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SensoryPaint: A Multimodal Sensory Intervention for Children with Neurodevelopmental Disorders

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ABSTRACT
Multimodal and natural user interfaces offer an innovative approach to sensory integration therapies. We designed and developed SensoryPaint, a multimodal system that allows users to paint on a large display using physical objects, body-based interactions, and interactive audio. We evaluated the impact of SensoryPaint through two user studies: a lab-based study of 15 children with neurodevelopmental disorders in which they used the system for up to one hour, and a deployment study with four children with autism, during which the system was integrated into existing daily sensory therapy sessions. Our results demonstrate that a multimodal large display, using whole body interactions combined with tangible interactions and interactive audio feedback, balances children's attention between their own bodies and sensory stimuli, augments existing therapies, and promotes socialization. These results offer implications for the design of other ubicomp systems for children with neurodevelopmental disorders and for their integration into therapeutic interventions.

Author Keywords
Large displays, natural user interfaces, autism, sensory-processing disorder, child-computer interaction.

ACM Classification Keywords
K.4.2 [Computers and Society]: Social Issues- Assistive technologies for persons with disabilities

INTRODUCTION
Many children with neurodevelopmental disorders, such as autism[1] and attention-deficit hyperactivity disorder, have sensory processing disorders [3]. People with sensory processing disorders lack appropriate sensory integration capabilities (*i.e.*, "the ability to use the neurological process to organize sensation from one's own body and the environment, thus making it possible to use the body effectively within the environment" [8]). Individuals with sensory processing disorders are often hyper- or hyposensitive to light, sounds, and/or touch [4] and experience poor body and movement awareness [6] that lead to atypical body-interactions. These interactions in turn act as "compensatory movements" or protective behaviors that children with sensory processing disorders frequently use when interacting with the environment [9].

Sensory impairments[1] cause great discomfort to the individual experiencing them. For example, a noise that is quiet or pleasant to those with typical sensory processing systems may be incredibly loud, unpleasant, or even painful to an individual with sensory processing disorders. Compared to other populations, individuals with autism and related neurodevelopmental disorders tend to have more challenges with processing sensory input [23,34] as well as motor coordination and functioning [23].

Pediatric therapies for sensory integration focus on teaching children how to integrate their senses, gain body-awareness, and adapt to the environment. One therapeutic approach to sensory processing disorders is to combine sensory integration and body-awareness therapies in Multi-Sensory Environments (MSE), also known as a multimodal environment. These are physical environments saturated with visual and audible stimuli. MSE also house specialized equipment for sensory stimulation, where children with sensory processing disorders use a variety of tools, including objects with various textures, mirrors, and tactile sensations [29] (see Figure 1). Therapists, typically psychologists, personalize "sensory diets" for their pediatric patients, prescribing specific interactions with the MSE (*e.g.*, a child must play in front of a mirror for 10 minutes with a fiber-optic rope for visual stimulation). However, therapeutic goals are often difficult to meet because children tend to become

[1]The term *autism* will be used throughout this paper to denote Autism Spectrum Disorder as well as Asperger's Syndrome as previously defined before the DSM-V changes [1].

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Figure 1: Traditional multisensory environment, with mirrors, balls, beanbags, and other therapeutic objects.

disengaged with their environments [27]. Therefore, helping children to turn their attention towards their bodies and the sensory stimulation being provided may improve the efficacy of these therapies.

In addition to the challenges associated with the multimodal features of a MSE, most activities conducted in such an environment are open-ended. As a consequence, sensory therapists frequently borrow strategies from occupational therapies to provide pediatric patients with goal-oriented tasks to maintain their attention [6]. In contrast, with open-ended tasks that offer a more subtle stimulation, occupational therapies can increase engagement with sensory therapies by giving children a sense of control over the stimulation and a sense of purpose when interacting with stimuli [24]. For example, while playing with balls of various colors, attention can be directed towards the size, texture, or color of balls, with the same objects alternately acting as kinesthetic or visual stimuli.

In our work, we explore how multimodal interactive displays detecting whole-body movements and interactions with physical objects augment sensory integration, supplement body-awareness therapies, and focus children's attention on their own bodies and sensory stimuli. In what follows, we describe the related work around natural user interfaces (NUI) to support body-awareness and sensory stimulation. We then briefly describe the design and development of SensoryPaint, a multimodal NUI system that enables users to "paint" with textured colored balls on a large surface (wall or canvas) while showing a reflection of the user's body projected onto the canvas [37]. We describe the qualitative results of two studies of SensoryPaint: a lab-based study of 15 children where they used the system for up to one hour, and a deployment study in which the system was fully integrated into existing daily therapy sessions of four children over five weeks. These results support our initial hypothesis that such a system can augment traditional therapies, balance children's attention between sensory stimuli and body awareness, and provide future direction and design implications for multimodal NUI for children with neurodevelopmental disorders.

RELATED WORK

Multimodal ubicomp systems provide opportunities for the novel treatment of sensory processing disorders. For children with motor and cognitive challenges, interacting with these multimodal systems through NUIs enables these children to engage with the activities, whereas previous applications may not fully support their particular circumstances and abilities. In this section, we describe work that supports multiple sensory modality inputs, including vision, auditory, tactile, and proprioception (*i.e.,* body-awareness) for children.

Tangible interfaces for multimodal sensory integration

Previous work has demonstrated how tangible user interfaces [10,17,28] support the visual and auditory systems of children with sensory processing disorders, particularly children with autism. Specialized devices that enhance musical therapies by providing additional visual [17,18] and auditory [11,12,13] stimuli have been shown to reduce the symptoms of sensory processing disorders. For example, Reactable [17,18] is an interactive tabletop surface used as a musical instrument. Reactable plays different melodies or sound patterns when users place acrylic objects on the surface. In a deployment study with children with autism, Reactable improved the social skills of participants [35].

Other systems with tangible interfaces have also been designed to combine sounds with visual stimuli [2,8,28,38]. The resultant sensory stimulation of these systems provides platforms for children's self-reflection [38], engagement in the activity [2], self-directed activity [28], and language usage [8]. The techniques utilized in these systems integrate physical and digital media. Examples include commercial devices (*e.g.*, liveScribe[2] running Tap&Play [28]) and the development of self-crafted devices to provide various means of interaction (*e.g.*, OnObject [8], T3 [10], and Topobo [12]).

Some projects have explored the development of tangible user interfaces following a task-oriented interaction model where users control the digital stimuli in large displays. For example, players controlled gameplay through a physical rope in Rope Revolution [36]. These projects show that tangible-based interactions support children with autism through the multimodal sensory integration. Existing research in this body of literature has not yet explored whether these tangible user interfaces can help children with sensory processing disorders gain body awareness.

Body-based interactions for self-expression

In contrast, projects exploring body-based interactions primarily focus on helping non-verbal individuals use their body to express themselves by redirecting users attention towards their own bodies. For example, MEDIATE [26] is a body-based interactive environment designed to stimulate creativity of non-verbal children with autism through vi-

[2]http://www.livescribe.com

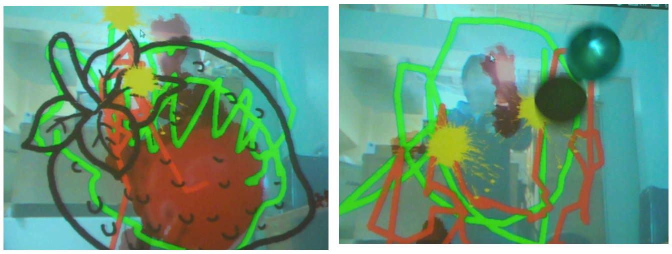

Figure 3: A user playing with the coloring book (left) and decorating paintings with "splashes" (right).

brotactile, visual, and auditory stimuli generated in real-time. When interacting with MEDIATE, children control the digital information displayed on a projected surface (*e.g.*, leaves, snow) by moving their bodies. During a laboratory study of the use of MEDIATE, children enjoyed using movement for self-expression [26]. While MEDIATE allows children to express themselves through their body movements, it does not fully support proprioception by giving feedback of the child's body [25]. In addition, MEDIATE does not support interaction with objects, which is important to retain children's attention during the therapy [29] and provide a multimodal sensory integration experience.

Following a task-oriented interaction model, other projects [11] have explored the use of casual games running on large displays to enable children to control the game by stepping on the floor or tapping on the wall. These systems use the *eyeclick*[3] and *touchmagic*[4] technologies to track basic user movements while displaying a variety of multimedia information (*e.g.,* photographs or animations). These interactive surfaces, although commercially available and deployed in shopping malls, have not yet been evaluated with children with special needs and are relevant as a more general case of providing visual and aural stimuli.

Taken together, these research projects indicate that integrating the physical and the digital world provides support for sensory impairments. However, these projects leave open the need for more work in understanding how these interactions can improve understanding and control over the body and its movements. Questions also remain as to what interaction model (open-ended vs. task-oriented) is more appropriate to provide a fully multimodal sensory integration experience, and regarding the potential therapeutic benefits of the multimodality of MSE already in use in sensory processing disorder therapy.

THE SENSORYPAINT SYSTEM

SensoryPaint [37] is an interactive painting tool showing a superimposed reflection of the user projected onto a canvas or wall to highlight the actions of the user. The system was iteratively designed during participatory design workshops with therapists and psychologists. The color of the user's reflection changes from red to green to demonstrate proximity of the user to the surface (see Figure 2). Rubber balls held by the user are detected by the system and act as paintbrushes of various sizes, textures, and colors, allowing for the painting of lines (see Figure 3, left). Users can either draw in a free form mode or use a template. Users can also splash color on the surface by throwing the rubber ball (see Figure 3, right). Finally, to complete the multisensory experience, sounds are played in connection with ball movement.

SensoryPaint has two main interaction modes. First, mimicking the open-ended interaction modality that is traditionally used during sensory integration therapies, users can freely interact with a variety of stimuli. Second, our design team selected two activities that use a coloring book with several drawing templates (see Figure 3, left) or a moving target. Using shortcuts, therapists can switch between modes and "clean" the painting canvas.

EVALUATION

We conducted two empirical studies of the use of SensoryPaint to understand the role of multimodal systems in support of sensory integration: one in the lab and one as an integrated part of an existing sensory therapy. These studies focused on uncovering the potential of this technology to support sensory integration, including stimulus sensitivity, body awareness, motor functioning, attention, and engagement.

Laboratory Study

We evaluated the use of SensoryPaint in a laboratory setting with children with neurodevelopmental disorders. Participants were recruited from a clinic specializing in the diagnosis and treatment of children with autism and other neurodevelopmental disorders. At the time of the study the clinic served approximately 3000 patients per year, ranging from infancy to 22 years in age. In total 15 children (all

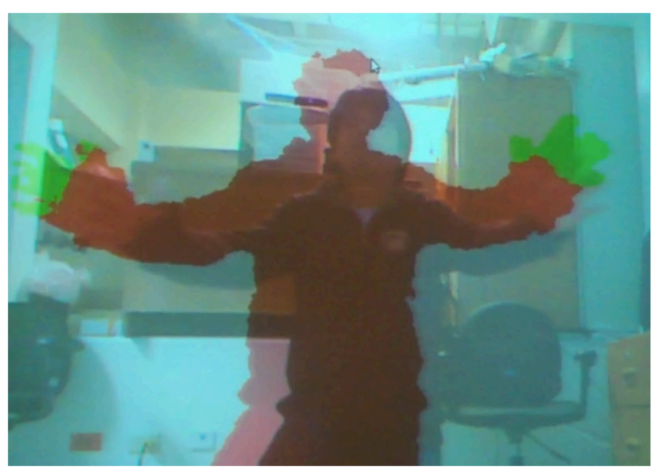

Figure 2: The SensoryPaint system showing the user's shadow on top of his reflection and coloring the fingers as they move closer to the screen

[3] http://www.eyeclick.com/

[4] http://www.touchmagix.com/

male) participated in the study, aged between 10 and 14 (M=11.2, SD=0.89). All of the children in the study were capable of communicating verbally but exhibited challenges with sensory processing and other symptoms related to autism. In this study the children played with SensoryPaint using three different modes (*i.e.,* free form, coloring book, and target practice) during a one-hour session in a controlled clinical setting. The children were asked to play with each mode in a randomized order during three sessions. The sessions lasted on average 9 minutes 46 seconds (SD=3:26) with the children being able to alternate between modes and end the session at whatever point they wanted (a maximum of 20 minutes for each mode was permitted). In a fourth session participants were allowed to choose one of the three modes to experience again. Participants were offered a 5-minute break between the sessions. They could print and take home drawings created during each session. The canvas was cleared upon starting a new session and at the participant's request (mean of 0.78 times per mode, SD=1.1). The participants were offered a variety of balls including different colors and sizes but similar textures.

Researchers observed participants using each mode and video recorded the sessions using two camera angles: 1) capturing the participant's face and major body movements, 2) capturing on-screen interactions. After the final session, audio-recorded face-to-face semi-structured interviews were conducted with all participants. The interviews focused on participant's opinions of SensoryPaint, (*e.g.*, which mode was their favorite and why), on design-oriented questions focused on how they might change SensoryPaint in the future, on what other ways they would like to use the system, and on their expertise with videogames in general. Interviews were generally short, lasting on average seven minutes. Due to the participant's limited attention not every topic was discussed in every interview.

Deployment Study

SensoryPaint was also deployed with four children with autism during daily 30-minute sensory therapies conducted in a public rehabilitation clinic in Northwestern Mexico. This clinic employs five psychologists and six physical trainers, serving approximately 100 children with motor and sensory dysfunctions (*e.g.,* children with autism or dyspraxia). The children, who are between four and twelve years old (M=8.25, SD=3.30, all male, one verbal), their primary caregivers, and two psychologists participated in the study.

The study involved two phases: *using-mirror* (two weeks) and *using-SensoryPaint* (three weeks). During the first phase we gathered ground truth data by observing children with autism engaged in traditional mirror-based therapies in the MSEs playing with balls with different textures. Researchers then installed SensoryPaint and gave a 15-minute training session to children and psychologists, explaining how to use the system. During the using-SensoryPaint phase, children with autism used SensoryPaint in the MSE, which replaced the analog mirror but used the same balls and similar visual and auditory stimuli. The balls were made of rubber or plastic, came in multiple colors, and tended to be too large for single-handed use but appropriately sized for children using two hands to paint. This ball size choice was made by the therapists to support gross motor skills as a higher priority to the fine motor skills users might develop painting with a traditional brush.

Members of the research team observed participants throughout the two phases of the study for approximately 22 hours (using-mirror: 9 hr. 18 min.; using-SensoryPaint: 12 hr. 35 min.). Participants' interactions with SensoryPaint during therapies were video recorded as consistent with our laboratory study, with the exception of one participant whose parent did not consent to video recording.

Weekly interviews (n=15) were conducted with psychologists and parents of the children with autism participating in the study. These participants were treated as proxies to gather the experiences of non-verbal children that participated in the study as suggested during user-studies with non-verbal populations [31]. Face-to-face semi-structured interviews were conducted across both phases. At the end of the study we interviewed the only verbal child that participated. Interviews generally lasted approximately 25 minutes and were recorded, transcribed, and translated from Spanish for analysis by the research team, which included both Spanish and English speakers.

During the using-mirror phase participants were asked about what they liked or disliked about the traditional MSE therapy, engagement and attention in relation to the therapy, their awareness of their own bodies (or those of their children or patients in the case of parents and therapists), and perceived therapeutic efficacy of the intervention. After using SensoryPaint, participants were asked to comment on how the system impacted body awareness, motor functioning, sensory skills, attention, and engagement. Participants were encouraged to tell stories and discuss what they found interesting, surprising, or different that week.

Analysis

All interviews and observations from both studies were recorded, transcribed, and inspected together. We used deductive analytical approaches (based on our initial questions surrounding the potential for SensoryPaint to improve attention and body awareness) and inductive approaches, allowing new themes to emerge from our data.

Once interviews were transcribed, all members of the research team read the transcripts from all participants. We examined the interview transcripts and field notes for data related to our initial research questions surrounding the potential feasibility of NUI systems in support of sensory integration. To support our inductive analysis, we used coding, memoing, and affinity diagramming throughout the data collection and analysis process, using techniques similar to those employed in grounded theory [7].

We first compared observations of each individual with data from other informants. As each piece of data was compared and differentiated from others, we assigned a preliminary code to identify types of behaviors. As the analysis and codification developed, patterns of common behaviors and situations began to emerge. We compared the patterns observed in each of the studies both within and across the two studies, making note of the ways in which they complemented or conflicted with one another.

For the deductive coding we used our initial hypothesis regarding the ability of SensoryPaint to augment traditional therapies (deployment study) and to be easily and enjoyably used in short sessions (laboratory study). We examined the ways in which observed behaviors and reported perceptions supported these hypotheses or not. Finally, we examined the themes in relation to our inductive analysis as a means to explain the results of our deductive analysis. We present in this paper the qualitative results from our two studies to more deeply understand the usage of the SensoryPaint system, as is commonly done in these kinds of preliminary studies [22].

RESULTS

In our two studies SensoryPaint balanced children's attention between their own bodies and sensory stimuli, improved sensory skills, and promoted socialization. All participants quickly mastered the features of SensoryPaint. Parents and psychologists involved in the deployment study universally expressed the desire to use SensoryPaint for longer periods and requested to buy the system for home use. To further explain these results, we explore the ways in which SensoryPaint was used and perceived, specifically in relation to interaction modes, attention and engagement, body awareness and motor functioning, sensory skills, and socialization.

Interaction modes

During our observation in the lab study when first introduced to SensoryPaint children with autism or other disorders sometimes engaged only superficially with the system. Extending SensoryPaint session times as well as prompting from therapists or informal caregivers can support children having a variety of interactions with the interface. For example, in the laboratory study in which children could spend at most 20 minutes in each mode and 60 minutes total with the system they often played with only one aspect of SensoryPaint (*e.g.,* scribbling with the paint, throwing the ball to make random splashes, or only using the paint to color in shapes).

During our deployment study over the course of several weeks more varied behaviors began to emerge. Participants typically began sessions with activities such as playing with their reflection, but would then move on to color pages and follow the behaviors modeled by the therapists. The range of interactions exhibited by participants show the importance of combining open-ended and task-oriented interaction modalities to enable children to gradually discover new interaction experiences with the stimuli available in the MSE.

Additionally, during these sessions, children and therapists often collectively used the system:

"We draw a circle around the child [to redirect child's attention] towards the screen, and to model how to draw. A child will later imitate us and starts drawing." (Jana, psychologist, deployment)[5]

During our deployment study psychologists recognized the importance of having "playful interactions" as interactive elements of the MSEs and as an engagement strategy, generally applauding SensoryPaint for being "fun and engaging". They also noted SensoryPaint as "useful and efficient."

The exploratory nature of this research required the inclusion of children with a variety of levels of skills and disabilities to understand how people with different capabilities might respond to the addition of ubicomp systems into their sensory therapy activities. Some children preferred to spend their time playing with the reflection and needed more prompting from specialists. Alternatively, others favored interactivity, spending their time drawing with balls and throwing balls towards the wall. We draw attention to the differences in participant preference here merely to demonstrate the need for a variety of interaction modalities (open-ended vs. task-oriented) in interactive surfaces for therapeutic uses. We would also like to draw attention to the potential of a multimodal NUI (*e.g.,* SensoryPaint) to be successfully integrated in therapeutic interventions for children with sensory processing disorders while supporting personalization and adaptation of therapy over time.

Attention and Engagement

Children with neurodevelopmental disorders have difficultly engaging in therapy and often more difficult to maintain their attention [27]. Of the 19 children who used SensoryPaint, 14 indicated that they thought the game was "fun," including all of the participants from the deployment study.

"[SensoryPaint] gave me energy. Energy!" (John, high functioning autism, laboratory)

"It was pretty fun. [I like] all of it actually." (Tim, neurodevelopmental disorder, laboratory)

Parents and therapists observing the children echoed these sentiments.

"He tells me that he had fun, he does not see [SensoryPaint] as a therapy. He says that he comes to play" (Lilo, mother, deployment)

"He is really happy when he comes to therapies" (Marley, father, deployment)

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[5] Participants' quotes were translated from Spanish to English, and some were slightly adjusted to fit English grammar conventions.

The five children who reported not enjoying the system all commented that it was "boring". These children went on to explain that they were looking for more game-like aspects to the system, such as built-in levels, achievements, or goals. These kinds of incentives are available in traditional therapies such as those used in the deployment study. Thus, helping users view SensoryPaint as an augmentation to therapy strategies rather than a stand-alone system may be beneficial in the future.

Conversely, one could imagine adding these types of elements to a system like SensoryPaint, thereby enabling it to be used as a self-contained therapeutic intervention in homes and other locations that may not have trained therapists. One child that participated in the lab study actually developed his own point system for the target mode of the game. He added his points out loud for the benefit of the researchers every time he hit the target. At the end of the session he insisted the researchers record his high score as a goal for the next participant. These results indicate that although structured game-like elements appeal to the children using the system and may even have therapeutic benefit, an open-ended system enables users to develop their own structures around the capabilities provided.

Although we did not explicitly recruit participants who had played video games in either study, every participant in the laboratory study had video gaming experience. Even though SensoryPaint was not designed as a game based on psychologists' design requirements, most participants still labeled it as a videogame. This tradeoff between children's expectations of having more game-like features built into SensoryPaint and the needs of physiologists to manually control when and how give away rewards needs further research.

As a combined tactile, visual, and auditory system, SensoryPaint includes elements that might appear differently to various children. In fact, in one case, a participant in the laboratory study went so far as to tease apart the physical act of throwing balls from the rest of the system, proclaiming:

"Nope, [I didn't like SensoryPaint]. I like throwing balls." (Andrew, high-functioning autism, laboratory)

While Andrew might have disliked SensoryPaint overall, the system still engaged his attention because he liked being able to throw the ball against the wall. Every participant attended to the different stimuli of SensoryPaint with varying levels of attention, but they all engaged in the system in some way.

Because SensoryPaint added interactive capabilities to the variety of sensations already present in their daily therapy, we were able to look at these differences more deeply in the deployment study. For example, therapists and parents perceived the SensoryPaint version of the mirror therapy to improve the children's ability to attend to the therapy.

"[SensoryPaint] calls children's attention more than the mirror, because with the mirror they will just stand there and leave, and with [SensoryPaint] children stay more time in front of the [SensoryPaint] and they move more." (Joan, psychologist, deployment)

Psychologists and parents attribute this improvement in attention to the "interactive elements" available in SensoryPaint. These elements go above and beyond what is available in the traditional mirror therapy and may serve to redirect children's attention towards the therapy instead of other distractions in the environment. Indeed, participants explained that the impact on attention is what truly makes SensoryPaint an assistive support tool and useful for improving sensory therapies.

"…more than anything I would use SensoryPaint for attention, so that children [could] pay attention" (Jana, psychologist, deployment)

We would not have predicted the kind of sustained engagement over time observed in the deployment study based on the results of the laboratory study alone. Although some participants (n=5) engaged heavily for the entire session in particular activities most participants interacted somewhat less intently. These less intent interactors were most likely to play with the system until they had tested its boundaries and discovered all potential functionality. Then they would abandon the system, either asking the researcher which mode was next or simply stop engaging altogether. Their interviews shed some light on this behavior:

"It was kind of both fun and not fun. [The parts I really like] is that I get to throw stuff at the target." (Mark, neurodevelopment disorder, laboratory)

"…it wasn't something you would do for that length... it kind of gets old after a while, it gets not fun. It wasn't that much fun. ... [I] didn't find it challenging" (Zach, high-functioning autism, laboratory)

This is consistent with the period of time a sensory integration therapy traditionally lasts, as over-stimulation can cause exhaustion. More research is needed to select the appropriate mechanisms for sustaining engagement across time in a NUI. In particular, engagement must be sustained for a time appropriate for therapeutic benefit. In the laboratory study participants were largely allowed to use the system as they chose, an intentional design for an exploratory phase of research. During the deployment study the system was integrated into existing therapeutic interactions to understand the importance of human facilitation for NUIs and other interactive therapeutic tools. Thus, any new design features created for supporting engagement should be balanced with the ability to integrate with human support by both professionals and familial caregivers.

Body Awareness and Motor Functioning

To increase the chances to redirect the attention of children towards their own body, we included interactive elements superimposed on top of children's bodies. In particular, we added a shadow projected on top of the reflected body that changes color as a child gets close to the surface. This feature tended to only begin to impact participants after they had used the system for an extended period of time.

Although a primary measure of success in sensory integration therapy is how well children perform tasks in session, the ultimate goal is to improve their abilities outside of therapy. Over the course of the deployment study and outside of therapy sessions, parents began to report improvements, particularly in gross motor skills. Parents described their children as increased interest and capability of playing sports and performing athletic movements (*e.g.,* running, walking, and using the stairs):

"…he is still scared to climb stairs, but when he goes down the stairs I noticed he feels more confident, and I didn't notice that before, he would struggle a lot when using the stairs." (Bella, mother, deployment)

"*…my husband told me my son improved his motor skills when playing tennis and soccer, and I have noticed he has not recently tripped up. Before [SensoryPaint] he would fall down a lot or hit himself with things. He repeatedly had several bruises, and now he is not bruised" (Lilo, mother, deployment)*

As demonstrated in the literature [23], improvements in physical activities are often a result of improved awareness of one's own body in space as well as in gross motor skills. When queried about the progress they witnessed at school, outside of prescribed sensory therapy time, therapists working with the children also described improved coordination. Additionally, they mentioned the connection of these improvements to the ability of the children to control the music with the painting.

"He can throw the balls with one hand for example. Before [SensoryPaint] he needed both hands. Now he does it only with one, following the music rhythm…" (Jana, psychologist, deployment)

Therapists particularly emphasized the potential for an ubicomp system like SensoryPaint to improve body awareness and provide variations to novel therapies for motor functioning.

"…we could tell children who do recognize their own body to circle body parts [with SensoryPaint], like circle your hand, circle you head, circle your right arm, because they get confused when seeing themselves in the mirror". (Jana, psychologist, deployment)

Similarly, in the laboratory study, participants reported SensoryPaint helped with coordination and motor functioning, even though these participants did not have the extensive motor function disorders or body awareness deficits.

"I like [the target] because it helps you aim." (Greg, high-functioning autism, laboratory)

"It's really eye-hand coordination. You have to look and throw. That's the hard part." (Tim, neurodevelopmental disorder, laboratory)

Staff at the deployment clinic noticed greater attention to the shadows, describing SensoryPaint as redirecting the attention of the children towards their own reflection.

"They do notice their body. Now they know it's their own body, because they start seeing how it moves. They move their leg, and they see that it's moving in front of them… they're more aware…" (Joan, psychologist, deployment)

Despite the substantial gains seen in the deployment study by working with the reflected image feature, only one child in the laboratory study mentioned noticing their reflection during interviews and described it as "weird." Researchers observed that the children in the laboratory study were not attending to the reflection during most of their interactions. The differences here could be attributed to the length of time with which each group of participants used SensoryPaint (daily versus once), the participant characteristics and level of functioning, or direction from therapists. Thus, more work is needed to explore the particular impacts of the reflected image feature, and what other interactive elements are appropriate to re-direct children's attention to their reflected image.

Overall, these results demonstrate that appropriately designed multimodal systems can increase body awareness for children with neurodevelopmental disorders. Additionally, it is worth exploring the potential to support other populations with disabilities such as motor conditions (*e.g.,* dyspraxia).

Sensory Skills

Sensory integration therapy is primarily aimed at improving skills related to sensory input [3]. Thus, during the deployment study, we evaluated the impact of SensoryPaint on the processing of external sensory input and mood enhancement. All of the children participating in the deployment study had been involved in daily sensory therapy for several weeks prior to the study. However, parents and therapists of these children still reported additional positive impacts in responses to visual, auditory, and somatosensory inputs. They attributed these further improvements to the addition of SensoryPaint to the therapy regimen.

"What was noticeable is that he improved his sensory skills. For example, now he tolerates more smells that he used to dislike, like the smell of eggs it used to gross him out… …what I've noticed too is that the noise of the insects doesn't bother him anymore. Whenever [there] was like a fly in his room, he started to cry, he would cover his ears, he would run out of his room crying with his ears covered. This behavior also stopped [since using SensoryPaint]" (Lilo, parent, deployment)

The underlying reasons for these effects provide the impetus for additional research. If participants report looking forward to therapy sessions and being more engaged, it could have a huge effect on outcomes without any real therapeutic benefit from SensoryPaint itself. However, parents and therapists also described effects that are more likely attributed to use of the system specifically. For example, therapists and parents reported that the children in the deployment study appeared calmer after using SensoryPaint.

"When he arrives to the therapy he is a little hyper and afterwards he is more relaxed. And after a while he continues to be relaxed" (Bella, mother, deployment)

"…only SensoryPaint and the beach have this 'calming' effect on him" (Marley, father, deployment)

Therapy session data confirms these reports made by parents as we often observed children lingering after sessions that included SensoryPaint, calmly playing with other toys or swinging on a swing. Additionally, parents explained that this "calming effect" usually lasted longer than effects they had observed previously from therapy, often for the rest of the afternoon or even until the next day. Researchers sometimes observed this "calming effect" when children stayed after the therapy session.

Although engagement and excitement with using the system were also observed in the laboratory study, the same kind of calming effect was not evident. There are several explanations for this difference, including the limited amount of time the system was used by the participants as well as the potentially anxiety-provoking interview that followed system use. However, we note that participants did describe the system as calming even without this explicit evidence in their behavior.

"Yeah, whenever you're angry, you can just like scribble and all of that. You would do it as hard as you can, and you will calm down." (Greg, high-functioning autism, laboratory)

Thus, this type of system might provide a physical outlet for challenging mental states, just as going for a jog does for many adults. Participants in both studies tended to work quite hard physically when engaging with the system, particularly when throwing the balls as indicated by their shortness of breath and sweating.

Some of the most extreme physical exertion in the studies emerged when children became interested with one mode (*e.g.,* target mode or coloring book mode). In these cases, researchers observed that some children would pass the time by becoming hyper-focused on detail-oriented painting or throwing the ball energetically. One participant in the laboratory study even spent his time dancing with the ball. In this sense, intense concentration may have facilitated post-therapy calm.

An increased tolerance for real-world stimuli, bolstered concentration, and the physical advantages of exercise are all benefits pertinent to therapeutic advancement as well as engagement in home and school environments. While the causal mechanisms of SensoryPaint's impact on calmness require further exploration, the therapeutic qualities of the system remain evident.

Socialization

While we designed SensoryPaint for individual use, during our deployment study, participants collaboratively used the system often. Parents and therapists noted that their children improved their language and social skills when using the system.

"I do see that [SensoryPaint] helps him a lot to interact more with other people, with other kids" (Bella, mother, deployment)

Parents also stated that SensoryPaint promoted social connectedness with the children who were using the system for extended time.

"He likes coming here, […] he sees this time as if he comes to hang out or something like that and since he struggles a lot with socialization, he feels that he has improved his social skills" (Lilo, parent, deployment)

These improvements in socialization may come in part from directly having to work collectively during sessions. In these cases, participants learned new protocols for the collaborative use of tools such as turn-taking or following directions by modeling therapist behaviors.

"…for example with Mat, if I tell him to draw a sun he will do it, with Aidan you have to model the behavior so that he would do it" (Jana, a psychologist, deployment)

Participants in the laboratory study frequently interacted with whoever was in the room while they were playing with SensoryPaint. They would converse, narrate their interactions, and even encourage others to participate with them. For example, one child painted the area of the screen where his mother appeared as a joke. Another child asked the researchers to help him draw on the screen.

"[SensoryPaint would] be a lot more fun with other people, because they actually do different things." (Josh, high functioning autism, laboratory)

These results indicate that multimodal NUI like SensoryPaint could explicitly support social interaction by adding elements of a multi-player game with shared objectives related to target practice and painting and even the incorporation of short, goal-oriented narratives.

DISCUSSION

The results of this work demonstrate that people can easily use a large display that takes both body movement and interaction with physical objects as input with limited instruction. Additionally, such a system can support sensory integration therapies, providing health and educational benefits, particularly in relation to socialization, body-awareness, and sensory integration. Reflecting on these results we have identified a set of design and practice-based recommendations for ubicomp researchers and practitioners developing innovative technologies for similar therapeutic interventions.

Implications for Design

Multiple interaction modes sustain engagement and help to develop different skills. As an augmentation to MSE, SensoryPaint was intentionally designed as an open-ended system through which participants could engage creatively with their own bodies and the MSE. At the beginning, the open-ended interaction mode was more appealing to the children in these studies. However, when task-oriented goals were available helped them deeply engage with SensoryPaint and obtain more personalized benefits. Thus, we recommend that therapeutic tools have multiple levels and modes of engagement that can be tweaked by therapists, parents, or individuals with autism to support the particular skill being learned or performed. Certainly, it is the case that in any kind of personalized learning environment, different levels of challenge or types of engagement might support different levels and types of learners (*e.g.,* [16]).

What is particularly compelling here is that we see the interaction models and input types having multiple benefits related to specific motor and sensory challenges as well as skill development over time. Given the benefits of using different modes at different times, there are open research questions around how to support therapists and families in developing cohesive experiences with optimal therapeutic benefits while configuring and personalizing system use. One must balance the need for evidence-based care [14]—which requires standardized care to some degree—with the dynamic and personal configuration potential of these types of interfaces [19].

Concurrently, producing end user configurable interfaces that are useful and usable by non-technical caregivers is its own challenge, but one that can be met. In particular, our experiences indicate that clinical processes already exist for parent training and ongoing education of teachers, therapists, and other professionals. Additionally, the use of capture and access tools and mobile sensing platforms embedded within tools like SensoryPaint can allow for diagnostic and monitoring work over time and even at a distance [15].

When used in therapeutic interventions, NUIs should mimic instructional scaffolding techniques. In the case of SensoryPaint, therapists both modeled technology uses and provided instructions directly. Both of these techniques are commonly used in MSE. Thus, in our case, mimicking these techniques enabled therapists to integrate the system into their current practices without disrupting student learning too substantially. As Kientz *et al.* have previously noted, the more similar you can make a system—and the records maintained within it—to its predecessor, the simpler adoption will be [21].

However, our experiences suggest that NUI can and should go beyond integrating into the therapies with support from therapists. It is possible, though not tested directly in our work, for these interfaces to scaffold learning on their own without—or with less—human support if appropriate techniques are used. For example, by providing additional reinforcement through sounds, text, or images, in the interface, the system might encourage use of the MSE (a therapist's role) while providing its benefits. Likewise, by providing video models that could be viewed prior to engagement, students might learn to use the NUI without the need for human modeling.

Appropriate goals and structure should be used to support specific therapeutic outcomes. Existing sensory therapies can provide this level of structure, as was done in the deployment study. However, open questions remain as to how these game-like reward mechanisms could be integrated into multimodal ubicomp systems like SensoryPaint without distracting individuals from the ultimate goal of maintaining attention towards the therapy and their own bodies. For example, rewards could be provided based on effort, such as by the system sensing that a child had attempted to model touching his head at least ten times, or based on skill development, such as by sensing the child successfully touched his head ten times when requested to do so. These kinds of rewards of course require high levels of accuracy in sensing, levels that are not required when a human therapist provides the rewards. They also require an interface by which such rewards—and the activities that must be sensed to achieve them—could be programmed for each child so as to avoid over taxing or over stimulating particular children by providing too little or too much reinforcement. Thus, balancing of gamification, interaction, and sensory stimuli must be considered in the design process for sensory intervention technologies.

Implications for Practice

Our experiences with SensoryPaint indicate that these kinds of systems will be most successful when implemented alongside existing therapies, a perhaps not shocking but still important finding. However, even though others have also found this to be true, integration into existing approaches is not necessarily straightforward [20]. In particular, although deployment studies often include a notion of inclusion into existing practice [30,33], outside of the confines of research, commercial technology designers and developers cannot always afford the same luxury of engaging communities of practice long-term. Thus, in this section, we include implications for conducting this kind of work outside the bounds of research.

In this work, we found "appropriation and replication" [32] to lead to the suitable integration of innovative technology into therapeutic and educational programs and expect that such an approach is particularly adoptable in clinical or educational settings outside of research. However, other approaches may be equally valid. The specific issues we found to be most central to successful integration of our system into clinical practice are described below.

Personalization promotes a sense of ownership. In particular, the kind of personalization that participants in our studies were able to accomplish was key to SensoryPaint's appeal in both studies. This personalization was in part possible due to the simplicity of the open-ended interaction mode of SensoryPaint. However, by providing end user authorable interfaces, such as described in the prior section, as well as ensuring appropriate training to use them, can empower therapists, parents, educators, and individuals with autism even more. Additionally, to the degree that technologies and the programs that surround them can be adapted—and intentionally adaptable even without intervention from the technologists—they will support the long-term sustainability of the changes made to both the tools and the practices surrounding them.

Collected data must be useful for many stakeholders. Most clinicians and educators value empirical measurement. In fact, in many settings—including those in which this work took place—law requires empirical validation of novel approaches. However, these measurements are often personalized for the clinician and clinic. Thus, by adapting data collection techniques slightly, designers can provide additional value to their clinical partners and ensure more active engagement. Likewise, parents and individuals with autism may have their own views on which data are useful and interesting. For example, reports created at various levels of granularity may provide some view for the different stakeholders into the same data without overwhelming any one person with information they do not want or need.

Therapeutic programs must be modified to take advantage of novel technologies. Although making use of existing therapies and modeling their successes is useful, new systems cannot simply be inserted wholesale into existing therapies without modification or adjustment. In our deployment study, we created new activities to be included in existing therapy sessions. Because this was a research study, we were able to leverage relationships we had built up amongst researchers from varying backgrounds and fields in the development of these activities.

Professional designers and developers may not have close relationships with the stakeholders they hope to serve, and likewise, clinicians and educators may not have software developers to call for custom solutions to meet their needs. Thus, we recommend using existing techniques for engaging with clinical and educational partners from other fields. For example, sales representatives have long used interviews, in-person demonstrations, and trainings to help gain buy-in from potential customers who then turn to them for consultation on developing new technologies and new processes around technology use. However, these approaches may not be enough. Special educators and medical specialists receive numerous "cold calls" for new technologies. They cannot—and would not if they could—adjust their therapies based on every new product that arises. Thus, open questions remain for each kind of therapy that ubicomp systems might augment as to how new practices might be co-developed alongside new technologies and who should be involved in those efforts.

CONCLUSIONS AND FUTURE WORK

We evaluated the SensoryPaint system to explore how multimodal ubicomp systems can support sensory integration therapies for children with sensory processing disorders. This work opens new possibilities for ubicomp systems to improve attention, sensory integration, body awareness, motor functioning, and habituation to stress-inducing stimuli. SensoryPaint may also have social benefits by enabling children with sensory processing disorders to more readily adapt to sensory information in different environments, engage in playful interactions with others, focus on goal-oriented tasks, and feel an enhanced awareness of their ability to influence their environments.

All of the participants in these studies successfully used SensoryPaint, indicating that NUI like SensoryPaint could be helpful for an even broader population than studied here. Having increasing levels of difficulty would facilitate the system's ability to engage the entire spectrum of children with autism as well as any other developmental challenges related to bodily awareness, sensory skills, attention, and socialization. Moreover, increasing levels of difficulty could also be used as a method for tracking progress automatically for therapists, parents, and children. Future work should examine ways to personalize and customize NUI for therapeutic interventions across a wide variety of contexts and users.

To properly calibrate the vision-based algorithms used by SensoryPaint, users must appropriately control the lightning conditions in the environment. The need for calibration limits the ability for families and therapists to use the SensoryPaint system and opens up research opportunities for exploring automatic and end-user calibration techniques.

Although the populations we were able to access during our studies affect our claims; the design, development, and evaluation of SensoryPaint support our initial hypothesis that multimodal systems with NUI can help augment occupational and sensory integration therapies. Additionally, our results indicate that further exploration may reveal ways in which these tools can be used in a variety of other therapeutic domains, particularly by building on the opportunities and challenges for design uncovered in this work. In future work, a larger deployment of a new version of the system will give us data to explore SensoryPaint's impact on body awareness, sensory skills, attention, and socialization.

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