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An Investigation of Collective Human Behavior in Large-Scale Mixed Reality Spaces

Abstract

Future mixed reality systems will need to support large numbers of simultaneous, nonexpert users at reasonable per-user costs if the systems are to be widely deployed within society in the short to medium term. We have constructed a prototype of such a system, an interactive entertainment space called Ada that was designed to behave like a simple organism. Using Ada we conducted two studies: the first assessing the effect of varying the operating parameters of the space on the collective behavior and attitudes of its users, and the second assessing the relationships among user demographics, behavior, and attitudes. Our results showed that small changes in the ambient settings of the environment have a significant effect on both user attitudes and behavior, and that the changes in user attitudes do not necessarily correspond to the environmental changes. We also found that individual user opinions are affected by demographics and reflected in overt behavior. Using these results, we propose some tentative guidelines for the design of future shared mixed reality spaces.

1 Introduction

1.1 Background and Motivations

Most current virtual reality and augmented reality systems use multichannel video displays and sound output to give the user a sense of being present at an alternate location or in a complex data space. Existing work in computer graphics has elucidated some of the relevant scene rendering parameters for maximizing presence (Cho et al., 2003), as well as various enhancements of both visual and sound modalities to enhance the sensation of presence. Such enhancements include immersive multiscreen surround projection, 3D stereo point-of-view projection (Hubona, Wheeler, Shirah, & Brandt, 1999) sometimes combined with head mounted position and orientation tracking), head mounted or hand held displays with superimposed data representations (MacWilliams et al., 2003), spatialized audio output, and so forth. Some systems add the modality of touch to further improve both the subjective sensation of presence and task performance (Basdogan, Ho, Srinivasan, & Slater, 2000; Sallnäs, Rassmus-Gröhn, & Sjöström, 2000).

While these methods are known to provide benefits for the sensation of presence, it is not known if collectives of nonexpert users can use such systems. Most of the above-mentioned methods for enhancing presence are not yet

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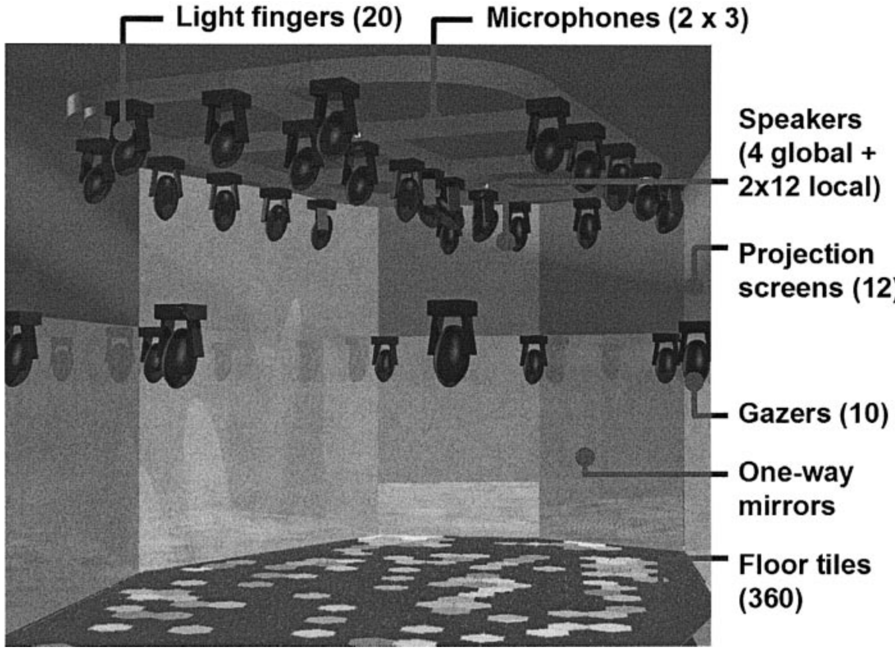

Figure 1. *Layout of components in Ada main space. From Eng, Klein, et al., 2003.*

suited for such large-scale deployment in populations of nonexpert users, as they typically have high per-user costs, and they require each user to wear or carry an (expensive) object such as a head mounted display, a tracking device, a joystick, or a personal digital assistant (PDA). Each user may also be required to be alone in a purpose-built room with high-resolution tracking systems and surround projections. In the short to medium term it will only be possible to expose large numbers of nonexpert users to immersive virtual or augmented reality environments that require an absolute minimum of specialized hardware for each individual person. Such constraints probably reflect the future reality of urban life more than scenarios where everyone has access to personal head mounted displays or personal CAVEs. To minimize the cost per user, such multiuser systems will be characterized by:

- Shared physical space
- Shared sensors and output hardware
- Multipurpose environment

We created such a space, an exhibit called Ada, which ran for 5 months during the Swiss National Exposition in 2002 and received 553,700 visitors from the general public. Ada is a multipurpose interactive space, conceived as an artificial organism, that is designed to engage visitors in entertaining interactions (Eng, Baebler et al., 2003; Eng, Klein et al., 2003). The space has also been used as an auditorium for an awards ceremony and as a disco. Ada's input modalities include visitor tracking using pressure sensitive floor tiles (Delbrück, Douglas, Marchal, Verschure, & Whatley, 1999) over a 160 m^2 floor area (Figure 1), detecting and localizing handclaps and simple sounds such as the spoken word "Ada" using two sets of three microphones, and capturing video in real time using ten pan-tilt cameras called *gazers*. Output is provided by local and global speakers, pan-tilt "light fingers" for illuminating selected visitors, colored neon lamps in the floor tiles, and BigScreen: a 360° projection surrounding the space that can show dynamic 3D objects and live video on a single virtual display. The system is controlled by a distributed mix of agent-based software, simulated neural networks and procedural code on a computer cluster (30 AMD Athlon 1800+).

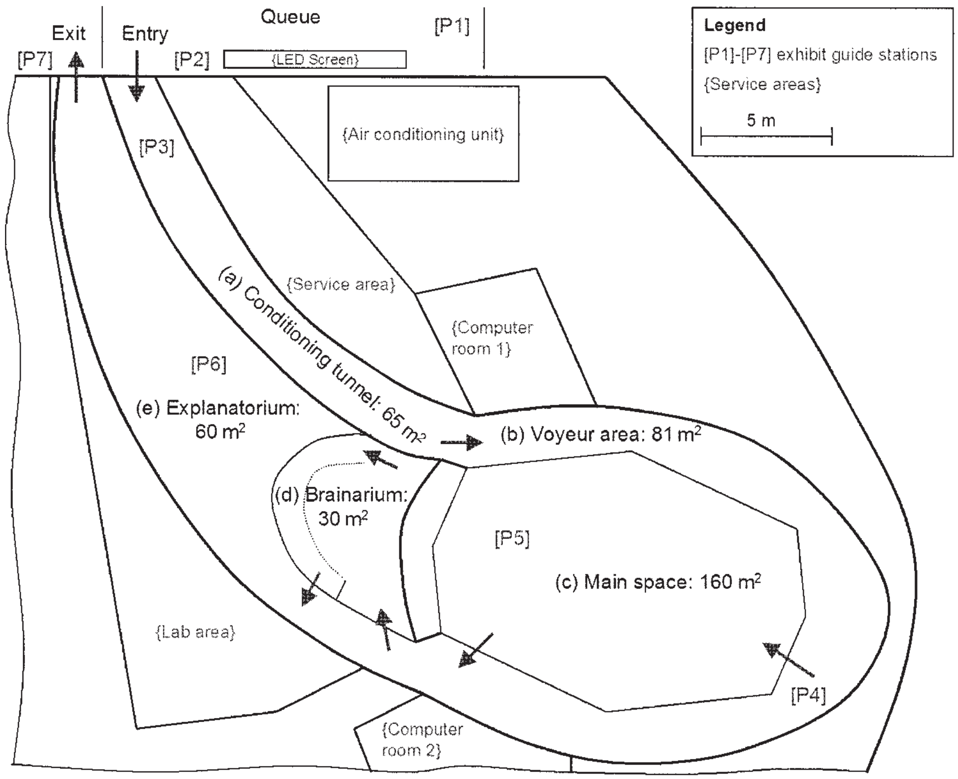

Figure 2. *Floor plan of the Ada exhibit. Arrows indicate visitor flow. Stations for exhibit guides are indicated by P1 through P7. The total publicly accessible floor area of the exhibit was 396 m^2. From Wassermann, Manzolli, Eng, & Verschure, 2003.*

The visitor flow (Figure 2) was controlled to guarantee a certain quality of visitor experience and throughput. Visitors queued for up to 90 minutes at the entrance, reading an explanatory leaflet and viewing a 10-minute video about Ada called *Brainworkers* (Zünd, 2002). They entered in groups of about 25–30, passing first through the *conditioning tunnel* with several interactive stations that introduced Ada's sensory and motor components. They then waited behind one-way mirrors in the *voyeur area*, observing the group in front of them in Ada's main space. Once it was their turn, they interacted with Ada before heading into the *brainarium*—an area where they could view real-time displays of Ada's internal states and see how they correlated with the actions of the following group. Finally, visitors entered the *explanatorium* area, featuring artistic and social discussion elements. Visitors spent about 5 minutes in each section, for a total stay of about 25 minutes.

Although Ada could support many interaction scenarios, the contractual exhibit requirements dictated a minimum level of "normal" Ada functionality. Hence the user interactions in the main space were built on six behavioral modes (Table 1) presented in a fixed visitor cycle of about 5–6 minutes in length, with interaction-dependent timing variations.

1.2 Ada, Mixed Reality, and Presence

Ada is a large-scale, multiuser interactive space, but where does it fit in the taxonomy of virtual reality systems? While Ada does fit one classical definition of a virtual reality system as being a means for humans to visualize, manipulate, and interact with computers and extremely complex data (Aukstakalnis & Blatner, 1992), it does not represent an external reality. Rather, it communicates with its users using what we call *reality-based*

Table 1. *Summary of Ada's Behavior Modes, Ambiences and Interactions**

Mode/length	Ambience and Interactions
Sleep 35 ± 3s	*Floor:* Blue, slowly pulsating *Screen:* Dark blue, slow upwards-drifting texture *Sound:* Soft, low-pitched soundscape *Interactions:* Blue transient pulses on floor and "splashing" noises in response to walking. Transition to *Wake* when visitors clap their hands while Ada is in "light" sleep.
Wake 24 ± 1s	*Floor:* Rapid change to bright yellow, then slow fade *Screen:* Bright yellow texture *Sound:* Higher volume, pitch *Interactions:* Tracking assigns colored tile to each visitor. Handclaps localized by briefly drawing halo around each clap source.
Explore 103 ± 8 s	*Floor:* Light gray *Screen:* Light brown rock texture *Sound:* Bright, open *Interactions:* Periodic "compliance" testing by deploying blinking white tile cues in front of visitors; those visitors who followed the cues for long enough were rewarded with a pulsating ring of tiles, light fingers, and a gazer that followed them around. In addition, live video, still snapshots, and the tracked path of the visitor were displayed on BigScreen in a position aligned with their direction of motion to maximize their chance of being seen. This simple viewpoint registration method is broadly similar to those found in augmented reality systems (Klinker et al., 1997).
Group 33 ± 6 s	*Floor:* Black *Screen:* Dark gray/black background, bright green highlights *Sound:* Foreboding *Interactions:* As for *Explore* Cue learning experiments were occasionally carried out during this mode, in which Ada tried to learn the most effective cues for influencing visitors' positions (Eng, Douglas, & Verschure, 2005).
Game 64 ± 10 s	*Floor:* Green, red borders *Screen:* Yellow/orange texture *Sound:* Lively, loud *Interactions:* Visitors try to step on a bouncing animated tile "ball."
End 35 ± 2 s	*Floor:* Red traveling waves towards exit *Screen:* Dark red/orange downwards-drifting texture *Sound:* Soft, sad *Interactions:* Animated white tile "bullet" cues direct visitors to the exit. Switch back to *Sleep* when last visitor leaves.

*Mode length ranges are shown as mean ± standard deviation.

metaphors that match what humans are accustomed to in real life: persistence of objects represented on the floor and the screen, Newtonian mechanics to provide "wave-like" effects and visual object motion and collision, colocation of visual events and their related sound effects, etc. It does provide basic reality augmentation—visitors can see their tracked path project on the screen in a display window that moves to match their walking direction—but since Ada is a physically immersive space, there is no "everyday" reality to augment. It was not possible to visit Ada remotely in a telepresence mode (Minsky, 1980); however, "virtual visitors" could be generated within the system to inhabit the floor space. These attributes of Ada mean that it does not seem to fit easily into the three-dimensional "transportation," "artificiality," and "spatiality" taxonomy of shared spaces proposed by Benford et al. (Benford, Greenhalgh, Reynard, Brown, & Koleva, 1998); in this scheme Ada would rate as highly artificial (no representation of external reality) and moderately spatial (some representation of relative positions in space), but the level of transportation is unclear since Ada represents its own abstract data space rather than a "real" environment. The concept of "spatiality" is also somewhat problematic in Ada, since the physical space of Ada is obviously highly "spatial" as a representation of itself. We suggest that the best available definition of Ada is that of a mixed reality space: a merging of real and virtual worlds to produce a new environment where physical and virtual objects can coexist and interact (*Mixed reality definition—Wikipedia,* 2005).

The measurement of presence in a space like Ada can be expressed as the extent to which users acknowledge that Ada is a computer-based social actor (Nass, Moon, Fogg, Reeves, & Dryer, 1995; Nass, Steuer, & Tauber, 1994) where the medium of Ada as a whole behaves as a social actor (Lombard & Ditton, 1997). The design of Ada explicitly expresses the idea of a social actor, with innate goals and an internal emotional model (Wassermann, Manzolli, Eng, Verschure, 2003). Users express this acceptance of the presence of Ada implicitly through their behavior (Hallnäs & Redström, 2002) and explicitly via their responses to questionnaires, which we tested using a question about the extent to which visitors perceived Ada as a kind of creature (see Methods I).

The experimental part of this paper is divided into two sections. The first section examines the extent to which Ada's visitors acknowledged it as a social presence, and explores the relationship between Ada's operating parameters and the attitudes and behavior of its visitors. The second section investigates the effects of visitors demographics on their attitudes and probes the extent to which individual attitudes are reflected in behavior. This is followed by a discussion of the implication of the results for the design of future large-scale, mixed-reality spaces.

2 Experiments I: Collective Human-Space Interaction

Generating the sense of presence of Ada as a medium requires coherence between the modalities being presented to the user. This is achieved using its emotional model and the reality-based metaphors described earlier. For users to discover this coherence, they need to actively explore the environment. This leads us to generate the following hypotheses:

1. *Hypothesis I.1:* Reductions in Ada's output coherence by reducing the level of one of Ada's output modalities should decrease reported presence levels and affect activity levels.
2. *Hypothesis I.2:* Reduction or removal of an output modality should reduce the reported effectiveness of that modality.
3. *Hypothesis I.3:* Excessively high user density should decrease activity and reported presence, since the density of other users will affect both the visibility of Ada via occlusion and the space available for individuals to interact with Ada. Conversely, low visitor density should increase activity and reported presence levels.

2.1 Methods I

Experiments were based on a standard control case and a set of small deviations from this case, in order to minimize any disruption to normal exhibit operation.

Table 2. *Ada Questionnaire Demographic Measures and Available Options*

Demographic measure	Available options
Gender	Male, Female
Age (years)	10−15, 16−20, 21−30, 31−40, 41−50, 51−60, 61+
First language	German, French, Italian, English, Other
Education level	Basic schooling, Completed high school, Apprenticeship, Technical training, University degree, Doctorate
Education type	Technical, Natural sciences, Arts, Social sciences, Business, Other

Floor tracking and floor occupancy data, audio processing signals and MPEG-4 video data were recorded from Ada (up to 5 GB/hour). A timeserver synchronized timestamps across the cluster to within 100 ms. Analysis was performed using Matlab 6.1 (Mathworks, MA, USA) and SPSS 11 (SPSS Inc., IL, USA).

Public preexposure to Ada consisted mainly of a mass-media advertising campaign (TV, print, web), in which prospective visitors were told that Ada was an "intelligent" space with a distinct identity. This framing may have influenced some visitors to expect to encounter a kind of entity, but anecdotal evidence suggests that almost all visitors had very little idea of what to expect from Ada before arriving at the exhibit.

Questionnaires were distributed to specific groups of visitors in their choice of German, French, or English (the first or second language of virtually all visitors) as they exited the main space. Because our audience consisted of the general public of any age, we opted for a very general phrasing of the questions rather than a specialized presence questionnaire (e.g., Lessiter, Freeman, Keogh, & Davidoff, 2001). Participation was voluntary, and a majority of visitors agreed to participate. Observers were on hand to ensure that visitors did not discuss or copy each other's answers. Almost all visitors completed the questionnaire within 5 minutes. The first section of the questionnaire collected demographic information (Table 2): the gender, age, first language, education level and main education type of the participants. The second section required visitors to respond to a set of statements about their interactions with Ada, with responses given on a ten-point scale (Table 3). The statements fell into four categories: Ada's sensory abilities (Q1−3), Ada's reactions to visitors' actions (Q4−7), perceptions of visitors' own reactions to Ada's actions (Q8−12) and overall impressions of Ada (Q13−16). Question 15 explicitly assessed users' opinions of the presence of Ada as a socially active medium ("I felt that Ada is a kind of creature"). Children under 10 years of age were excluded from taking the questionnaire. Questionnaires with more than four unanswered questions were discarded. Every valid questionnaire was included in the analysis, except where a single clear response to a particular question could not be ascertained. The visitor demographics in each test session were balanced as necessary by discarding randomly selected questionnaires, or by pooling results from multiple sessions with equivalent operating conditions. For analyzing the responses to the statements, the boxes ticked by the visitors were converted into integers from 1 to 10, with 1 corresponding to most "disagree" with the statement and 10 corresponding to most "agree" with the statement. The question items were analyzed separately without creating combined scales.

The experiments themselves were divided into three sections:

1. *Control case:* group behavior and attitudes under normal operating conditions.
2. *Effect of Ada operating parameter variations (test of Hypothesis I.1 and I.2):* various operating parameters of the space were manipulated to gauge their effect on visitor behavior and attitudes. Visitors

Table 3. *Ada Questionnaire Text (English Version) and Control Case Responses (N = 86)**

Category	#	Question body (response 1. . .10)	Mean	SD
Ada sensed me with:	1	Eyes	5.70	2.89
	2	Ears	6.74	2.96
	3	Skin	7.10	2.88
Ada reacted to my actions by:	4	Producing light patterns on her skin	7.25	2.59
	5	Projecting patterns on the BigScreen	5.65	2.94
	6	Projecting my image on the BigScreen	5.18	3.19
	7	Producing sound effects and music	5.50	2.87
I reacted to Ada's behavior by:	8	Moving faster on the floor	7.93	2.13
	9	Following the patterns on the floor	8.48	1.92
	10	Looking more at the big screen	4.23	2.56
	11	Making more noise	6.84	2.92
	12	Trying to imitate the behavior of visitors who seem to have Ada's attention	4.25	3.23
Overall opinions	13	My behavior was affected by Ada: (not at all. . .a lot)	6.66	2.48
	14	Interacting with Ada made me feel: (sad. . .happy)	7.86	1.97
	15	I felt that Ada is a kind of creature. (disagree. . .agree)	4.61	2.83
	16	I like Ada: (not at all. . .a lot)	7.08	2.43

*1 = most disagree, 10 = most agree (except where indicated).

did not have the opportunity to observe "nominal" Ada behavior beforehand.

3. *Effect of group size variations (test of Hypothesis I.3):* on behavior and attitudes.

2.2 Results I

2.2.1 Control Case. Visitor behavior during the control case followed characteristic patterns that were affected by Ada's behavior modes (Figures 3 and 4). During Sleep, new visitors entered the space from the lower left corner while the previous group exited via the upper left corner. Visitor-generated sonic events—handclaps and spoken events of the word "Ada"—were detected at around 0.5 Hz and 0.015 Hz, respectively. In the subsequent modes, Wake, Explore, and Group, the visitor occupancy tended towards a uniform spatial distribution, but visitors avoided the entrance area. They increased their handclap rates to ≈1.4 Hz and their spoken "Ada" rates to ≈0.02 Hz, with a dropoff during Group mode. During Game mode they spent more time in the half of the space closest to the exit compared to the other half, handclap activity dropped to below 0.5 Hz and spoken "Ada" detection increased. The distributions of tile on/off events during this mode was very different to that in Explore and Group, with two tile event rate peaks in the top and bottom half of the space. These peaks correspond to the playing fields for the games where people were moving very fast, while those standing at the borders did not generate as many tile events. During End mode, visitors accumulated at the exit and they all but stopped making noise.

The control case questionnaire responses ($N = 74$, 0 invalid questionnaires) showed that Ada's modalities elicit different visitor ratings relative to each other (Table 3). Ada's sensory modalities (Q1−3) were assigned varying importance by the visitors. All tests in this section are ANOVA (the number of degrees of freedom indicates the total number of individual responses across questions 1−3 and all control case questionnaires) $F(2, 234) = 4.29$, $p = .015$. Ada's vision was rated significantly lower than tactile sensing (all post-hocs with Bonferroni correction, $p = .013$), but equal to auditory

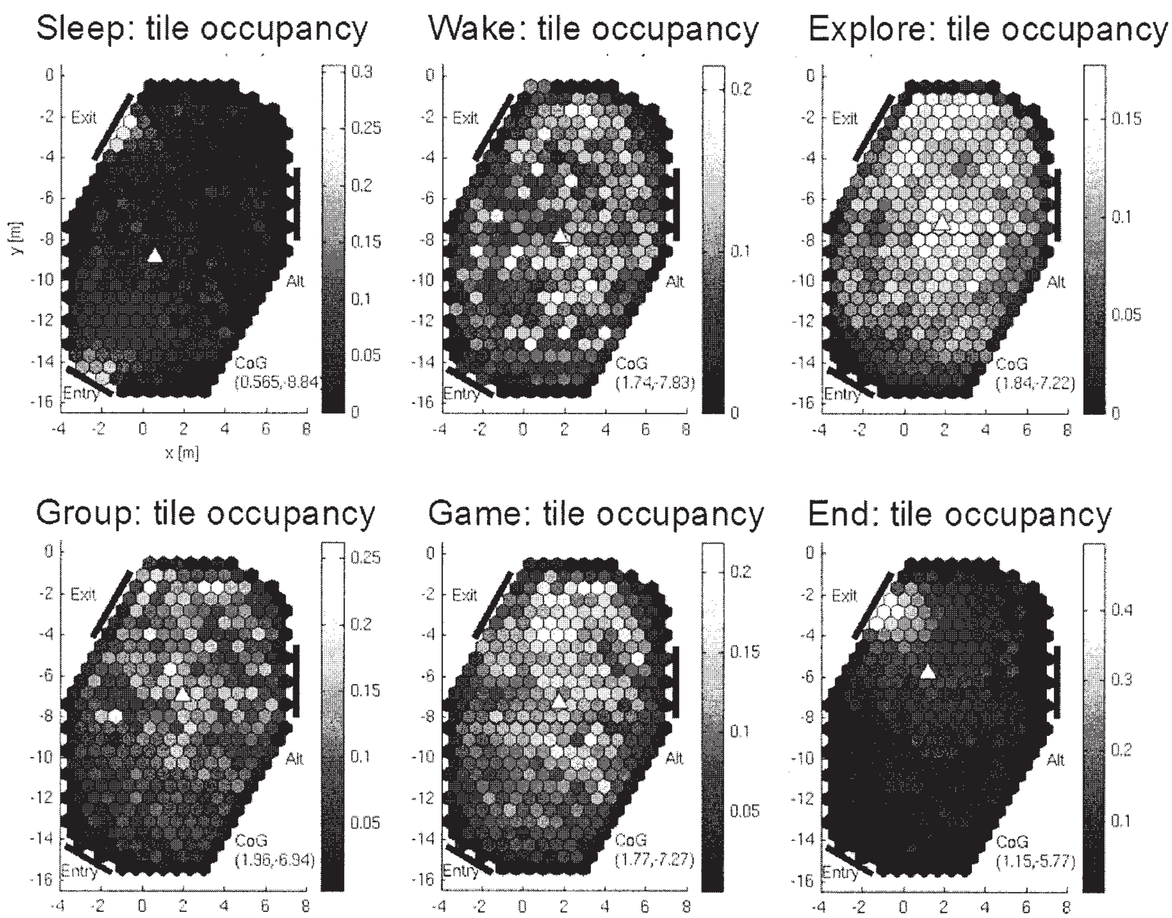

Figure 3. *Control case mean floor occupancy for each behavior mode. Averaged over 12 visitor cycles. White triangle = center of gravity of distribution. From Eng, Mintz, & Verschure, 2005.*

sensors ($p = .199$). Ada's effector modalities (Q4−7) were rated differentially $F(3, 297) = 7.43$, $p < .001$, due to the high rating of the floor output (Q4; $p < .012$ for all comparisons between Ada's floor effects and the other modalities); the other modalities were indistinguishable from each other ($p > 0.5$ in all comparisons).

Visitors claim they are very active and not imitating other visitors. Visitors' ratings of their own reactions to Ada (Q8−12) were significantly different to each other, $F(4, 388) = 45.3$, $p < .001$: the ratings were all distinct (post-hoc, $p < .011$) except the pairs of questions (Q8 and Q9, $p = 1.0$) and (Q10 and Q12, $p = 1.0$). Thus, the visitors' ratings in this section fell into three broad groups: very high (visitor self-motion, Q8 and Q9), medium (making noise Q11), and low (looking at BigScreen and imitation of other visitors, Q10 and Q12).

Some visitors thought that the interactive space had creature-like properties. The overall ratings of Ada (Q13−16) were significantly different to each other $F(3, 325) = 28.6$, $p < .001$: only the question pairs (Q13 and Q16) and (Q14 and Q16) were indistinguishable ($p > .2$), while all other pairs of questions were significantly different ($p < .005$). Visitors stated most strongly that they liked Ada and were happier after being in Ada (Q14, 16). Almost as high was their tendency to say that Ada affected their behavior (Q13), while their ratings were lowest for the statement that Ada was a kind of creature (Q15). However, the high

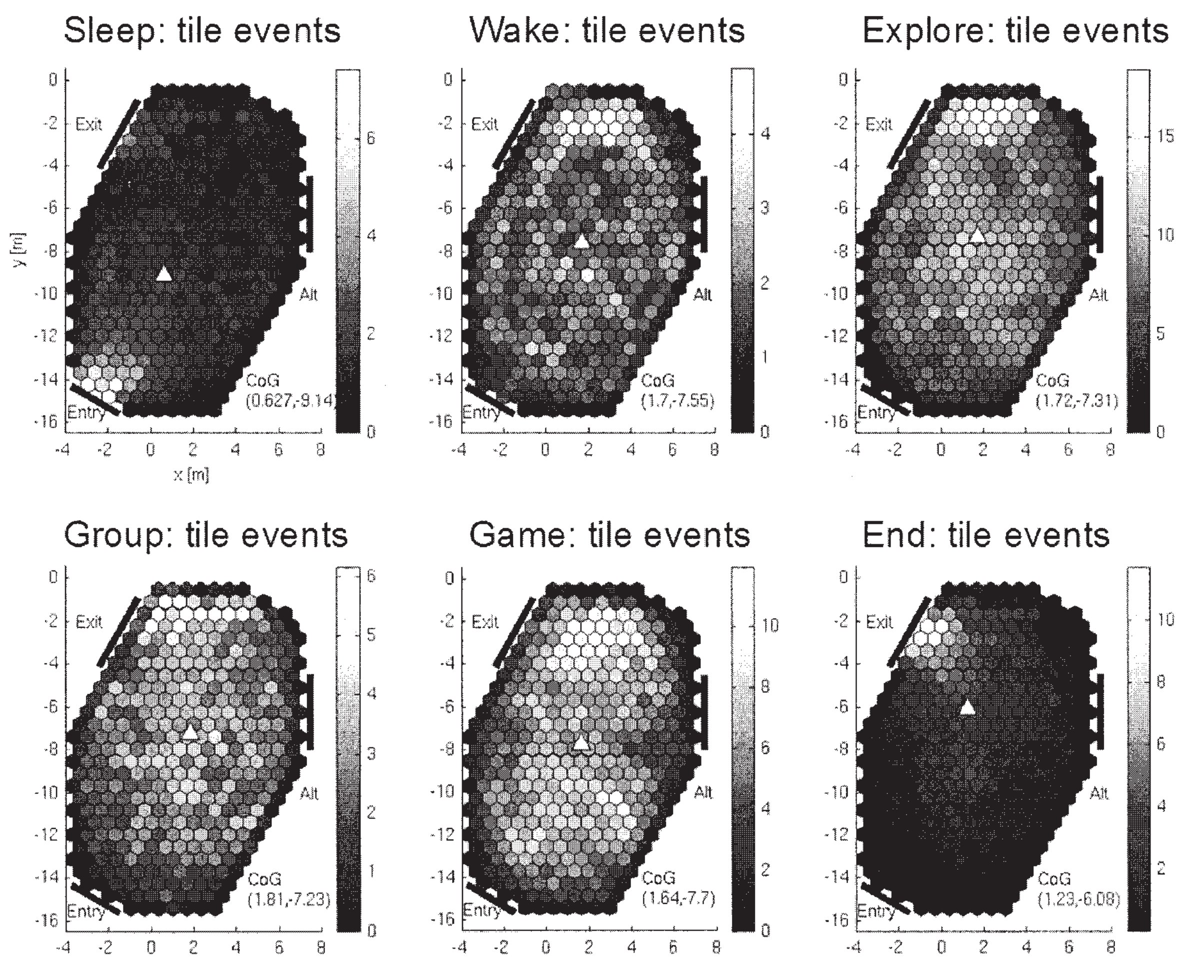

Figure 4. *Control case mean event rate for each behavior mode. Averaged over 12 visitor cycles. White triangle = center of gravity of distribution. From Eng, Mintz et al., 2005.*

standard deviation for this statement and the distribution of the responses indicate that a considerable minority was amenable to the idea that the space was acting as a unitary entity, rather than as a collection of components. This was borne out in anecdotally observed responses such as some visitors waving goodbye to Ada when they left, and messages left in the visitor guest book addressed "personally" to Ada.

2.2.2 Effects of Operating Parameters on Behavior and Attitudes.

To understand the effects of Ada's output modalities on the visitors' behavior and their attitudes, tests were run in which different output components were disabled or reduced in intensity. The questionnaire responses to the cases, and the significant effects compared to the control case (t tests, $p < .05$), were as follows:

Sound and music reduced to barely audible level (N = 136, invalid = 0): visitors' rating of Ada's hearing was lower (Q2, $p = .019$), but their rating of Ada's sound output was unchanged (Q11, $p > .1$). In addition, their rating of the role of Ada's eyes (Q1, $p = .049$) was higher, but they spent less time looking at the Big-Screen (Q10, $p = .042$). These effects had nothing to do with what actually changed: visitors seemed to be confounding Ada's outputs (the reduced sound level) with the inputs. They seemed to blame Ada's silence on deafness rather than its being mute, while attributing increased visual processing capabilities to Ada as compensation for the perceived reduction in auditory processing capabilities.

BigScreen background plain dark blue (N = 58, invalid = 0): visitors did not score the BigScreen significantly lower (Q5 and Q10), possibly since they did not know that some of its capabilities were not being used (as opposed to the sound and music in the previous case, which were being used fully but at low volume). However, they seemed to think that Ada could not hear well (Q2, $p = .022$). This may be due to visitors relating darker, more static rooms with quietness, which was then confounded with deafness as in the reduced sound case.

No gazer images on BigScreen (N = 55, invalid = 0): in this case, visitors rated the visual output lower (Q5, $p = .024$) and also looked at the output less (Q10, $p = .008$). As in the previous case, they also seemed to think that Ada could not hear well (Q2, $p = .004$). However, their response to Q6 (the "correct" BigScreen image response) was not affected—a surprising result, since they were imagining something that never actually happened! They were also less inclined to think of themselves as imitating other visitors (Q12, $p = .005$), suggesting that observation of "successful" visitors' images/videos on the BigScreen are motivating factors for imitating the actions of those visitors.

No guide instructions (N = 60, invalid = 1): as might be expected, visitors gave generally lower ratings due to the lower level of priming they received. Two of these were significant: visitors' self-assessment of their viewing of BigScreen (Q10, $p = .023$) and their own noise-making (Q11, $p = .003$). These differences imply a reduced knowledge of how to interact with Ada.

To quantify the effect of the different test conditions on the rate of visitor-generated tile events, we define the tile event rate modulation index as follows:

$$\text{Modulation index} = \frac{1}{N}\sum_{i=1}^{N}\frac{R_c^i - R_0^i}{R_0^i}$$

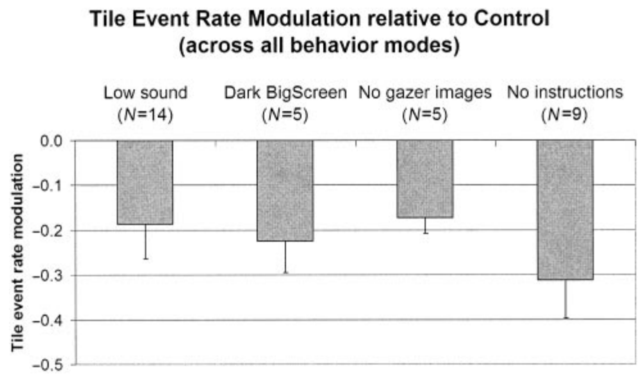

Figure 5. *Comparison of tile event rate modulation effects for different experimental conditions, relative to the control case. Error bar = one standard deviation. N = number of visitor groups tested (mean 27 visitors per group; i.e., approximately 135−378 visitors per sample).*

where N = number of behavior modes

R_c^i = mean tile event rate for test condition during behavior mode i

R_0^i = mean tile event rate for control case during behavior mode i

In all cases the changes in the operating conditions caused a highly significant reduction in the tile event rates ($p < .001$), with the largest decrease for the case with no guide instructions (Figure 5). However, the rate of detection of handclaps and the spoken word "Ada" was not significantly altered. It is interesting to note that despite this change in behavior, the visitor responses to the overall questions about Ada (Q13−16) were not significantly affected by the different manipulations to the space; that is, the degraded conditions in Ada were still good enough to elicit positive overall visitor responses.

2.2.3 Effect of Group Size on Behavior and Attitudes.

To gauge the effect of visitor density on behavior and ratings, two test cases were created with a smaller (≈15 visitors/group; $N = 76$, invalid = 1) and larger (≈32 visitors/group; $N = 77$, invalid = 0) number of visitors per group (normal group size = 27 visitors). In Game mode, each visitor generated tile events at about 1.3

Hz in small groups, 1.1 Hz in medium-sized groups and 1.0 Hz in large groups. The per-person tile event rates for the cases were distinguishable by group size, with larger groups tending to move slower (ANOVA, $p = .017$). However, the clap rate and spoken "Ada" detection rates were not distinguishable by group size (ANOVA, $p \geq .089$ and $p \geq .4$). The questionnaire responses confirmed the prediction that small groups would enjoy and understand Ada more: 14 out of 16 questions elicited a higher response (mean +0.62 points) compared to the control case, while the large group size scored lower in 13 out of 16 questions compared to the control case (avg. −0.56 points). For small groups, significantly increased ratings ($p < .05$) were found for Ada's eyes (Q1), Ada's floor output (Q4), and the perception of Ada as an entity (Q15). The responses from the larger group revealed significantly lower ratings for two questions ($p < .05$), related to perceptions of Ada's hearing (Q2) and visitors' tendency to make noise (Q11).

2.3 Discussion I

None of the manipulations of Ada's operating parameters significantly affected visitors' perceptions of the presence of Ada as a kind of creature; that is, we were unable to confirm Hypothesis 1.1. This could be because the small, unimodal changes that were made to the operating parameters were not enough to significantly disturb the overall coherence of the space. It is possible that larger unimodal manipulations or smaller multimodal manipulations may have resulted in a measurable effect, but there was considerable pressure to avoid this type of experiment due to the adverse affects on the quality of the experience for the paying visitors. However, in all cases the small manipulations did cause a significant reduction in the mean tile event rate, although this may not necessarily point to an implicit reduction in presence.

Several significant cross-modal effects were found for all operating parameter manipulation cases that did *not* correspond to the output modality that was changed—an interesting result that falsifies Hypothesis I.2. This result may indirectly support the notion that visitors treat the environment as a whole, rather than as a collection of individual input/output modalities where cross-modal effects would not necessarily be expected.

It is possible that the results observed here mean that the reductions of the output levels did not change the overall coherence of the space by very much. Other methods, such as changing the time lag of the interactions, may have been more effective in introducing severe disruptions of coherence.

A significant change in the reported presence of Ada was found for smaller group sizes, confirming Hypothesis I.3. This may reflect the improved visibility of the space due to less occlusion from other visitors and/or improved visitor interactions with Ada in terms of the compliance tests. A corresponding reduction of presence was not found for the larger group, possibly because the group was not much larger than in the control case—a decision motivated, again, by considerations of the quality of the visitor experience. An inverse relationship was found between group size and movement speed as measured by tile event rate, as would be predicted by particle-based models of pedestrian motion (e.g., Helbing, Farkas, & Vicsek, 2000). However, no corresponding relationship was found for vocalizations of the word "Ada" or handclaps for reasons that are unclear, but could possibly be related to the tendency of the sound event detection software to saturate at around 1.5−2 Hz.

3 Experiments II: Individual Effects on Presence

Different users of a shared mixed-reality space will report different levels of presence and differing attitudes in the questionnaire described in Methods I. Two factors that may be important in determining these different responses include the demographics of the individual users and their individual levels of interaction with Ada. This leads us to postulate two hypotheses:

1. *Hypothesis II.1:* User attitudes and reported levels of presence will be more positive for cases where the user has extensively interacted with Ada; that is, when they have successfully completed the

compliance testing process and seen their image projected on the screen.

2. *Hypothesis II.2:* User attitudes will vary with demographics. In particular, since Ada is a space that emphasizes whole-body movements, older (less physically mobile) people will have lower activity levels and thus lower questionnaire responses. Older people may also typically be less receptive to new technologies such as those used in Ada, also leading them to give lower questionnaire responses.

3.1 Methods II

To see if individual behavioral differences were correlated with attitudes to Ada (Hypothesis II.1), a few subjects (2–4) in randomly selected visitor groups during normal operation were classified as most active or passive by two psychologists, and asked to complete a questionnaire (Active: collected = 60, valid = 60; Passive: collected = 58, valid = 57). Active visitors were defined as those who followed Ada's cues in Explore mode and noticed their own image projected on the BigScreen. Passive visitors were those who remained largely static. All selected visitors were asked what their preferred language was (French, German, or English) before being given the questionnaire in that language. Almost all of the active visitors approached agreed to complete the questionnaire; about one quarter of the passive visitors refused to participate. The demographics of the active and passive visitor pools were selected to be well balanced.

The data from the different test cases was pooled for the analysis of the demographic effects (Hypothesis II.2). To prevent effects due to the test cases, the individual responses for each question in each test case were compared to the control case responses and excluded from the pool if the responses for that question were significantly different to the control case ($p < .05$). The result of this process was a pool of questionnaires for each individual question ($N > 600$ for each question).

3.2 Results II

Hypothesis II.1 was confirmed: the average ratings of the active visitors were higher than those of the passive visitors in 11 out of 16 questions, with a mean overall rating difference of +0.36 points. On a question-by-question basis, only one of the modality-specific questions related to Ada's 360° surround projection BigScreen (Q6, $p = .006$) elicited significantly higher responses from the active group. However, the differences were very clear for the overall questions: active visitors said that Ada influenced their behavior more (Q13, $p = .037$), they were happier as a result of their experience (Q14, $p < .001$) and they liked Ada more (Q16, $p = .003$). In addition, there appeared to be a trend for active visitors to report that Ada was a creature (Q15, $p = .087$), although this effect was not significant at the 5% level. On the other hand, passive visitors were more likely to say that they were imitating the actions of others (Q12, $p = .005$). Hence we can conclude that the extent of interaction with Ada is predictive of the levels of visitor attitudes and reported sense of presence.

Many demographic effects were found in the pooled data, confirming the predictions of Hypothesis II.2. The effects were:

Visitor ratings of the floor decrease strongly with age. The rating of the floor input and output (Q3, $N = 706$ and Q4, $N = 639$, respectively) were highly age-dependent (ANOVA, $p < .001$ for both questions). Younger age groups rated the floor significantly higher than older age groups (post hoc, $p < .05$ with Bonferroni correction), with a peak for both questions in the 16–20 year old age group (Figure 6).

Reported presence decreases with age. The responses to the statement that Ada is a kind of creature (Q15, Figure 6) were found to be age-dependent (ANOVA, $N = 637$, $p = .04$). The 31–40 year old age group gave significantly lower ratings than the 10–15 year old age group (post hoc, $p = .019$); the other post hoc comparisons were not found to be significant.

Cultural differences are evident in visitor attitudes. German speakers gave lower question ratings than other language groups. In 9 out of 16 questions, people who nominated German as their first language gave signifi-

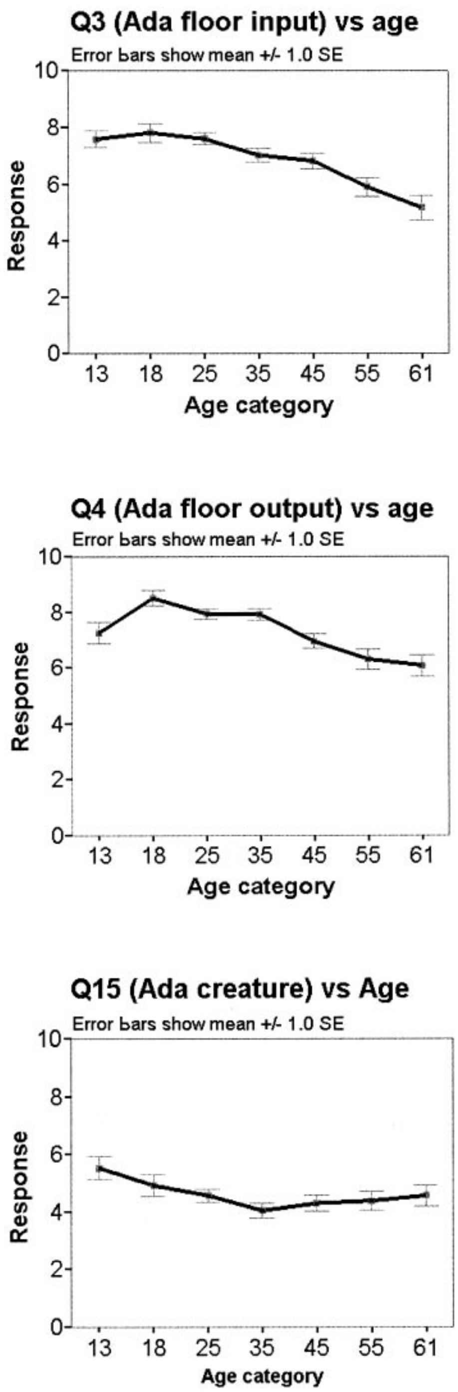

Figure 6. *Age-dependence of Ada questionnaire responses. Error bars show mean ± standard error.*

cantly lower responses compared to French speakers ($p \leq .046$ for Q11, $p \leq .009$ for Q1, Q2, Q5, Q7, Q8, Q9, Q12, Q15). In Q12 German speakers also gave significantly lower responses than English speakers ($p = .005$). No other language-dependent effects were found.

Females report higher engagement with Ada than males. Females reported increasing their movement speed more than males (Q8, $N = 682$, $p = .026$), and were happier as a result of being in Ada (Q14, $N = 671$, $p = .014$). No other gender-specific effects were found.

3.3 Discussion II

The major finding in this section is the enhanced sense of presence reported by active and young visitors. Active involvement with an artifact has previously been considered a prerequisite for enhancing a sense of presence (Hallnäs & Redström, 2002). Consistent with the *law of effect* of operant learning (Thorndike, 1911), Ada was programmed to select, test and finally engage only the most active and responsive visitors. Thus, only active visitors (covered minimum distance), with low social tameness (arrived at the center of the space) and high drive for interaction (responded to the cues on the floor) were rewarded with the "personal" interaction with Ada. The active visitors scored higher on all questions of overall attitude to Ada; they were influenced more by Ada, were happier after the experience, liked it more, and showed a trend of increased perception of Ada as a creature (i.e., higher acceptance of Ada's presence). On the other hand, passive visitors reported more imitation of the other visitors in the space. This implies a somewhat nondirect interaction with Ada, possibly explaining their lower appreciation of Ada, and lower sense of presence of Ada.

The fact that active visitors were identified by interacting with Ada means that it is possible for Ada to deduce something about the internal state of the visitor through this interaction. In other words, the compliance test can also be seen as a simple kind of "personality" test. This type of test-based interaction is important for developing interactive spaces since the results of the tests can be used as signals for allocating system resources and customizing interactions to individual users.

The demographic group that stood out in appreciation of Ada as an entity consisted of youngsters. In fact, the youngest age group of children 10–15 years old showed the highest ranking on this question. This readiness to acknowledge the presence of Ada may be inherent in youngsters (perhaps similar to believing in Santa Claus) and thus they may be particularly suited to experiences in mixed-reality space. Alternatively, their enhanced sense of presence may have been triggered by particularly attractive features of Ada, such as the floor-based interactions in Game mode and other modes, which may have been less to the taste of older visitors. This may have been why youngsters showed significantly higher appreciation for the input and output capabilities of the floor than other age groups.

The cultural differences found in the questionnaire responses, showing that German speakers gave many lower responses than French speakers, could be due to at least two reasons. One reason could be simply that German speakers tend to give lower responses to questionnaires in general, regardless of questionnaire content. The other possible reason is that there was some sort of genuine cultural bias in the visitors' opinions of Ada. The causes of this bias, if it exists, could be related to many factors including the aesthetic presentation of Ada, the nature of the interactions, the location of the exhibit (in the French-speaking part of Switzerland), and so forth. However, the exact cause was unclear.

4 Implications, Applications, and Limitations

In this paper we have shown that a large-scale, multiuser mixed reality space is able to engage with and sustain at least some sense of presence with a test user set taken from the general population. The reported sense of presence and interactions depend on user demographics, the number of users per unit area, and the ambient conditions of the space. In addition, it is possible for the space to deduce user attitudes at a coarse level by interacting with them and observing their behavior. We also observed that user interaction with a mixed reality space leads directly to an enhanced sense of presence. It thus seems reasonable to suggest that, in order to be accessible to a large number of people with widely varying backgrounds, shared mixed reality spaces need to offer interactions at several different levels of sophistication in order to draw as many users as possible into experiencing the space. These interactions need not be extremely complex, but they should provide a graded set of interactions that are suitable for different users.

At the most basic level, the results show that it is possible to judge levels of presence in a mixed reality space which supports large numbers of simultaneous users sharing the same infrastructure. The ability to predict opinions of levels of presence using only observation of overt behavior suggests that it may be possible for an interactive space to deduce levels of presence in real time without the need for physiological recording, provided that the system is suitably calibrated with groups of test users. Considering this result in the light of our work on learning to deploy maximally effective visitor cues (Erig, Douglas et al., 2005), we suggest that it may be possible for an interactive environment to learn the conditions for achieving maximum presence and/or maximally influencing user behavior. Related work has been done on automatically estimating the interruptibility of humans in office work situations (Fogarty et al., 2005).

As shown in several other studies of virtual reality systems (e.g., Slater, Usoh, & Steed, 1995; Ware & Balakrishnan, 1994), varying the operational parameters of Ada affected both user behavior and questionnaire responses. Virtually all of the effects seen served to reduce the level of reported presence and user activity. In addition, several cross-modal effects were seen, suggesting the inherent nonlinearity of these effects on behavior and attitudes. This result implies that it is important to consider the overall effect of different strategies for maximizing presence in a virtual environment, as the combined effect of the strategies will not necessarily reflect those of the individual effects. Similarly, the number of physically present users in a given area must also be considered when designing a mixed reality space.

This study is unique in its attempt to bring presence-related applications to the general population. Due to the high cost of such a study and the need for many test subjects, it is necessarily quite limited in terms of the sophistication of the sensors and effectors than can be allocated to each individual user. The partial success in generating sensations of presence within the technological limitations of these studies conducted in 2002 opens the way for future studies, using more sophisticated sensor/effector technologies that are rapidly decreasing in price, to realize more sophisticated, personalized applications with higher levels of subjective presence.

An important question about the results shown here is their generality—will they apply to all large-scale mixed reality spaces, or are they specific to the particular configuration of Ada that we used? We suggest that the nature of the effects we have seen are general, although the details of individual effects may differ in magnitude and/or sign. To go further, we speculate that similar effects will be found in all shared spaces, whether interactive or not. Verifying or falsifying these claims will require a large database of observations to be compiled on a wide variety of shared spaces in different urban settings.

5 Future Directions

In future experiments we plan to introduce several enhancements and related investigations to improve the quality of the conclusions that we are able to draw from the data, for example:

- Physiological measures to assess presence in real time (e.g., Meehan, Insko, Whitton, & Brooks, 2002; Slater, Brogni, & Steed, 2003).
- Investigations of whether the gender specificity of Ada's name and outputs affects visitor attitudes and behavior, as reported in other studies (Nass, Moon, & Green, 1997).
- Investigate the effect of time estimation on presence by adding a question to the questionnaire: how long were you inside Ada? This duration estimation can be correlated with reported presence (IJsselsteijn, Bierhoff, & Slangen-de Kort, 2001) and demographic variables.

Upgrades to the hardware and software components of Ada will also occur, and a virtual visit component will be introduced to permit interactions between real and virtual visitors. Completely synthetic visitors will also be introduced into the space to interact with real and remote visitors.

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