

Collective Human Behavior in Interactive Spaces*

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Abstract – We extend the study of human-robot interaction into the area of large-scale, multi-user, robotic interactive environments. Using our experimental infrastructure – the interactive space Ada, an exhibit at the Swiss national expo in 2002 that received 553,700 visitors – we show that human movement is predictive of key attitudes towards a space and other humans, and that subjects' behavior and attitudes are influenced by subtle modifications of environmental parameters. We also found several demographic effects on visitors' opinions of interactive spaces. These findings enhance our quantitative understanding of collective human behavior in interactive spaces and are a first step towards the construction of active environments that can automatically influence human motion and experience. This knowledge will be important in the design and construction of future interactive environments for enhancing the safety and enjoyment of shared areas for large numbers of people.

Index Terms – *human-machine interaction, interactive space, crowd behavior, human movement, human attitudes*

I. INTRODUCTION

The question of how groups of humans behave when immersed in large-scale interactive environments is largely unexplored territory in the field of human-robot interaction. Such knowledge will be important to ensure that future living and working environments, laden with interactive elements, will be both safe and beneficial for their inhabitants. Current theoretical and empirical knowledge in this area concentrates on pedestrian behavior in non-interactive urban environments [2, 3], with a focus on optimising person flow in corridors and building or stadium evacuation [4-7]. In these studies, the key technical challenge – tracking human behavior – has been solved in relatively rudimentary ways. With the advent of interactive spaces that can track and interact with a few users over small areas in activities such as everyday apartment living [8-11] and office collaboration [12, 13], the means for conducting systematic behavioral studies with small numbers of subjects seems to be available. However, real-time interactions over larger areas and with larger numbers of users have proved to be more difficult to achieve. Building control systems have been developed that can learn user preferences by using passive infra-red sensors and light switches to control room lighting and window blinds [14], and input-only (non-robotic) surveillance systems have been created that can track humans and other objects over relatively large areas [9, 15-18]. Despite these advances, the technical and logistical challenges of tracking large numbers of willing human subjects and providing them with repeatable stimuli still present a considerable barrier to

conducting behavioral experiments. There are also ethical problems with inducing realistic behavior under conditions such as crowd panic. Perhaps the best way to obtain suitable subjects is to take advantage of existing factors that encourage human congregation behavior, such as sporting events, discos and shopping malls. If the flow of people can be regulated (such as at well-defined entry/exit points) then so much the better, and if the experiment is entertaining enough to be an attraction in itself then the subjects can help to defray the costs of the experiments. We created such a combination of factors in the Ada project, an interactive entertainment space designed and built for the Swiss National Exhibition Expo.02 (May 15 to October 20, 2002).

Here we investigate the factors influencing human behavior in the Ada exhibit, and show how visitors' opinions can be manipulated by varying the operational parameters of the space. We also show a link between individual attitudes towards Ada and human behavior within the space, and suggest applications for the results presented.

II. ABOUT ADA

Ada is an interactive space, conceived as an artificial organism, that engages visitors in entertaining interactions [19]. It tracks visitors using pressure-sensitive floor tiles [20] over a 160 m² area (Fig. 1), detects and localizes handclaps and simple sounds such as the spoken word "Ada" using two sets of three microphones, and captures 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 RGB neon tubes 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+).

The visitor flow (Fig. 2) was controlled in order to guarantee a certain quality of visitor experience. Visitors queued for up to 90 min. at the entrance, viewed a 10-minute video about Ada [21] and read a leaflet explaining Ada. They entered in groups of about 25-30, passing first through the *conditioning tunnel*, a corridor with interactive stations that introduced Ada's components. They then waited behind one-way mirrors in the *voyeur area*, observing the group in front of them interacting with Ada. In the *main space*, they interacted with Ada before heading into the *brainarium* – a "control room" where they watched real-time displays of Ada's internal states while looking back into the space to see how the displays correlated with the actions of the group behind them. Finally, they entered

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the *explanatorium*, featuring artwork by HR Giger and videos of statements by scientists discussing the future of intelligent interactive systems. Visitors spent about 5 minutes in each section, for a total stay of about 25 minutes.

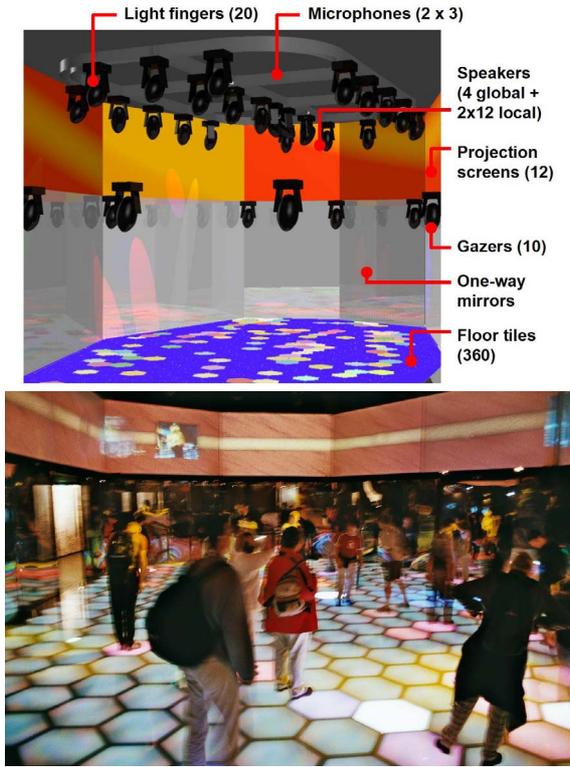


Fig. 1: (Above) Layout of components in the Ada main space. (Below) Visitors in the main space.

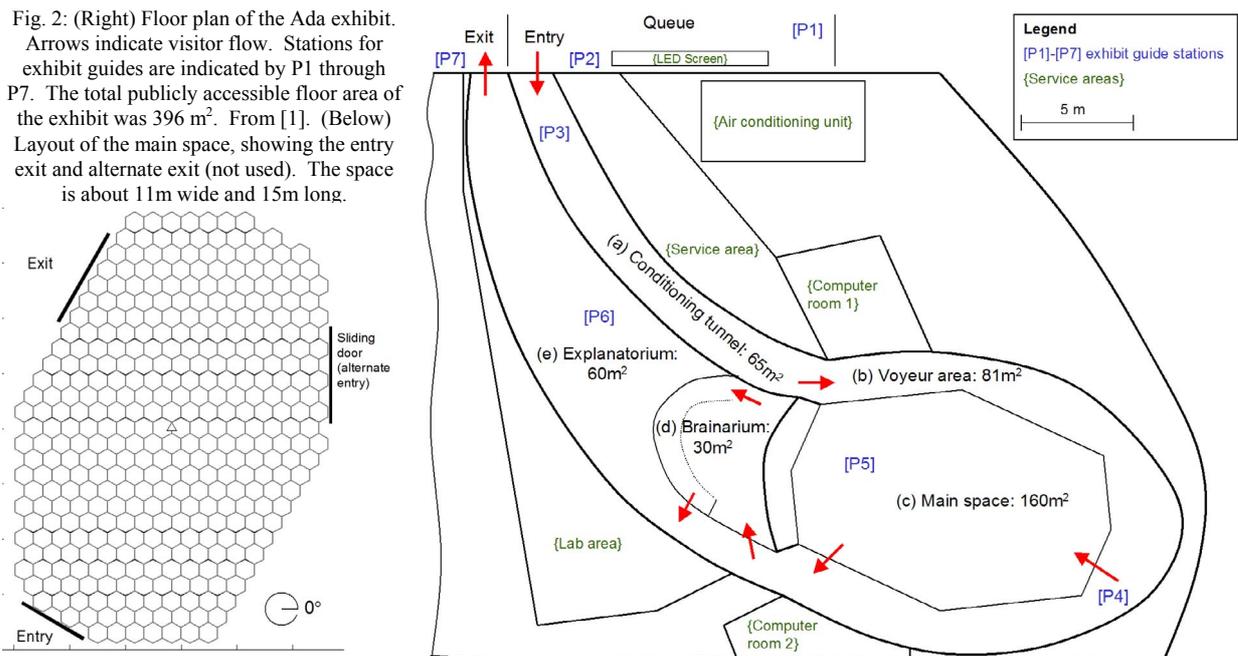
The user interactions in the main space were built on six behavioral modes presented in a fixed *visitor cycle* of about 5-6 min. with interaction-dependent timing variations:

1. *Sleep*: a blue, slowly pulsating floor, with local transient pulses and “splashing water” sound reactive effects as people stepped on the tiles was accompanied by a soft, low-pitched soundscape and a dark blue

2. *Wake*: the floor and BigScreen rapidly changed to bright yellow and the music increased in volume and pitch. This effect faded away over about 24 ± 1 seconds. At the same time, individual visitor tracking began, with each visitor assigned a different colored tile, and the space began to localise handclaps and draw a halo around the person closest to the source of each clap.
3. *Explore*: (103 ± 8 seconds) Visitors walking around the space were tracked and their “compliance” was periodically tested by deploying blinking white tile cues in front of them; those visitors that 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.
4. *Group*: (33 ± 6 seconds) had similar functionality to *Explore*, but with dark, foreboding colors and music. This mode was used to run experiments in which the space attempted to learn how to actively induce visitors to move to a set location by deploying cues [22].
5. *Game*: (64 ± 10 seconds) visitors chased a bouncing “ball” (an animated floor tile) and tried to capture it by stepping on it. The floor was broken into multiple playing fields, dependent on the number of visitors.
6. *End*: when it was time for visitors to go, red traveling waves appeared, directed toward the exit, the room became darker and the music became sad. Individual visitors also saw traveling tile “bullet” cues showing the way towards the exit. The space switched back to *Sleep* when the last visitor departed after 35 ± 2 seconds.

Although Ada could support many interaction scenarios, the contractual exhibit constraints dictated a minimum level of “normal” Ada functionality. Hence all experiments were based on a standard control case and a set

Fig. 2: (Right) 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 m². From [1]. (Below) Layout of the main space, showing the entry exit and alternate exit (not used). The space is about 11m wide and 15m long.



of deviations from this case, allowing us to see how visitors' perceptions and actions were affected by changes in Ada. Using this approach, we addressed several questions:

- Does Ada induce a coherent visitor behavioral profile?
- What do visitors think of Ada?
- Do manipulations of Ada's components influence the visitors' behavior in some measurable way?
- Is there a relationship between opinions and behavior?
- What factors affect visitors' behavior and opinions?

III. METHODS

Visitors knew of Ada before entering the exhibit through media publicity, information booths in department stores and a school information program in the German-speaking part of Switzerland. While public awareness of Ada was high, anecdotal evidence suggests that most visitors had little idea of what was actually inside Ada upon arriving in the queue. Six or seven guides distributed around the exhibit (Fig. 2) were available to answer visitors' questions and provide a short explanation of the exhibit.

Floor tracking and floor occupancy data, audio processing signals and MPEG-4 video data were recorded from Ada. Up to 5 GB/hour of data was generated during logging and transferred to a repository each evening for backup on to DVD-R. A timeserver synchronised timestamps across the cluster to within 100 ms.

Questionnaires were distributed to specific groups of visitors as they exited the main space, in their choice of German, French and English (the first or second language of virtually all visitors). Participation was voluntary; a majority of visitors agreed to participate. Observers ensured that visitors did not discuss or copy each other's answers. The first section collected demographic information: gender, age, first language, education level and main education type. 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 I). 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). Children under 10 years of age were excluded from taking the questionnaire. Questionnaires with more than 4 unanswered questions were discarded (~2.6% of all questionnaires). 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 equalised as necessary by discarding randomly selected questionnaires, or by pooling results from multiple sessions with equivalent operating conditions. For analysing 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.

Analysis was performed using Matlab 6.1 (Mathworks, MA, USA) and SPSS 11 (SPSS Inc., IL, USA). Because the length of each behavior mode varied due to visitor interaction dynamics, the time-based data was resampled and time-normalized for time-averaging over trials. A normalized numbering scheme was used for referring to

Ada's behavior modes: 0-1 = *Sleep*, 1-2 = *Wake*, 2-3 = *Explore*, 3-4 = *Group*, 4-5 = *Game*, 5-6 = *End*. The experiments fell under three main headings:

1. a control case, looking at group behavior and attitudes under normal conditions;
2. personality effects, looking at the correlation between individual extremes of behavior and attitudes, and
3. behavioral/attitudinal effects, looking at changes caused by manipulating the space's operating parameters.

In the first experiment, a control case (several visitor cycles under normal operating conditions) was analysed in detail. The second experiment was designed to see if individual behavioral differences were correlated with attitudes to Ada. A few subjects in each group were classified as most active or passive by two psychologists, and asked to complete a questionnaire. Active visitors were defined as those who followed Ada's cues in *Explore* mode and noticed their image projected on the BigScreen. Passive visitors were those who remained largely static. All selected visitors had the requirements of the questionnaire explained to them in their preferred language (French, German or English). 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 reasonably well balanced. In the third set of experiments, various parameters of the space were manipulated to gauge their effect on visitor behavior and attitudes (visitors did not have the opportunity to observe "nominal" Ada behavior beforehand). The effect of group size on behavior and attitudes was also investigated.

IV. RESULTS

A. Control Case Behavior & Questionnaire Responses

Visitor behavior followed characteristic patterns (Fig. 3). During *Sleep*, visitors entered the space from the lower left corner while the previous group exited via the upper left corner. Handclaps and spoken "Ada" events were detected at around 0.5 Hz and 0.015 Hz, respectively. In the subsequent modes, *Wake*, *Explore* and *Group*, they tended towards a uniform spatial distribution, but avoided the entrance area of the space. They increased their handclap rates to ~1.4 Hz and their spoken "Ada" rates to ~0.02 Hz, which dropped off during *Group* mode. During *Game* they spent more time in the half of the space closest to the exit than in the other half, handclap activity dropped below 0.5 Hz and spoken "Ada" detection increased. The distribution of tile on/off events during this mode was different to that in *Explore* and *Group*, with two peaks in the top and bottom half of the space. These peaks correspond to the game playing fields where people were moving fast, while those standing at the borders generated few tile events. In *End*, visitors accumulated at the exit and made very little noise.

By considering the mode-specific mean tile on/off event rate, the variance of the event rate, the variance of the tile occupancy and the rate of detected handclaps, each behavior mode could be individually resolved (pairwise t-tests with Bonferroni corrections, $p < 0.05$ for each mode compared to the others in one or more measures). Hence we can conclude that Ada was able to induce characteristic, mode-specific visitor behavior.

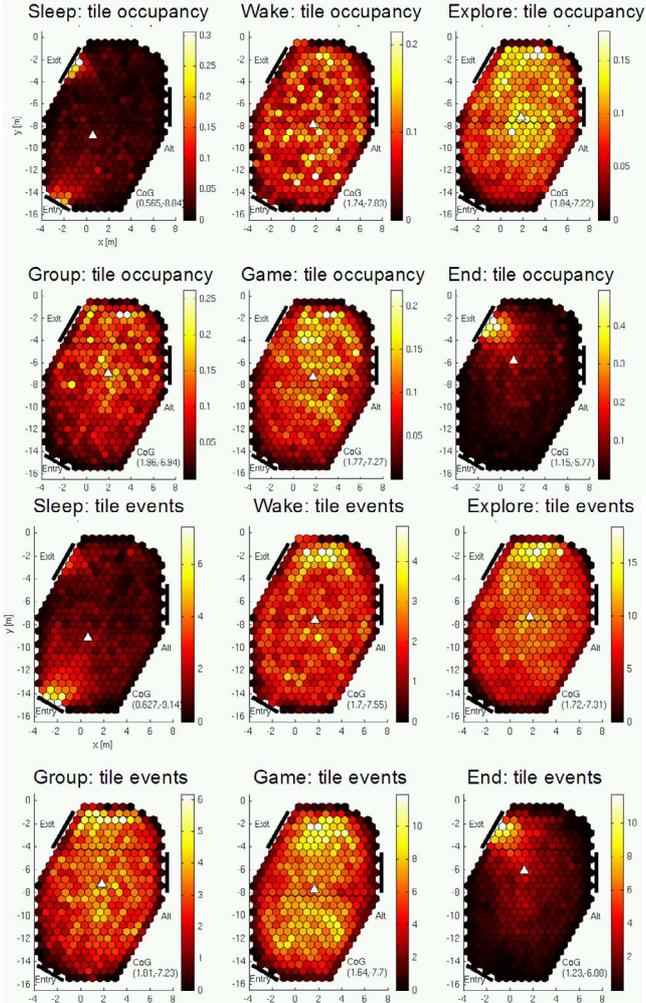


Fig. 3: Control case Mean floor occupancy (top) and event rate (bottom). Averaged over 12 visitor cycles. White triangle = CoG of distribution.

Visitors' responses (Table I) revealed effects within each subgroup of related questions. They rated Ada's sensory modalities significantly differently (Q1-3), ANOVA, $F(2, 234) = 4.29$, $p = 0.015$. Post-hoc analysis (with Bonferroni correction) revealed that visitors rated Ada's vision significantly lower than tactile sensing ($p = 0.013$), but not auditory sensors ($p = 0.199$). For Ada's reactions (Q4-7), the significance of the response differences, $F(3, 297) = 7.43$, $p < 0.001$, could be attributed entirely to the floor output (Q4); the post-hoc analysis showed $p < 0.012$ for all comparisons between Ada's floor effects and the other modalities. Indeed, the other modalities were indistinguishable from each other ($p > 0.5$ in all comparisons). Visitors' evaluations of their own reactions to Ada (Q8-12) were also different to each other, $F(4, 388) = 45.3$, $p < 0.001$. Post-hoc analysis showed that the responses were all distinct ($p < 0.011$) except the pairs of questions (Q8 & Q9, $p = 1.0$) and (Q10 & Q12, $p = 1.0$). Thus, the visitors' evaluation in this section fell into three groups: very high (visitor self-motion, Q8 & Q9), medium (sound, Q11), and low (looking at BigScreen and imitation of other visitors, Q10 & Q12). The overall impressions of Ada (Q13-16) were significantly different to each other at the overall level, $F(3, 325) = 28.6$, $p < 0.001$. Post-hoc comparisons showed that the question pairs (Q13 & Q16)

and (Q14 & Q16) were indistinguishable ($p > 0.2$), while all other pairs of questions were significantly different ($p < 0.005$). Hence we can see a response level ordering, with visitors saying most strongly that they liked Ada and were happier after being in Ada (Q14, 16). Less high was their tendency to say that Ada affected their behavior (Q13), while their responses were weakest to the statement that Ada was a kind of creature (Q15).

TABLE I
ADA QUESTIONNAIRE TEXT AND CONTROL CASE REPNSES (N = 86)
1 = MOST DISAGREE, 10 = MOST AGREE (EXCEPT WHERE INDICATED)

Category	#	Question body (response 1...10)	Mean	Std.
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:	4	Producing light patterns on her skin	7.25	2.59
	5	Projecting patterns on the Big Screen	5.65	2.94
	6	Projecting my image on the Big Screen	5.18	3.19
I reacted to Ada's Behavior by:	7	Producing sound effects and music	5.50	2.87
	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
(General)	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

The responses were analysed for demographic effects of age, gender, language, education level and education type. Significant effects were found for visitors' self-assessment of their own behavior (Q8-12):

- Gender: Males rated themselves as more interactive than females (Q8 & Q9, $p = 0.003$ & 0.006).
- Age: 41-60 year old visitors rated their ability to follow Ada's cues higher than other age groups (Q9, $p = 0.016$). Conversely, they rated their sound generation behavior lower than others (Q11, $p = 0.034$).
- Education type: people with an artistic or technical education gave lower answers for their own sound generation than others (Q11, $p = 0.017$).

After pooling questionnaires between different test runs, significant effects were also found for the responses to Ada's floor input and output (Q3 & Q4, Fig. 4): people above 55 years old, people with apprenticeship-level education and those with an arts-oriented education gave consistently lower responses to these questions (ANOVA, $N > 600$, $p < 0.05$).

B. Visitor Opinions and Behavior

The average responses for the passive and active visitors (Table II) showed that the active visitors gave higher responses for 11 out of 16 questions, and their mean responses were 0.36 points higher than the passive visitors. On a question-by-question basis, one BigScreen-related question (6) and three overall questions (13, 14, 16) elicited significantly higher responses (t-test, $p < 0.05$) from the active group. It is clear that active people were more positive about the Ada exhibit as a whole; however, passive visitors were more likely to say that they were imitating the

actions of others (Q12). Hence, the categorization of visitors into passive and active groups was able to isolate attitudinal differences to Ada. This suggests that the compliance testing procedure in *Explore* mode correctly identifies “interesting” visitors, i.e. those who understand the interactions and have positive opinions of Ada.

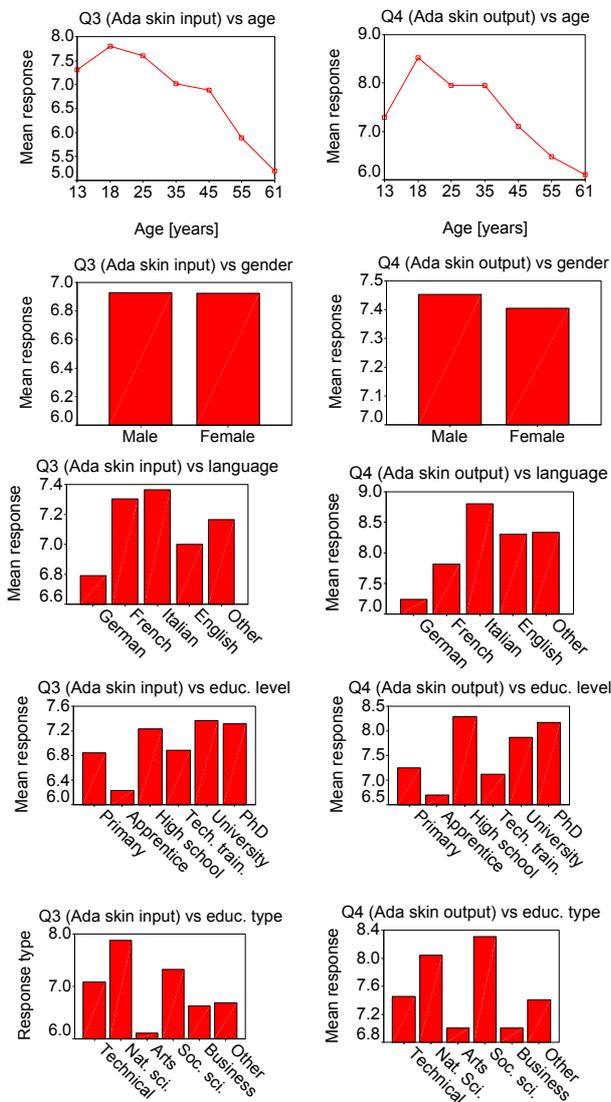


Fig. 4: Questionnaire responses for Ada floor input (Q3, left) and output (Q4, right).

C. Factors Affecting Behavior and Opinions

To understand the effects of Ada’s output modalities on the visitors’ behavior and their attitudes, a set of tests was 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, $p < 0.05$), were as follows:

Sound and music removed (volume reduced to barely audible level): visitors’ perception of Ada’s hearing was significantly lower (Q2, $p = 0.019$), but their perception of Ada’s sound output was unchanged (Q11, $p > 0.1$). In addition, their perception of Ada’s eyes (Q1, $p = 0.049$) was higher, but they spent less time looking at the BigScreen (Q10, $p = 0.042$). 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, and appeared to attribute increased visual processing capabilities to Ada as compensation for the perceived reduction in auditory processing capabilities.

TABLE II
ADA QUESTIONNAIRE RESPONSES: PASSIVE-ACTIVE VISITORS

	#	Keywords	Passive (N=58)		Active (N=60)		T-test Sig.
			Avg	Std.	Avg	Std.	
Ada Sensors	1	Eyes	6.16	2.91	5.93	2.67	0.347
	2	Ears	5.60	2.79	5.78	2.76	0.184
	3	Skin	6.27	2.83	6.36	3.38	0.703
Ada React	4	Floor	6.93	2.49	7.40	2.95	0.676
	5	BigScreen	5.09	2.67	5.29	2.34	0.489
	6	Image	4.71	2.87	6.05	3.12	*0.006
	7	Sound	5.09	2.76	4.24	2.60	0.438
Visitor React	8	Move fast	6.78	2.72	7.41	2.31	0.796
	9	Follow	7.91	2.25	8.18	1.94	0.197
	10	Look-BigScreen	4.59	2.75	4.39	2.47	0.251
	11	Make noise	5.55	2.88	4.85	2.95	0.233
	12	Imitate	3.68	2.82	2.83	2.67	*0.005
Overall	13	Effect	5.78	2.56	7.12	2.28	*0.037
	14	Affect	6.80	2.01	8.22	1.70	*0.000
	15	Entity	3.80	2.78	4.80	2.81	0.087
	16	Like	5.88	2.38	7.45	2.06	*0.003
Average			5.66	2.65	6.02	2.56	
# higher			5	-	11	-	

* = significant effect ($p < 0.05$)

BigScreen background plain dark blue: visitors did not score the BigScreen significantly lower (Q5 and Q10) since they did not know it could do more than what was shown. However, they seemed to think that Ada could not hear well (Q2, $p = 0.022$). 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: similar effects to the previous case were seen, but visitors also noticed reduced visual output (Q5, $p = 0.024$). 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, $p = 0.005$), suggesting that images/videos of visitors on the BigScreen are motivating factors for imitating the actions of others.

No guide instructions: as might be expected, visitors gave lower responses, imply a reduced knowledge of how to interact with Ada. However, only two of these were significant: visitors’ self-assessment of their viewing of BigScreen (Q10, $p = 0.023$) and their own noise-making (Q11, $p = 0.003$).

Most of the test cases had the effect of reducing the rate of tile events ($p < 0.05$) in most behavior modes except *Sleep* and *End*, with the largest decreases for the case with no guide instructions. However, the rate of detection of handclaps and the spoken word “Ada” was not significantly altered. It is interesting to note that the visitor responses to the overall questions about Ada (Q13-16) were not significantly affected by the different manipulations to the space; i.e. the degraded conditions in Ada were still good enough to elicit positive overall visitor responses.

Group size variation: Ada’s design specified 16 visitors per group (10 m² per visitor). However, due to the large

number of visitors wanting to see Ada, the group size in practice was about 27 visitors. To gauge the effect of visitor density on behavior and perceptions, two test cases were created with a smaller (n=15) and larger (n=32) number of visitors per group. The data showed that, in *Game* mode, visitors generated tile events at about 1.3 Hz in small groups, 1.1 Hz in medium-sized groups and 1.0 Hz large groups, with different effects for other behaviour modes. The tile event rates for the cases were distinguishable by group size (ANOVA, $p = 0.017$). However, the clap rate and spoken “Ada” detection rates were not distinguishable by group size (ANOVA, $p \geq 0.089$ & $p \geq 0.4$). The questionnaire responses confirmed the prediction that small groups would enjoy and understand Ada more: 14 out of 16 questions elicited a higher response (avg. +0.62 points) compared to the control case, while the large group size scored lower in 13 out of 16 questions (avg. -0.56 points). For small groups, significantly increased responses ($p < 0.05$) were found for Ada’s eyes (Q1), Ada’s floor output (Q4), and the perception of Ada as an entity (Q15). This may reflect the improved visibility of the space due to less occlusion from other visitors. The larger group gave two responses with significantly lower values ($p < 0.05$), related to perceptions of Ada’s hearing (Q2) and visitors’ tendency to make noise (Q11). Only a few responses to specific questions (Q2, 5, 11) were significantly dependent on the group size, but their overall impressions of Ada (Q13-16) were strongly affected by the number of visitors they shared the space with.

CONCLUSION

The results presented here are among the first in the field of human-space interaction combining data from human activity, human opinions and the activity of the space under investigation. They highlight some of the important factors influencing human opinions and behavior in interactive environments, and demonstrate how human attitudes can be inferred from observing behavior. This knowledge can be used in the design of future interactive spaces for automatic estimation of human attitudes and customisation of individual interactions. It could also be used to automatically deduce group attitudes through their activity levels, allowing automatic measures to be taken to influence attitudes and behavior. One simple example of where such a system could be useful is in crowded shopping malls and nightclubs, where the building could automatically detect potentially unsafe situations and induce visitors to disperse before a panic situation arises. More subtly, a suitably calibrated system of the same type could also be used to influence visitors’ tendencies to move to target locations in order to maximise system goals (visitor enjoyment, purchasing activity, etc.). Further experiments are planned to expand on the results presented here.

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