
- **Constraining movement in the space according to context:** in the spaceship circle, torch use meant that children were instructed to sit down if they had stood up; during exploration of the planet, closeness to the wall was avoided.
- **Using the torches only at particular times and in particular ways:** Rachel began to abandon more 'free' torch use during the exploration phases because of

increased experience of breakdown. Torch use in the spaceship also circle became regulated by turn-taking.

Adaptations, breakdown and repairs were for the most part essentially spatial in character, and autochthonous in that they were exhibited and generated by the arrangement of technology and participants in the space. An appreciation of the complexities of this space had to be developed and managed by Rachel during the storytelling. As we have seen, some of the adaptations to this spatial character were due to explicit information or rules about the technology, such as "keep in the centre," "don't let children get too close to the wall" and attending to the position of the children with respect to the tape marker. Other adaptations were through a developing appreciation for the interactions between the 'interference' and 'interaction' spaces, effectively building up a working body of knowledge relating to the character of the space in general. What is important to note here, then, is the way in which the simple positioning and design of the space fundamentally impacts this character of the space, and the appreciation for it.

DISCUSSION

In our study, we have examined a very simple instance of a sensor system, in which the role of camera and torch occlusion primarily featured. In spite of this, however, a rather complex underlying structure was revealed. It is reasonable to assume that ubiquitous computing systems and their myriad sensors could produce vastly more sophisticated and subtle spatial characters of interference and interaction, and it is with this in mind that our study gains relevance with respect to user-sensor interactions. In this section we shall briefly examine, within the context of the framework we have developed, other sensor-based systems in which spatial character is a component, and the various ways in which problems were or were not overcome.

The canonical "seamful" example put forth in [3] was a simple game in which players, equipped with Wifi-enabled PDAs, collected resources ("coins") distributed within their vicinity (in a city) and uploaded them when in (Wifi) network coverage. Wifi coverage can be somewhat patchy, meaning that locating interaction space can be only sporadically successful. Players' PDAs built up a map of this coverage as they played the game, so that players developed an understanding of locations to upload coins (i.e., Wifi hotspots). Thus the spatial character of the network as experienced by players was exploited and repurposed as part of the game. For a game without such revealing of spatial character or one that does not in some way manage these interaction spaces for the player, patchy coverage could create serious breakdown. This problem was sidestepped by using breakdown an unpredictable element in the game. The spatial character of this game arena was thus experienced as very much part of the game's dynamic as players 'discovered' network coverage.

Can You See Me Now? (CYSMN) was a mixed reality game played between online players faced with a map of a city, and runners on the ground in the city itself. Online players navigated the virtual map as the runners, equipped with GPS units and PDAs with which to see the online players' locations, attempted to catch the online players by physically getting within a few metres of their virtual location. Of particular interest was the way in which runners on the ground exploited and manipulated the inaccuracies of GPS in order to ambush and catch online players [5]. For example, runners sometimes relied on 'hiding' in the GPS 'shadows' created by buildings obscuring satellites in order to obfuscate their position from online players until the last moment, when runners would then spring out from the shadows and ambush unsuspecting players. In this example, again, spaces in which interaction is impossible (i.e., GPS shadows) became an exciting and special dynamic within the game, deepening the playing experience rather than being a source of breakdown for runners and players to constantly repair. Here the spatial character was created by the contingencies of GPS coverage; this was experienced for runners as a developing "body of knowledge," informing them of, for example, 'good' times of day for being in particular locations and appropriate places to 'hide.'

Savannah [1] was a GPS-based educational game that involved (teenage) players assuming the role of 'lions' roaming a virtual savannah (a playing field), and receiving information on PDAs via a simple interface. The savannah was 'contoured' with virtual regions of different terrain, within which might also be some prey to feed on; players needed to traverse this unmarked flat space of the field in order to locate the prey. The game was also collaborative in that in order to fell larger prey (such as wildebeest), several players had to coordinate an attack within the same region. Analysis of the game described how the invisibility of region boundaries (and occasionally the uncertainties of GPS) caused discrepancies between participants' views of the action, and thus their ability to coordinate attacks successfully. Players would typically stop on the boundaries, and, when a cluster of co-players began to form around them, half would be inside the boundary of the region, and the other half, outside. The Savannah environment was 'flat' rather like the environment of the Journey into Space; whereas the Journey into Space's environment was shaped and given spatial character by the qualities of the camera and torch, Savannah's space was shaped by the combined qualities of GPS and prescribed regions as experienced via the PDAs. Whilst interaction space for Savannah players was largely all-pervasive and consistent (unlike the previous examples of sensor technology such as Wifi and GPS in use), players' appreciation for their spatial whereabouts within this interaction space was problematic. Players encountered difficulties in this featureless environment precisely because the boundaries between regions were exposed to the player only in one dimension, i.e., as a point. This vastly reduced the resources available to the player and co-players in their coordination of attacks. The design implications drawn from Savannah eschewed a design that revealed the terrain of the interaction space (i.e., exposing the region boundaries to players) in favour of invisibly extending the region around players when performing a collaborative attack, thus shielding them from the effects of differing views due to standing on the edge of regions problems.

The examples so far have all been games, whereas the Journey into Space was a storytelling event. At this point we consider MIT Media Lab's Kidsroom [2]. This was a vision-driven experience in which children were guided through an adventure story by computer-generated characters projected onto the walls of a large room. This room was furnished with a bed, a chest of drawers, rugs and so forth. During the story, the children were required to perform actions (such as pretending to use a bed as a boat, hiding behind a piece of the furniture, or dancing on a rug) in the space that were then detected by the vision system. There were several points in the story when participants had to be guided into particular spaces of interaction for the purposes of detection, such as being directed towards particular rugs, or all moving onto the bed that was in the room. Due to the need to detect the participants performing certain actions (such as dancing), the spaces of interaction were mutable, sometimes covering a small mat, at other times covering a bed and again at other times the whole room (in the case of hiding away from any camera). These moments were managed by coaxing children, as part of the narrative of the story, to the appropriate interaction spaces and away from the interference spaces that might obstruct detection by the system. For example, care was taken when creating the script for the projected creatures guiding the children through the experience, such that instructions about these spatial requirements were woven into the spirit of the story. The spatial character of the room created by the sensor technology was thus not revealed to participants but was rather worked into the narrative in an endogenous fashion so that the children could be guided into the correct places.

These examples illustrate a range of approaches to the ways in which interaction and interference spaces are handled and presented (or not presented) to the user. The seamful game fully exploited and was designed around these spaces, meaning that breakdown was from inception employed as a purposeful and valid game feature. Runners' work in CYSMN also exploited the spatial aspects of sensor technology, however this was not designed as part of the game or particularly exposed, but was rather an emergent feature of the practical outworking of the game. Similarly, in Savannah, the exact spatial character of the field was only partially exposed and yet suggested solutions indicated that this character could be hidden from participants, and an approach that guided players through the contingencies of the spatial character would be most appropriate. For the Journey into Space event the interaction space was partly exposed in breakdown during the storytelling, and yet partly hidden by the adaptations made in order to manage these breakdowns. Thus it occupies some ground between Savannah and Kidsroom. For Kidsroom, participants were very much guided around interaction and interference spaces by the system, in order to hide the spatial character of the room from them. This 'hiding' was achieved through accounting and designing for interference and interaction spaces.

We therefore can construct a simple axis (Figure 12). At one extreme end interaction and interference spaces are revealed to users who are expected to fully manage breakdown as part of their interaction, whereas at the opposing end, such interaction and interference spaces are hidden from the users, and they are guided through the spatial arrangement by the system in some way. Towards the centre are systems in which spatial aspects of interaction and interference are partially revealed, however users are provided with some system support to resolve breakdown.[4]

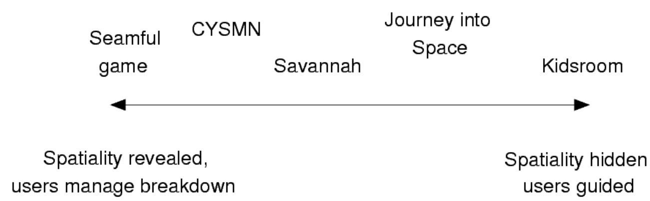

Figure 12. A spectrum of spatial character

DESIGN IMPLICATIONS FOR FUTURE WORK

As a result of our study and subsequent comparison with various other sensor-based systems, we have illustrated the importance of considering the spatial character of such systems when designing them. In particular, identifying the relevant interaction and interference spaces produced by placing sensors in a space is vital to understanding how interaction within that space will unfold.

The design spectrum we have presented admittedly does not point in any particular way to the times when revealed ('seamful') or hidden ('seamless') design strategies will be most appropriate. The analysis of the Journey into Space, for example, has shown how a performance-like environment can suffer from breakdown induced by a structure that is not revealed to the users, and yet at the same time has illustrated how repair and adaptation to that mostly-invisible spatial character can develop, and result in (at least) limited management of breakdown. As such a redesign of the Journey into Space could conceivably take either design route; the spatial character could be further revealed by barriers to stop participants getting too close to the wall, or on the other hand the spatial character could be further hidden, perhaps by providing the storyteller with a more developed understanding of the space that enabled them to

[4] We note that this spectrum places systems involving younger children towards the right, whereas the left features systems involving adults or older children. It is possible that this fact has implications for the use of the different strategies.

manage its spatial character and thus guide users through it in a more graceful manner.

In addition to this, there is the issue of the cognitive ability of different varieties of users to deal with seams. The users in the case of the Journey into Space and Kidsroom were young children, whereas the other examples cited involved teenagers or adults. It is thus possible that different design strategies could be appropriate for different demographics of users; for children, a designer may wish to intentionally hide seams for pedagogical reasons, or perhaps in order to create certain forms of experience, such as a "magical" system where the effects produced by the interface are exposed, but the underlying structure is hidden from the user.

The primary intention of this paper has been to identify the spatial character of sensor technology and as such, in order to make stronger recommendations about the use of design strategies along the spectrum, further work is needed.

CONCLUSION

In this paper we have uncovered several key design issues that directly relate to the deployment of sensor-based technology in public places. A central and recurrent notion has been the *spatial character* of a sensor space. This spatial character and has been shown to be the production of a complex supposition of various technological attributes when sensor technology is placed in a real world setting. Breakdowns, repairs and adaptations make the spatial character of interaction visible. The cohort of technological attributes become embedded in the space and therefore construct this spatial configuration that is then experienced as phenomena in social interaction within the space.

Initially we drew on ubiquitous computing's notion of 'invisibility' and seams, and the current critiques this has been subject to. Through analysing a sensor-based system in situ, the essential spatial character of interaction and interference spaces was exhibited by breakdown, repair and adaptation.

This spatial framework was then applied to comparatively analyse several other systems in which sensor technology formed a central part of interaction. A simple spectrum of design was then formed from this, contrasting system designs in which sensor spatiality is revealed to designs in which such spatiality is hidden and users are protected.

Finally we suggested that designers using sensor systems might consider the complexities of the spatial character generated by sensor devices in considering the interference and interaction space model, and briefly examined the relative merits of hiding and revealing these to users.

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