A Smart Environment for Children with Autism

Deploying pervasive technology is problematic when it's intended for long-term use in challenging environments. However, the gradual deployment of various technologies in a school clinic for children with autism is showing how smart environments can positively impact current therapeutic practices.

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Challenging environments such as hospitals and school clinics can often benefit greatly from using pervasive technology integrated as a smart space to help individuals cope with mobility, collaboration, and behavior demands.[1–3] However, deploying smart spaces in these challenging environments isn't an easy task, as most individuals living in such spaces face numerous behavioral and cognitive challenges that limit the ability to deploy novel technologies.

School clinics specializing in the care of children with autism are an example of such an environment and thus are appropriate places to study the long-term use of smart spaces for several reasons. First, the working conditions of specialized caregivers in these environments are intrinsically tied to the physical domain in which children live and interact. Solutions integrating the physical and digital world—such as augmented reality (AR) and tangible computing—could be instrumental in supporting the children's and caregivers' needs. Second, clinical case assessment heavily relies on direct observation and manual record keeping, which would be easier to accomplish with wearable and mobile sensing platforms. Third, therapeutic interventions for children with autism heavily rely on repetition, which is boring and leads to poor behavior and decreased cooperation with such interventions. Ambient displays supporting behavior change and exergames sustaining engagement could encourage positive behaviors and help children stay focused during therapeutic interventions.

Here, we describe our vision of the school clinic of the future as a highly interactive physical world furnished with sensors, actuators, and novel displays that are seamlessly embedded and connected through advanced communication technologies. This type of smart environment could augment existing educational curriculums and therapeutic interventions that target challenges associated with child development. We also reflect on our experiences deploying such a smart environment to support the needs of the Pasitos school clinic in Tijuana, Mexico, where 15 physiologist-teachers serve approximately 60 students with autism who range in age from 3 to 21 years. Our work's main contribution is to provide evidence of a smart environment's real-life deployment (see the related sidebar) and show how individuals with autism and their caregivers might intuitively, effectively, and ubiquitously interact with smart environments over the long-term.

Designing the Smart Environment

For the past five years, we followed an interactive user-centered design approach that uses multiple design methods to discuss prototype

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Related Work in Smart Environments

Pervasive computing researchers have recognized the importance of deploying smart environments to study users in natural conditions, and they understand how pervasive technology might effectively enhance users' interactions with their world.

Several researchers have been building *living laboratories*.[1] These environments—which are more natural than the typical laboratory—let individuals experience pervasive technology that is truly integrated into the fabric of their everyday lives. For example, the PlaceLab[1] is a residential apartment building with hundreds of sensing components installed in nearly every part of the apartments, which are occupied by volunteer subjects who agree to live in them for varying lengths of time. Although literature in pervasive computing shows that living labs are appropriate for adequate empirical measurements, users still must move into the lab outside their living environment to truly experience the benefits from using these technologies.

Recently, researchers have emphasized the importance of increasing ecological validity when studying individuals' experiences with pervasive technology. In this regard, a recent trend has been to make living labs by instrumenting the field site with innovative monitoring and displaying technologies. For example TigerPlace[2] is a senior independent living and care community that lets residents "age in place," living in their own apartments equipped with state-of-the-art monitoring technologies. However, real deployments of living labs are still scarce and limited in challenging environments. Descriptions of such real-life smart space deployments are urgently needed.

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TABLE 1
Overview of our formative studies to iteratively design and evaluate the prototypes.

Prototypes		Starting	Duration (weeks)	No. of interviews	Observation (hrs)	Participatory design sessions
Mobile (running on Android tablets in the classrooms)	Mobis	2010	13	13	75	2
	BxBalloons	2013	5	17	28	3
Kinnect-based (installed in the exergames room)	FroggyBobby	2013	18	5	4	2
	SensoryPaint	2012	9	9	4	5
Total		4	45	44	111	12

ideas, share design insights, and iteratively design our prototypes. Tables 1 and 2 shows a summary of the data collected during the formative and summative studies to iteratively design and evaluate our prototypes. Our design team is multidisciplinary, involving experts in special education, autism, HCI, ubicomp, and interaction design.

During this time (and up to the present), we've been designing, developing, and pilot testing pervasive technology to augment several dimensions of the therapy cycle of children with autism; here we present three such technologies, which are still in use today.

Using AR to Combine Digital and Physical Supports

Most children with autism present numerous cognitive impairments. During cognitive training, teachers at Pasitos conduct repetitive trials in which students are given an object and a cognitive goal (to discriminate between various items to identify the object). Teachers frequently use real objects enriched with interactive visual supports and teacher-initiated prompts to help students reach their cognitive goals. AR, which can integrate the physical and digital worlds, could offer a new type of physical support capable of integrating the benefits of both paper-based and interactive visual supports.[4]

To test this idea, we developed the Mobile *O*bject *I*dentification *S*ystem (Mobis),[4] an AR system that lets teachers superimpose digital content—including text, audio-recorded messages, and visual shapes (such as circles)—on top of physical objects used for cognitive training. First, teachers use their tablet (Figure 1a) to create a database of images used during therapies and associate digital content that will be later discovered by children (see Figure 1b). Next, teachers select from the tablet the object children need to discriminate, and monitor students' responses on each trial (Figure 1c). Children later put their smartphones on the physical object, using it as a "visor" to uncover the digital content tagged on top of the object (Figure 1d).

TABLE 2
Overview of our summative studies to iteratively design and evaluate the prototypes.

Prototypes		Starting	Duration (weeks—baseline + deployment)	Users	Baseline: No. of focus groups	Baseline: Total hours of observation	Deployment: # of focus groups	Deployment: Total hours of observation	Follow-up focus group
Mobile (running on Adroid tablets in the classrooms)	Mobis	2012	2 + 5	19	2	27	15	15	2
	BxBalloons	2014	3 + 3	24	2	28	2	76	5
Kinnect-based (installed in the exergames room)	FroggyBobby	2014	1 + 6	17	2	2	6	15	5
	SensoryPaint	2014	1 + 6	17	2	3	6	15	5
Total		3	27	77	8	60	29	121	17

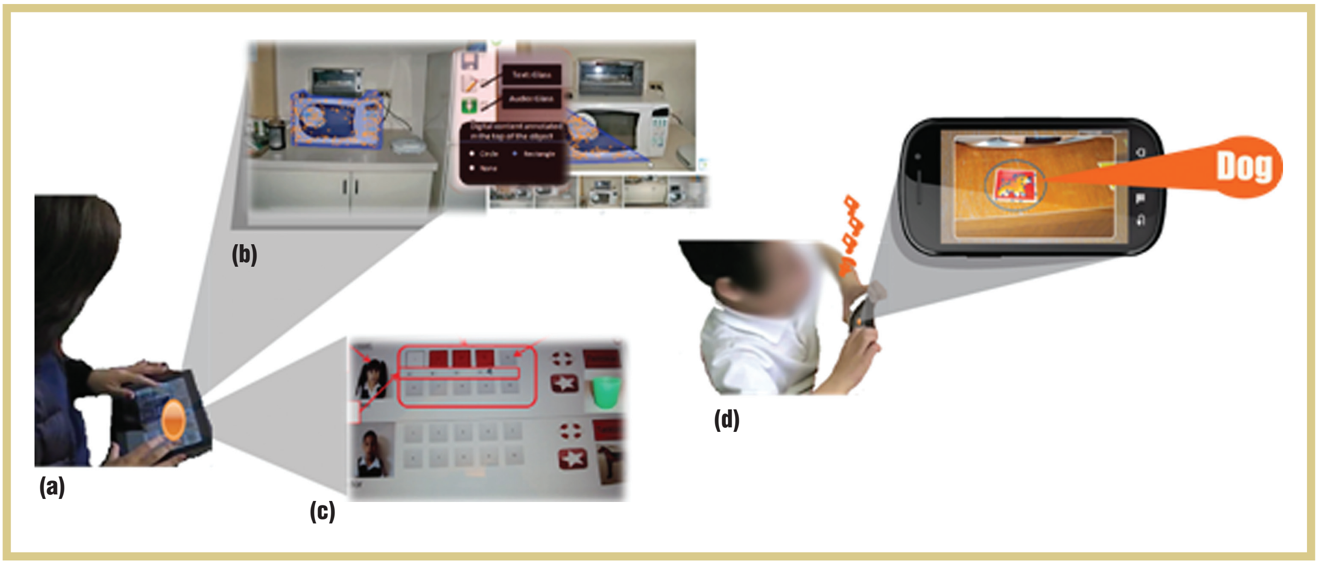

Figure 1. Mobis in action. A teacher at Pasitos (a) uploads photographs, (b) tags objects, and (c) monitors student responses. A student can (d) use his smartphone to discover digital content (the circle) on top of the object (a card with a çpicture of a dog on it).

To recognize objects, we used the Speeded-Up Robust Features (SURF) algorithm to extract features as "interest points" from images. Mobis keeps a knowledge database that stores a set of images that are later used to compare against the source image. Teachers use a GUI (Figure 1a) to create the image database. To create a tag, teachers select an object of interest from the database images and associate digital content—a shape or an audio or text message—to be superimposed on top of the object. Mobis will later display this digital content as a prompt superimposed over the object (Figure 1d).

Ambient Displays and Positive Behavior

Children with autism exhibit behavioral problems that are often inappropriate and might be disruptive or dangerous. Behavioral management of children with autism at Pasitos mainly involves raising awareness of each student's behaviors over a period of time. Ambient and situated displays enable reflection on behavioral patterns; encouraging positive behaviors could also help children reflect on their behavior.[5,6]

We developed the ambient display BxBalloons (Figure 2) to provide children with awareness of their behavior. BxBalloons' goal is to help the child "pilots" travel through five world continents, each representing a day of the week. The aircraft deflates when students exhibit poor behaviors. The child's goal is to maintain enough air in the aircraft to reach the next continent. Collectively, if 80 percent of all aircrafts fail to reach the next continent, all aircrafts deflate and must start over. Weather conditions affecting aircraft speed change from sunny to cloudy and rainy based on the amount of yelling detected in the classroom. To recognize behavior, each child wears a fitbit, which infers "atypical" movements labeled as poor behaviors. Teachers compliment this information by recording each child's behavior in their tablet using Electronic Behavior Record (EBR), a Web-based application that systematically stores students' behavior information.

To recognize yelling, we used sound entropy to extract features from environmental noise. The recorded audio passes through a sound processing filter and classification unit every 30 seconds, and the BxBalloons system decides, in tandem, whether the segment contains a considerable amount of sustained yelling. For our audio feature, we modified the Multi-Band Spectral Entropy Signature (MBSES) using the Mel perceptual scale. The process to compute the Mel-MBSES segments the audio signal in 1,024 samples, with an overlap of 50 percent. We apply a Hamming window to every frame and compute the N-point Fast Fourier Transform. We then apply a 12-band Mel-filter bank from 0 to 20,050 Hz to the resulting spectrum.

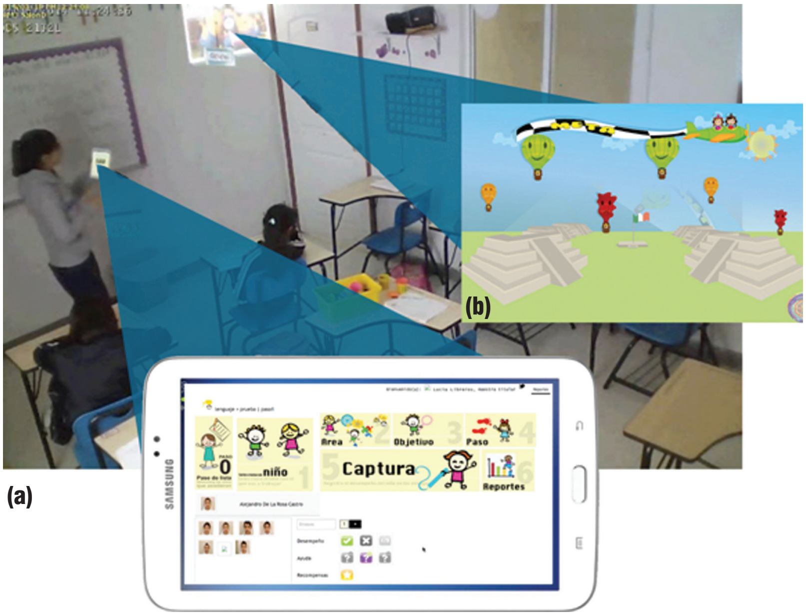

Figure 2. Teachers and students using ambient displays for in-class behavioral management at Pasitos. (a) A teacher uses a tablet running the Electronic Behavior Record (EBR) to record students' behavior. (b) The students fly aircrafts across five continents, from America to Africa. The happy-faced green aircrafts represent good behavior, while orange aircrafts represent regular behavior, and deflated red aircrafts represent poor behavior.

Exergames: Sustaining Engagement in Motor Therapies

Most children with autism lack body awareness and have motor and sensory processing disorders. Motor therapies at Pasitos involve the continuous practicing and repetition of different gross-motor and coordination exercises, supplementing mirror therapies in which children move their body in front of a mirror to help them gain body awareness and develop age-appropriate motor skills. Because children find them engaging, exergames can help children practice their motor skills; they are also instrumental in supporting motor rehabilitation for other populations.[7]

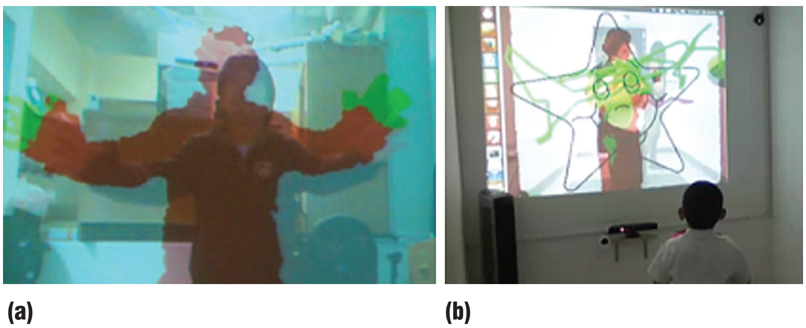

Figure 3. An exergame to support mirror therapies. (a) *A screenshot of the SensoryPaint system's mirroring projection. (b)* A child using SensoryPaint to color a star in Pasitos.

To mimic motor therapies, we developed two exergames: SensoryPaint and FroggyBobby. Both help children pay attention to body movements and conduct exercise repetitions.

SensoryPaint[8] is an interactive painting tool that shows a superimposed reflection of the user on a mirroring projection displayed on the wall (Figure 3a). The color of the user's reflection changes from red to green to demonstrate proximity to the surface. Students use texturized balls as paintbrushes of various sizes, textures, and colors to draw either in a free form mode or in connection with a template drawing (such as the star shown in Figure 3b).

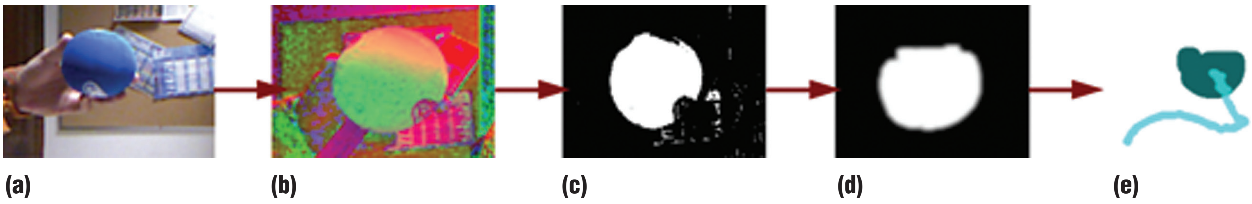

Figure 4. Transformations to track the ball's position. (a) The original RGB image. (b) The RGB image in HSV form. (c) The segmented image. (d) The image after noise reduction. (e) The system locates the ball's "centroid."

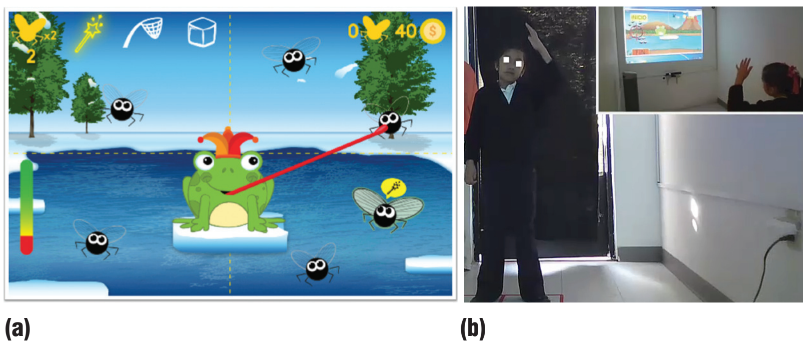

Figure 5. An exergame to support gross-motor therapies. (a) A screenshot of *FroggyBobby shows how children use their arms to catch flies in between the yellow and red buttons. (b) A child reaching for FroggyBobby's yellow button in Pasitos.*

SensoryPaint uses Kinect sensors and computer vision techniques to recognize user interactions and the ball's trajectory. Specifically, the ball's color and form are uniquely identified to detect the ball's position (Figure 4). The system first transforms the image from the RBG model (Figure 4a) into the HSV model (Figure 4b). It then uses thresholding[6] to segment the image (Figure 4c). Next, the system reduces the noise, isolating the pixels that don't match the original object's form; it eliminates these unmatched spots using morphological operations and dilation of the binary image connecting the isolated points (Figure 4d). The ball's centroid is calculated using the image moment; the centroid is used to determine where to paint the line by calculating the Euclidean distance between two points (Figure 4e).

SensoryPaint uses the Kinect's depth camera to infer when a ball hits a wall and to display the user's shadow. The depth camera sends a stream of distances between the Kinect and the nearest object found. The user's shadow is reproduced by extracting the pixels on any given threshold. Sounds are played in connection with movements and when users earn points.

FroggyBobby[9] requires children to move their arms in a coordinated manner to catch flies by controlling the tongue of a frog avatar (Figure 5a). FroggyBobby has different levels, varying the amount of prompting, the difficulty of catching flies, and the exercises children use. FroggyBobby uses all the joint positions available from the user's skeleton extracted through the Kinect SDK; to determining motion and the player's arm position (see Figure 5b), it uses raw image data. To create the exergame animations, we used the Farseer Physics Engine 3.5.

Deploying a Smart Environment

We deployed all of the prototypes just described in the Pasitos school clinic.

Training and Scheduling

We conducted a set of workshops with parents, where we showed them how to use each prototype and explained the potential benefits and the study plan. During the workshops, parents used the prototypes, asked questions, and gave consent to participate in the study. Pasitos changed its school schedule and curriculum to specifically include the use of our prototypes as therapeutic interventions.

Hardware and Software Installation

We equipped each Pasitos classroom with one cloud camera and three android tablets: two used by teachers and one connected to a multimedia projector through Google Chromecast. We also gave fitbits to each child in the two classrooms with BxBalloons. The classroom's ambient display was located next to the marker board; the cloud video camera was located in the classroom's corner. Tablets were wirelessly connected to a server storing the database that managed the EBR and ran servers for the mobile prototypes. We installed client versions of the mobile prototypes in each tablet.

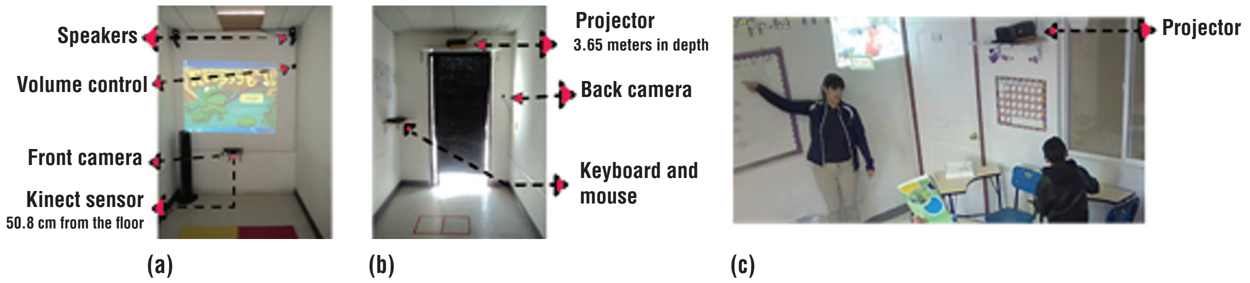

Figure 6. The hardware and software installation at Pasitos. (a) The back camera overlooking the multimedia projection from the exergames' room, along with the loudspeakers and Microsoft Kinect. (b) The front camera at the entrance to the exergames' room, along with the multimedia projector and the mouse and keyboard. (c) A cloud camera installed in a Pasitos classroom showing the situated display.

As Figure 6 shows, we equipped the exergames' room with a Kinect sensor, a pair of speakers, a multimedia projector, two cloud video cameras, and a keyboard and mouse. The Kinect sensor tracks the user's body movements, and the speakers play the exergames' sounds and music. The camera in the front of the room monitors user interactions, while the one in the back monitors users' reactions and movements. The keyboard and mouse controls a server placed behind the projection wall running our exergames.

All cloud cameras are wirelessly connected to a network-attached storage unit, and all prototypes are connected to the EBR. All prototypes have their own preferences panel, which lets participants adjust therapeutic goals, level of prompting, and the type of rewards.

Data Collection and Analysis

We calibrated the installed prototypes for one week, adjusting each application's settings to each user's needs and personalizing some elements of the interaction modes and interface design to fit children's interests.

Therapies were automatically video-recorded. Although we planned each prototype's deployment study to last for approximately two months, all prototypes were adopted and have been in continuous use since 2012. However, our data collection was extensive only during the first two months of each prototype usage. During these two months, we conducted weekly interviews with teachers and some of the students (those with verbal abilities), asking them questions about how the system use went during that particular week and how the prototype impacted their current practices, with particularly attention on behavior and engagement. Following that first two months of usage, we began conducting monthly follow-up focus groups with teachers and verbal students, discussing technology adoption issues and interesting uses that have emerged from the long-term use of our smart space. These focus groups continue today.

Our data analysis followed a mixed-method approach. To analyze our qualitative data, we used techniques to derive grounded theory and affinity diagramming (such as open and axial coding). Using these techniques, we grouped quotes or events obtained from interviews and recorded videos to uncover both emerging themes related to system usage and adoption, and the developmental areas impacted by our smart environment, including attention, motor functioning, socialization, and behavior.

To analyze our quantitative data, we used techniques inspired by Henry Mintzberg's structured observation method and lag sequential analysis. With these techniques, we estimated, for each participant under each condition, the total and descriptive statistics of the time students spent paying attention and exhibiting behavior problems, and the time teachers spent prompting students. Finally, we used an Analysis of Variance (ANOVA) test to compare the time our participants' engaged in such behaviors before and after using our prototypes. Inter-Observer Agreement (IOA) for coding video data was acceptable.

The School Clinic of the Future

Our smart environment successfully supplemented specialized education curriculums and augmented therapeutic interventions. Our results indicate that students gain numerous benefits related to motor functioning, attention, and behavior.

Our smart environment was rapidly and successfully integrated into the Pasitos curriculum. Overall, all teachers and students positively received the smart space, finding it "useful, fun, helpful" and "easy to use," with minimal training required when learning how to use the prototypes.

Collaboration and Socialization

Students also benefited from collaboration and socialization. Teachers explained that, when using the smart space, the students improved their social skills and language and learned to take turns; this smoothed classroom transitions and made students more willing to participate in role-modeling activities.

For example, our observations records indicate that teachers paired up two students when using SensoryPaint to promote peer imitation. Teachers said that role modeling has numerous benefits for sensory stimulation but wasn't possible before using SensoryPaint. Participants frequently interacted with whomever was in the room while they were playing with SensoryPaint, conversing and even encouraging others to participate with them. For example, one child asked the researchers to help him draw on the screen, explaining that SensoryPaint would "be a lot more fun with other people, because they actually do different things."

The technology itself uncovered a wide range of collaboration practices, encouraging children to share their achieved goals, invite others to share their experiences using the technology, and ask for help from peers when facing problems interacting with the smart environment.

As these results show, collective experiences play an important role in smart space adoption and facilitate both technology use and the creation of new processes, adjusting current practices to the context in which these technologies will be used.

Motor Development and Functioning

From a motor development standpoint, students using SensoryPaint and FroggyBobby mastered several gross-motor movements and gained benefits related to body-awareness, posture, and balance. For example, after a week of using FroggyBobby, most children showed better eye-hand coordination by more accurately positioning their hands on top of the moving flies. As one teacher noted,

> *At the beginning, we had to help students to raise [their arms], but then my hand felt like a magnet, like I did not have to [use a lot of strength] to help students raise their arms, it was like their hand was following mine. They were doing the motor coordination exercise by themselves. Now, I only prompt them by saying: "raise your arm higher."*

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Teachers not only observed such improvements while practicing motor skills in the exergames' room but also during classroom activities when students grabbed objects or practiced fine-gross motor movements.

Attention and Behavior

Compared to traditional therapeutic interventions, Pasitos teachers said that the smart space "better caught children's attention" in a simple and effective way. In addition to the teacher's feedback, we recorded the following differences in terms of engagement time:

- Mobis: a three-hour increase in attention span (baseline = 0:17:15, deployment = 3:12:47, $p = 0.003$);
- FroggyBobby: a slight increase in attention span (baseline average = 0:07:40, deployment average = 0:08:34, $p = 0.13$);
- SensoryPaint: a slight decrease in attention span (baseline = 2:29:30, deployment = 2:16:57, $p = 0.38$).[4]

Although our qualitative results for Mobis and FroggyBoggy show an increase in engagement, results for SensoryPaint weren't statistically significant, indicating that the system at least maintains attention equally with traditional therapy.

While in the smart space, the children with autism were more engaged, particularly with task-oriented prototypes—such as FroggyBobby and BxBalloons—that targeted specific developmental goals. However, some teachers explained that these prototypes were "not flexible enough." In contrast, teachers using an open-ended interaction model found that they were "easier to customize and personalize" to support multiple developmental goals. For example, with Mobis, teachers asked children to move around the classroom discovering objects available in the environment (rather than those simply on their desks). Paradoxically, when teachers learned that the children more rapidly disengaged from the therapy during open-ended activities, they redirected student interactions to more goal-oriented tasks. For example, when using SensoryPaint, teachers incorporated task-oriented goals by asking students to use the ball to pinpoint different body parts, leveraging the mirroring projection. These examples show the importance of combining open-ended and task-oriented interaction modalities to let users more freely personalize the smart environment to their needs—as well as uncover other potential practices mediated by the technology—while also sustaining engagement.

From a behavior standpoint, all students using the BxBalloons prototype were more aware of their behavior (BxBalloons: baseline = 31 (number of instances in which a child realized he or she was behaving poorly and stopped the behavior), deployment = 180, $p = 0.036$). They exhibited more positive behaviors and had fewer tantrums. One teacher described it as follows:

> *Students work more. Sometimes some children don't want to work, but the minute we told them that their balloon will deflate, they started to work so the balloon will turn green. They were constantly aware of the [BxBalloons] display.*

Socio-Technical Challenges

After the teachers and students had used the smart environment for more than six months, their relationship with the technology changed. This opened up numerous HCI evaluation and design challenges particular to developing smart environments for long-term use in challenging settings.

First, there's a gap between the clinical research methods used to evaluate and design the clinical interventions' effectiveness and those used in ubicomp to conduct usability evaluations. New models and methods that enable the participatory design of user studies and tools for empirical measurement could

- promote the active engagement of clinical partners, and
- let HCI researchers uncover new, clinically relevant metrics to measure users' attitudes and behaviors.

Second, our experiences show that having a smart environment saturated with different monitoring technologies is an opportunity to gather verifiable and quantifiable data in the form of a massive heterogeneous database of videos, audio from interviews, photos, and sensor data. The challenge for ubicomp researchers is to adequately specify how complex the data analysis is going to be and selectively reduce the data's dimensionality. Using appropriate tools for feature selection and extraction could more easily help researchers isolate data segments relevant to understanding the target phenomenon and significantly reduce the burden and workload associated with data capturing and analysis. The sustained use of smart environments could generate the rich databases required for the continuous tuning and personalization of classifiers and models for predicting behavior.

Finally, it's not clear when it's appropriate to start redesigning already deployed prototypes, or when it's suitable to deploy new prototypes or a new version of existing ones. It takes time for the novelty effect to wear off and for participants to start feeling comfortable using the prototypes; this heavily limits the trend of building "semiworking" technologies and deploying them as quickly as possible because frequent technology updates could be very disruptive to existing practices related to adoption. So, we must find new methods to promptly and appropriately integrate incremental, transformative innovations into existing smart environments.

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Application Themes

Applications and user experiences are of course one of ubiquitous computing's biggest challenges as researchers continuously look for the "killer app, the Holy Grail of Ubicomp"[10] that will give us enough insight on how pervasive technology affects our lives. Our results indicate two potential application themes that could serve as a springboard for future research questions.

New Interaction Paradigms

The drive for the correct interaction experience will require

- important changes to the input and output to incorporate more humanlike interaction capabilities, and
- better display technologies that are easily integrated into the environment.

Beyond the typical natural interfaces that use speech, pens, gestures, and so on, paradigms are emerging that could push the limits of our imagination. For example, brain-computer interfaces could give users feedback about their own brain activity and adapt the smart environment accordingly—some exergames might turn off some features when children with autism start losing attention. Likewise, innovative ways to provide neurofeedback could give clinicians more information about developmental milestones. However, open questions remain as to how brain-computer interfaces could be integrated into existing smart environments to both enable multimodality and give users new controllers to manipulate digital and physical objects.

Recent advances in computer vision and audio recognition also make possible the creation of novel interfaces with innovative means for interaction. For example, blendable or flexible surfaces could let users more freely gravitate and manipulate digital objects displayed in the surface.

The affordances of flexible surfaces invite users to grasp, push, or bend the surface, which in turn lets them discover multisensory interaction experiences.

Embedded Systems

Integrating heterogeneous software and hardware is always a challenge. Not only will some prototypes deployed in smart environments become legacy systems once the host hardware's novelty expires, but also the increasing installation of new software and hardware in smart environments will add an extra maintenance and integration burden on users. With the miniaturization of computer hardware, new technologies such as Raspberry Pi have made it possible to create embedded systems with dedicated functions in small and powerful hardware. Embedded systems and the Internet of Things could facilitate interaction as each prototype's functionality is encapsulated in a physical object that users might more easily manipulate—mimicking how appliances usually work. This would also promote flexibility and technology updates.

Our understanding of this smart space's context has opened up several research questions related to the need for new methods for automatically measuring clinical data and economical models to cope with technology maintenance and appropriately incentivize users to participate in iterative development.

We've recently begun to explore the use of several ambient displays to provide teachers and clinicians with continuous awareness of the clinical data being captured both through the EBR and automatically through the smart environment's sensors. We've also been improving the design of our smart space to better fit the emergent practices and uncover other potential opportunities in which our smart space could successfully augment autism therapies. Finally, we've just finished new versions of FroggyBobby and SensoryPaint that combine gross and fine movements to provide a better motor development experience; we plan to deploy them later this year.

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