Words Become Worlds:
The LIT ROOM, a Literacy Support Tool at Room-Scale.

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ABSTRACT

Illiteracy is a global problem impacting the growth and development of individuals and society. Studies indicate that picturebook reading within a facilitated storytime setting is an important tool for children's language acquisition. In the research reported here, we hypothesized that literacy, in an increasingly digital society, can be cultivated in a robot-embedded environment that is physical, digital and evocative of the picturebook being read. *Words become worlds*. To test our hypothesis, we designed, prototyped, and implemented the LIT ROOM, a cyber-physical room for literacy. As a *Research through Design* [RtD] exemplar for interactive systems at habitable scale, the LIT ROOM featured a multi-phase, iterative process of design and evaluation for usability and efficacy. Evaluations with 35 children and 6 librarians in a public library serving a population with grave literacy challenges suggest that our reconfigurable learning environment facilitates a diversity of children's literary responses during the dialogical reading of picturebooks.

Author Keywords

Computer Support Tools; Children; Emergent Literacy; Intelligent Environments, Architecture, Design; Human Factors, HRI.

ACM Classification Keywords

H.5.2 [Information Systems]: User Interfaces—*Theory and methods, and* H.1.2 User/Machine Systems—*Human factors;* K.3.1 [Computers and Education]: Computer Uses in Education—*collaborative learning*.

INTRODUCTION

According to an UNESCO study, roughly 20% of the world's population is illiterate [35]. In the United States, 14% of the nation's residents are illiterate; 32 million Americans cannot read the directions on a medicine bottle, and 50 million Americans cannot read above the 5th

grade (ten-year old) level [24]. The cost of illiteracy to society, not to mention the cost to the individuals who can't read, is staggering [19]. Efforts to enhance early literacy are necessary to address the significant societal problems that illiteracy poses [24]. As such, public libraries direct much of their resources toward literacy acquisition programming, especially for at-risk children [17]. There is evidence that public libraries effectively leverage technologies (physical and digital) to reduce illiteracy in their communities [17]. There is also a body of literature focused on the usability and efficacy of technology-enhanced tools and texts for children, including electronic books (e.g. [8, 23]), augmented books (e.g. [4, 36]), multi-media tools (e.g. [3, 14]), robotic-enhanced literacy tools (e.g. [29]), and technology-enhanced story rooms (e.g. [5, 7]). But despite the efforts of libraries and technologists, little is known about how technology, particularly when deployed at larger physical scales, may be leveraged to augment children's literacy during *read-alouds* [17], even though these instructional events, where adults read books aloud to children, have been shown to be essential for children's literacy attainment [9, 10, 16, 17, 37].

Figure 1. The LIT ROOM, from inside.

In response to this shortcoming, we designed, implemented and evaluated the LIT ROOM (Figure 1), a cyber-physical room set within a public library. In a typical LIT ROOM activity, a librarian and a group of 4-8 children engage in a multi-sensory read-aloud of a printed picturebook. Prior to reading the text, librarians program wall and ceiling-mounted robotic panels by selecting, on a tablet computer, from a wide palate of lighting, sound and shape/movement

effects to create "scenes" that they imagine are evocative of key aspects of a picturebook they select from the library collection. Multi-sensory scenes are saved into the system and replayed in sequence during an interactive read-aloud. When activated, each scene enhances the text and serves as a spatial prompt, providing the adult reader an opportunity to elicit children's literary responses and facilitate reader-child dialogue. This type of *scaffolding*, where the adult reader actively guides the discourse – is critical for children's meaning-making during interactive read-alouds [33]. In the LIT ROOM, the adult works in tandem with the lighting, sounds and shape/movement effects to facilitate connections between children's understandings, the multisensory environment and the text.

As a story-extension tool, the LIT ROOM system also provides opportunities for adult readers to engage children users as co-creators of their learning environment, which is very motivational to children [13]. The ideas, understandings and connections of these young readers shape their physical surroundings, *giving form* to their ideas about the text. When the form of the picturebook offered by the adult reader's pre-programmed scenes fails to match those envisioned by the children, they are afforded the opportunity to make visible and tangible their own imaginations for inspection by themselves and others. Using the touchscreen tablet to manipulate the environmental effects, children can increasingly assume ownership of the environment, providing real-time feedback for their creative expressions. The broader aim of this exemplar of interdisciplinary "Research through Design" [12, 38] is to successfully leverage technology in the creation of a reconfigurable environment augmenting the dialogical reading of picturebooks within an engaging, exploratory space for the advancement of literacy – one that facilitates a wider range of children's literary responses and scaffolds a diversity of textual interpretations.

Informed by new thinking about literacy that recognizes knowledge as "situated," the LIT ROOM may be understood "in terms of a relationship between an individual with both a mind and a body and an environment in which the individual thinks, feels, acts and interacts" [13]. The LIT ROOM's wide-ranging pallet of lighting, sound, form, and movement at room-scale finds inspiration in Gee's argument that "people are smarter when they work in smart environments; that is, environments that contain, integrate, and network a variety of tools, technologies, and other people, all of which store usable knowledge [13]. Similarly, the LIT ROOM's reconfigurability is inspired by *embodied interaction* in children which foregrounds the body of a child in a physical environment that affords "multiple spatial configurations," thereby advancing the "child's grasp of our universe through active, creative exploration" [2]. An elaboration of our motivations for the LIT ROOM including our review of the literature on literacy support tools can be found in our foundational publications [30, 31].

ITERATIVE DESIGN

The LIT ROOM was developed and evaluated by a research team of architectural and interaction designers, roboticists, a literacy expert, and a library scientist. Conceptualization of the LIT ROOM followed its pilot project, the LIT KIT (Figure 2—left) – essentially a LIT ROOM reduced to a low-cost, compact, and easily transportable box that supports multi-sensory picturebook read-alouds in classrooms and private dwellings [31]. While the LIT KIT offers a compelling facsimile of the LIT ROOM experience, the LIT KIT amounts to a lesser social, lesser spatially-rich literacy support tool.

LIT ROOM Conceptualization and Early Prototyping

The conceptualization of the LIT ROOM benefited from the team's extensive, iterative development and evaluation of LIT KIT as reported in [31]. Our early photo collage established the LIT ROOM's key components, including a reconfigurable ceiling, represented in the collage by our photo of a matchbook manipulated to show different physical configurations (Figure 2—center). Other key components include: a transportable superstructure that defines the read-aloud context and supports the robotic elements; wall and ceiling-mounted robotic elements containing integral lighting, sound, and actuated panels that transform the environment, and a touchscreen tablet that serves as the interface for read-aloud design and activation.

Figure 2. The LIT ROOM collage; LIT KIT; early prototype.

To "make mistakes faster" [21] in our early prototyping and evaluation activities, we cobbled together a full-scale prototype of the LIT ROOM (Figure 2—right) using Bosch aluminium framing [6], polyethelene foam actuated by a pulley and tendon system, digital projectors, and audio speaker. Physical reconfigurations were operated manually to simulate a full-function system following the "WoZ" method [11]. Low-fidelity prototypes like this one were developed using design and engineering principles developed in our laboratory [15], evaluated by usability methods common to the design and evaluation of interactive technologies for both adults [25] and children [20]. Multiple, formative evaluations provided information that guided design decisions as the project developed from small and full scale, low-fidelity prototypes to the full-scale, robotics embedded LIT ROOM implemented in the children's room of our public library test-bed.

Phase-1 Evaluation: Heuristic Evaluation & Co-Design

We performed heuristic evaluations and co-design activities on low and high-fidelity prototypes of the LIT ROOM, and report here on overall results.

Heuristic Evaluations

Heuristic evaluations were performed in order to: (1) identify usability errors impacting the technical design (such as lag time between motor activation and panel actuation); and (2) identify usability errors impacting the educational context (such as the need for task light sufficient for reading the picturebook balanced against a space dark enough for the LIT Room's environmental effects). Additionally, the evaluation served as a pilot for procedures used to gather usability data for the children participants.

Co-design Activities with Children and Librarians

Three studies engaged children and librarians as co-designers of the LIT ROOM. A focus group of six children's librarians used task analysis and paper prototypes of three touchscreen formats to reveal preferences for both the format and functionality of the LIT ROOM interface. Another focus group of librarians co-designed lighting, sound, and moving panel designs for picturebooks included in the study, revealing preferences for the multi-media effects in the space. Finally, sixteen second-grade children (typically seven and eight-year olds) co-designed scenes from picturebooks with team members. These studies built upon established participatory design techniques that have proven effective with children [22].

Development of the Fully Functioning Prototype

For library implementation, the LIT ROOM prototype was assembled to partial completion in our lab where it was evaluated and refined to address issues related to constructability and technical functionality. The prototype was then disassembled and installed in the children's reading room at Richland Library [27] in Columbia, South Carolina – the largest public library in the state, located approximately 100 miles from our lab.

LIT ROOM Superstructure

The LIT ROOM superstructure inscribes a twelve-foot square in plan. The primary frame defining the vertical walls is eight feet high. For ease of assembly and disassembly, the superstructure is reduced to the fewest structural members required to both create a rigid frame and to structurally support the weight of the wall and ceiling-mounted robots. Black, extruded plastic conduits are attached to the superstructure at the top of the beams, facilitating power distribution to the four robots.

All connectors and fasteners are either flush with the extruded profiles or hidden, resulting in a clean, sleek appearance. The installation is clad with white and red, aluminium-composite panels, digitally fabricated using CNC routers, creating two distinctly visual elements (Figure 3). The horizontal, overhead portion of the red arch serves as an electrical plenum, concealing wiring running from the main control cabinet (located in the white tower) to the extruded plastic conduit connecting to the individual robots. Aesthetically, the red archway spatially defines the entry to the LIT Room, serving as the threshold between the

ordinary space of the library and the extraordinary world within. The archway also houses a bookshelf to hold a small collection of picturebooks for read-alouds.

Figure 3. LIT ROOM in the library – front façade.

LIT ROOM Robotic Components

What was a reconfigurable ceiling in our photo collages (Figure 2) became one of four identical robotic modules (Figures 4 and 5) in the fully-functioning prototype. Each robotic module contains integral lighting, sound, and a motor assembly for actuation. Three of these robotic modules are mounted within the wall frames; the fourth is suspended from the ceiling frame. Each robotic module measures three feet, four inches horizontally and seven feet, four inches vertically. The four-inch margin around each robotic module allows for connection to the superstructure.
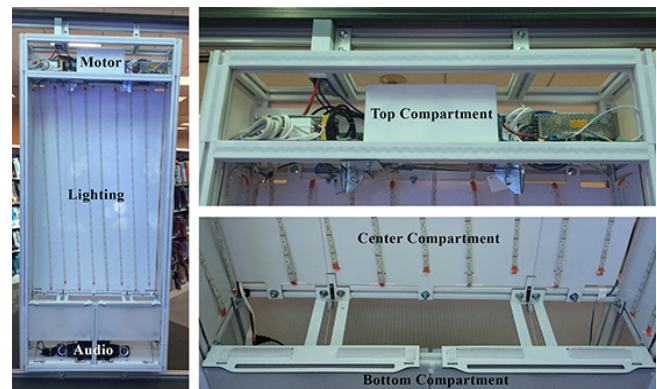

Figure 4. Details of one of four identical robotic modules.

Aesthetically, this gap creates the appearance that the robotic modules are "floating" within the structural frame. The modularity of their design is intended to create the suggestion that the LIT ROOM could be populated by additional robotic components, resulting in a variety of enclosure conditions. The depth of each robot, ten inches, is a function of the dimension of the technological components housed within, and the depth required for adequate panel deformation.

Each robotic module is faced with translucent, 4mm thick, light-weight, corrugated plastic, digitally cut and scored

using a CNC router fitted with a drag-knife attachment. A library of such corrugated panels is provided with the LIT ROOM (Figure 5 shows examples). Within each robotic module, a plastic pulley system guides a nylon cable connecting the motor to each plastic panel. When actuated, the plastic panels create abstract shapes, shadows, patterns and/or movements inside the LIT ROOM. Adhesive Velcro, attached to tabs at the top and bottom of each plastic panel, secures the plastic panel to the robotic panel, allowing the librarians and children to easily change-out plastic panels to achieve different formal possibilities (Figure 5). The Velcro can also be repositioned on either side of the panel, resulting in a wider variety of potential profiles. For example, a panel that creates a concave arc will create a convex arc when the Velcro is repositioned on the opposite side. We created approximately thirty pairs of panels for the initial study. Many panels were designed with librarians and children, inspired by picturebooks used in the participatory studies (elaborated here, later).

Figure 5. Four different corrugated panel designs, actuated.

LIT ROOM Interface

A touchscreen tablet (Figure 6) serves as the interface for the LIT ROOM. The interface facilitates the design of a multi-media, environmentally-situated read-aloud and allows adult readers to replay saved scenes while reading the picturebook to children. A home screen (Figure 7—top-left) displays an image of a three-dimensional model of the LIT ROOM installation, and contains two buttons: "Start," which guides users into the system, and a "Sleep" button, which provides a real-time demonstration of the lighting, sound and movement effects.

Figure 6. The LIT ROOM GUI interface in use with children.

By touching the "Start" button, users advance from the "home" screen to the "My Read Aloud Library" screen

(Figure 7—top-center). This screen displays a listing of pre-programmed picturebooks. The initial LIT ROOM prototype contained six pre-programmed read-alouds designed in collaboration with the children's librarians. The cover and title of each picturebook is displayed in a list that is navigated by a standard, vertical swiping motion on the interface. The library can hold an infinite number of programmed read-alouds, with new picturebooks added to the listing in simple, sequential order using the "Create New" button. When users press the "Create New" button, the interface advances to a "Create New Read Aloud" screen, where users are prompted to enter the name of the picturebook into the system. By tapping on the entry field, a keyboard appears. Pressing "Go" saves the title into the system, and returns users to the "My Read Aloud Library" screen. The new read-aloud is populated into the system at the bottom of the picturebook listing.

Pressing a saved read-aloud on the library listing screen allows users to access design and reading features for that picturebook. Upon touching the desired picturebook, the interface advances to a screen that lists the text title, displays an image of the cover, and indicates how many (and if any) scenes have been programmed for the read-aloud. On the picturebook screen (Figure 7—top-right), four options are provided to users: "Create New Scene" which allows users to add a new scene to the read-aloud; "Edit Scene" which provides access to existing scenes for revision; "Read" which advances to the screen that activates the multi-media read-aloud, and "Delete Book" which allows users to delete a read-aloud from the library.
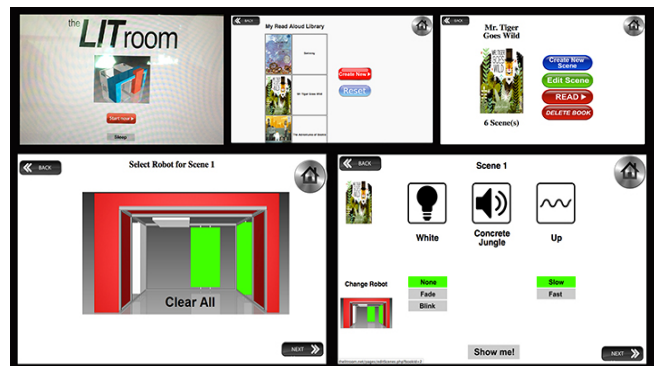

Figure 7. Screen shots of the LIT ROOM tablet interface.
Top row: **Home, Library, and Read/Create/Edit Scene**
Bottom row: **user-controls of lighting, sound, form/movement**

To add a new scene to a read-aloud, users touch "Create New Scene." The interface advances to a robot selection screen (Figure 7—bottom-left) that depicts a three-dimensional image of the LIT ROOM. Prior to selection, the robots are depicted in their resting state as solid white elements. Touching a robot selects it for activation during the scene. The interface provides visual confirmation by highlighting selected robots in bright green. Users can select one, two, three, or all four robots for activation for a scene. All robots selected for the scene will activate in

unison and will display the same choices for lighting, sound, and movement effects. A "Clear All" button is provided so that users can reselect and revise choices during the robot selection process. Designers save their robot selections by touching "Next," which also advances the interface to the effects customization screen.

Users can select lighting, sound and movement settings on the effects customization screen (Figure 7—bottom-right). This screen orients the user to the read-aloud (an image of the picturebook is depicted in the upper left-hand corner) and the scene being designed (listed at the top-center). A small image depicting the robot selection made on the previous screen is displayed in the bottom left-hand corner. Users are also afforded the opportunity to change their robot selection by touching the "Change Robot" button above the image. Lighting, sound, and movement settings are accessed through three, large icons in the center of the display. Touching on an icon activates a listing of options for that effect. For example, pressing the light bulb icon results in a listing of lighting options directly below the icon. A standard, vertical swiping motion on the interface navigates the list of color options. Users select a color option (the color "Red," for example, is displayed using red text). Upon selection, the listing of options disappears and the color selection populates the space beneath the light bulb icon. Designers are also given three options for light timing effects ("None," which results in continuous light in the robot, "Fade," and "Blink") after making a color selection.

The LIT ROOM effects library includes: nine standard options for color, three options for light timing; fifty-five options for sound including contextual sound files such as "Tiger Roar," "Train" and "City Night Crowd," music sound files such as "Melancholy" and "Tango" named to suggest their inherent emotional quality, and ambient sound files with the least specificity such as "Hum," "Danger," "Alien," and "Static;" and three options for panel actuation including "Down" which leaves panels dormant in the resting position, "Up" which raises panels to the maximum vertical position emphasizing the shapes created by panel scores and perforations, and "Up/Down" which activates panels in a continuous motion from resting position to the maximum vertical position, emphasizing movement over shape.

A "Show Me" button is provided on the effects customization screen, allowing users to see their choices in real-time within the LIT ROOM. When pressed, the button turns from grey to green, indicating that the real-time feedback feature is activated. The "Show Me" feature is provided in the interface as an option. Frequent users who are familiar with the lighting, sound and motion effects after repeated use may prefer to opt out of the real-time feedback feature. Novice users, however, are likely to desire environmental feedback as they customize scenes and explore options provided in the effects library.

Pressing "Next" on the effects selection screen saves the choices made for the new scene, and advances the interface to the scene-listing screen for the picturebook (Figure 8—left). This screen displays the title and an image of the picturebook as well as a listing of scenes designed for the read-aloud. For each designed scene, the choices for lighting, sound, and movement effects are displayed. Users have the option of adding additional scenes for a read-aloud (a maximum of six scenes can be designed for each picturebook), or pressing the "Home" button to return to the read-aloud library screen.
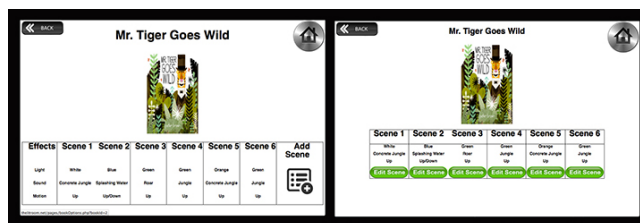

Figure 8. Tablet interface: Save Scene and Edit Scene pages.
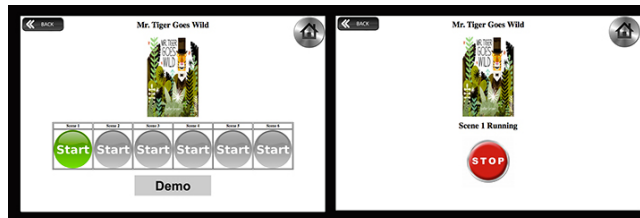

Figure 9. Tablet interface – Read and Stop pages.

Once all of the desired read-aloud scenes have been designed and saved for a specific picturebook, users can easily access them for refinement through the "Edit Scene" feature. The edit read-aloud screen (Figure 8—right) displays the title and image of the picturebook, and a horizontal listing of the scenes saved into the system for the read-aloud. Saved settings for lighting, sound and movement effects are displayed for each scene, and users can access saved settings for revision by touching the "Edit Scene" button under the desired scene. The interface then advances to the standard effects customization screen, where saved settings are displayed and desired changes can be implemented.

In order to play-back scenes during a LIT ROOM read-aloud, users press "Read" on the picturebook screen. The interface advances to the read-aloud screen (Figure 9—left), which displays the title and cover of a picturebook as well as a horizontal listing of its pre-programmed scenes. Each scene is activated by a "Start" button, which, when pressed, activates the lighting, sound, and movement effects in the LIT ROOM. The interface guides users through the read-aloud by only allowing for sequential scene activation (only one "Start" button is active at a time). This ensures that the effects of the LIT ROOM track sequentially with the picturebook as read, protecting readers (for example) from mistakenly activating "Scene 3" when they intend to activate "Scene 2." Visually, the "Start" button for a scene

that is available for activation displays bright green, while non-available scenes are grey.

Activating the effects for a scene advances the interface to a blank screen containing a large "Stop" button (Figure 9—right). When a scene is activated, the lighting, sound, and movements transform the LIT ROOM for thirty seconds, providing the adult and children an opportunity to engage in discourse and make connections to the text. The "Stop" button allows adult readers to adjust to the discourse and return to the picturebook sooner, if necessary, to ensure optimum pacing for the read-aloud.

A "Demo" button is also provided on the bottom of the read-aloud screen. This button activates a pre-set demonstration of the environmental effects, creating an opportunity for adults to prime children adequately for the LIT ROOM experience. The standard demo plays for ninety seconds, during which an adult reader can engage with children in a discussion about the technology before the read-aloud begins. During the demo, children can comment on the lighting, sounds and movements, touch and inspect the robotic panels, and ask questions about how the system functions. The demonstration feature hypothesizes that children who are adequately acclimated to the LIT ROOM effects are more likely to attend to the picturebook during the interactive read-aloud in this setting.

The interface also includes buttons for ease of navigation and troubleshooting on most screens. The "Back" button, located in the upper left-hand corner of each screen, allows users to move back to the previous screen. The "Next" button, located in the bottom right-hand corner of screens, advances the system forward and. in some instances, saves selections into the system. The home button, located in the upper right-hand corner of the interface and represented by a house icon, returns users to the read-aloud library screen. A "Reset" button is also provided as a safety measure for when the LIT ROOM system is malfunctioning. Pressing the "Reset" button arrests the effects (lighting and sound) in the LIT ROOM, returns the moving-panel actuators to their resting position ("Down"), and navigates the interface back to the home page.

SCENARIO (DIRECTLY FROM OUR TRANSCRIPT)

Barbara, a children's librarian, is planning a storytime program in the LIT ROOM for a small group of second graders. Barbara selects the picturebook *Little Beauty,* written and illustrated by Anthony Browne [41], about a gorilla in captivity that can communicate using sign language. Barbara aims to design a read-aloud in the LIT ROOM that leverages the lighting, sound, and moving panels to emphasize the emotional aspects of the book. Barbara is intrigued by the book's use of pattern to create the background for Gorilla's home, and by the book's use of wordless spreads, especially one that depicts Gorilla and Beauty swinging from a chandelier. She decides to emphasize these features for the "happy" scene during her LIT ROOM read-aloud.

On the LIT ROOM tablet, Barbara presses "Start Now" which brings her to the "Read-aloud Library." As *Little Beauty* is not yet in the library, Barbara presses "Create New." As she selects the three wall panels for Scene 1, the tablet provides visual feedback to confirm her selection by changing the panels from white to bright green. Barbara presses the "Next" button, and the tablet displays options for lighting, sound, and movement. For Scene 1, Gorilla is sad, so Barbara selects the color "blue" in the "fade" setting, the sound "melancholy," and decides to leave the panels in the "down" position. She presses "Show Me," and the LIT ROOM activates. Pleased with her selections, she presses "Next," saving Scene 1 into the read-aloud library. Barbara repeats this process to design and save Scenes 2-5.

Next, Barbara browses through the plastic panels provided with the LIT ROOM. As Barbara wishes to scaffold the book's use of pattern, she selects pairs of panels with different perforations that match her vision for the scenes of the book. Barbara attaches each plastic panel to its robotic panel with Velcro, and marks her printed copy of *Little Beauty* with adhesive tabs to reminder her to activate the scene on the touchscreen after reading the page.

The children arrive for storytime, intrigued. Barbara asks them to seat on the floor at the center of the installation.

Barbara: "Today we are going to be sharing a book together." [Barbara touches the "Demo" button on the interface. The panels on the wall and ceiling robots begin to slowly move up and down. Their lighting fades from color to color, and an ambient tone fills the room].

Children: [Laughing, looking around and pointing at the environmental effects, and displaying interest and curiosity.] "Whoa! Cool! What's happening?"

Barbara: " What are you noticing?"

Tony: "The walls are changing colors!"

Allison: "I see this wall moving up and down."

Barbara: [Presses the "Demo" button again, halting the lighting, sound, and movement.] "As we read the book in this space, there will be moments when the room will change color, play sounds, and change shape!" [Picks up the picturebook and displays its cover.] "Today, we'll be reading *Little Beauty*, […]. "'Once upon a time there was a very special gorilla who had been taught to use a sign language'" […] [Points to the illustration.] "What are you noticing here?"

Tony: [Laughs and points to the illustration.] "I'm noticing the gorilla is watching TV and eating a hamburger! That's funny!" […]

Allison: "Maybe he's watching a sad movie."

Barbara: "He could be watching something sad, that's a good thought." [Focusing the children on the illustrator's

style, pointing at the background.] What are you noticing on this page about the wall and the chair?"

Allison: "It's really colorful and looks like trees and flowers."

Barbara: "It's kind of like a floral pattern, isn't it? Can anybody tell me what a pattern is?"

Ellie: "Um, a pattern is like, when there's lots of lines and stuff, like plaid is a pattern, but it's not like trees and flowers like that." [Points at the illustration.]

Barbara: "That's right. A pattern is like a design when something is repeated. Let's keep reading and see how Gorilla might be feeling." [Turns page and notices a tab indicating Scene 1.] "'But the gorilla was sad.'" [Touches the "Start" button for Scene 1. The walls glow blue, fading gently; light shines through the perforated, patterned panels. Melancholy piano music plays.] "What are you noticing?"

Tony: "The walls are blue. And music is playing."

Barbara: "The walls are blue. Why do you think they're blue?"

Fatima: "Well, sometimes people say that they're blue when they're sad. That's what I think." […]

Barbara: "That's a good connection, Fatima. […] What are you guys noticing about the walls other than the color?"

Allison: "They kind of have patterns. That one [points to left wall] kind of looks like stars, and…" […]

Barbara: [Pressing the "Stop" button to arrest the effects.] "Patterns? Kind of like the patterns the illustrator is using in the book. Great observations. Let's keep reading."

Barbara continues through the remainder of *Little Beauty*, pausing for discussion, and scaffolding the children's discourse, particularly related to the emotional arc of the characters, for each of the LIT ROOM's transformations. After a brief discussion of the book, Barbara begins a story-extension activity using the LIT ROOM by engaging the children as co-designers of the environment. She begins by redirecting discussion to address one of Tony's comments following the reading of Scene 1 when Gorilla was sad. With help from his peers, Tony, by touchscreen, fine-tunes the LIT ROOM so that its effects better match his vision for how the LIT ROOM should look, sound, and move.

The LIT ROOM serves to facilitate a diversity of children's literary responses and encourage diverse meaning-making strategies as they make connections to the text during the read-aloud. Additionally, the LIT ROOM functions as an "object-to-think-with" [26] by engaging children as co-designers during the story-extension activity.

USABILITY AND EFFICACY EVALUATIONS
Installed in Richland Library, the fully functioning LIT ROOM underwent Phase-2 (a formative usability evaluation) and Phase 3 (concurrent summative evaluations

of usability and efficacy) of our evaluation cycle. Participating children were drawn from two public elementary schools identified as "Title 1" where high numbers or high percentages of students are from low-income families. Phases-2 and 3 aimed to understand: (1) the preferences of librarian and children participants for the design of the LIT ROOM; (2) how users rate the LIT ROOM on measures of usability as a context for an interactive picturebook read-aloud; and (3) the nature of literary understanding exhibited by children during shared picturebook reading in this context.

For these evaluations, as reported in this section, the two picturebooks used were *Mr. Tiger Goes Wild* by Peter Brown [39] and *Gorilla*, by Anthony Browne [40]. In order to ensure fidelity of the read-aloud protocol across the two texts, librarians were assigned to read one of these titles in both the control (a traditional storytime room, Figure 10—left) and treatment (the LIT ROOM, Figure 10—right) settings. The two picturebooks were pre-programmed into the tablet to match the librarians' specifications for the effects (lighting, sound, and actuated panels) identified during previous participatory design sessions. The librarians followed a protocol (script) for administering the interactive read-aloud for the picturebooks that was designed and piloted by members of the research team with an expertise in children's literacy. The scripts were designed to ensure fidelity to the read-aloud protocol across readers and settings (control and treatment). For a short video depicting scenes from a LIT ROOM read-aloud of *Gorilla*, see https://www.youtube.com/watch?v=SjH-mNwzi7k#t=220.

For the various evaluations reported here, interactive read-alouds and the customization sessions were audiotaped and videotaped. Focus group sessions were audiotaped. Approval for all evaluations was obtained from the appropriate institutional review boards and parental permission was provided.

Phase-2 (Formative) Evaluation for Usability
Our research team evaluated the LIT ROOM with respect to usability through one formative cycle. (A summative usability cycle is presented in the next section devoted to Phase-3). Twelve children participants (six males and six females), ages seven and eight, were from three second-grade classrooms. Prior to the study, children participants were divided into two groups, randomly determined by one of the classroom teachers. In lieu of Measures of Academic Progress (MAP) scores, the school categorized each child as (L) low, (M) medium or (H) high "literacy level." Additionally, some of the children were differentiated by classroom type, such as (SN) special-needs or (M) Montessori. The classroom teacher was instructed to create two groups that, to the extent possible, represented a cross-section of learner characteristics. Each group was evenly split along gender.

A convenience sample of four children's librarians from Richland Library participated in the evaluation. The librarians were members of the core focus group that was integral to the research activities spanning the three-year iterative design, installation and evaluation of the LIT ROOM. During the study, two of the children's librarians facilitated the interactive picturebook read-alouds in both settings, while two functioned as observers.

The study featured the following activities: two small-group interactive picturebook read-alouds for two texts (one per group) in the LIT ROOM; a customization activity in the LIT ROOM with one group; piloted participatory design sessions and usability assessments (via facilitated questionnaire) with all children following their LIT ROOM read-alouds; and a focus group with the children room's librarians after all activities were completed.

Group 1 engaged in a read-aloud in the LIT ROOM using *Mr. Tiger Goes Wild* [39]. Following the read-aloud, children individually (1) completed a facilitated questionnaire (with Likert "Smileyometer" scales and open-ended questions) to assess usability and satisfaction [20]; and (2) participated in a story-extension design activity which, from a printed image of the LIT ROOM, asked participants to draw their favorite scene from the book supported by LIT ROOM effects, and offer an explanation for why this was their favorite. Group 2 followed the same procedure with *Gorilla* [40]. Concurrent with the participatory design and usability assessment activities for Group 2, the children in Group 1 were provided an opportunity to customize scene effects for the LIT ROOM and interact with the tablet interface for a third picturebook, *Little Beauty* [41]. Guided by a children's librarian, the children were asked to collaboratively design lighting, sound, and actuated panel effects to represent the emotional arc in the text. After reading the book aloud to the children, the children took turns making selections to evoke an environment that, *to them*, represented sadness, happiness and anger. A member of the research team with an expertise in engineering observed the session and notated errors [34] in the interface. At the end of the study, a brief focus group was conducted with the children's librarians who participated as readers and observers. We asked open-ended questions regarding the usability and effectiveness [34] of the tablet interface, and facilitated a discussion about their experience reading a book and customizing scenes with children using the LIT ROOM.

Results

The results focus on three main areas: an analysis of observed or reported usability errors and preferences related to the LIT ROOM's tablet interface (and the refinements made to the system as a result); an analysis of observed or reported usability errors and preferences related to the LIT ROOM as an effective system for reading picturebooks and customizing scenes with children; and findings on the validity of the protocols used during the piloted participatory design and usability assessment sessions with children.

Overall, the technology in the LIT ROOM functioned as expected. The research team, however, observed librarians struggling to resolve a system error using the tablet. The tablet did not adequately provide the librarian user with information about the type of problem that was occurring, nor did it guide the user as to how to resolve the system error. Nielsen would identify this as a feedback error [25]. The research team subsequently identified the system error (i.e. when a scene mistakenly replayed) to be related to a "bug" in the coding (one that occurred randomly and unpredictably). Because the issue could not be fixed by a revision in the code, the tablet was augmented to allow users to quickly and efficiently replay a scene when this system error occurred. A "Reset" button was also added to the interface on every screen where the room effects could be activated. The team also observed that the length of each pre-programmed scene (the length of time that the lighting, sound, and panels were actuated), originally set at fifteen seconds, was not enough time for the children to adequately experience and identify the effects, discuss them with the adult reader, and make connections to the text. The system was redesigned to set the scene time to thirty seconds.

All of the librarians reported being surprised that the children did not seem distracted by the environmental effects in the LIT ROOM. We meanwhile found that written responses and drawings offered by the children could not be productively leveraged for useful, specific data that might guide the design team on preferences for the affordances of the LIT ROOM effects; according to [20], this was not an unexpected outcome from young participants.

Phase-3 Evaluation for Usability and Efficacy

Our research team conducted a usability and efficacy evaluation of the LIT ROOM in one summative cycle. In the study conducted over two days, 17 second-grade children from two local classrooms participated, as did six children's librarians from the core focus group. Nine children (6 males, 3 females) participated on the first day and eight (5 males, 3 females) participated on the second day. Participants engaged in interactive read-alouds in two settings: the traditional storytime room (Figure 10—left) and the LIT ROOM (Figure 10—right).

Figure 10. Storytime room and LIT ROOM read-alouds.

The procedures for the summative usability evaluation follow closely the procedures for the formative usability

evaluation elaborated in the previous section: (1) we conducted four small-group interactive picturebook read-alouds – two for each group – for the same two texts, with each group exposed to both texts in the control and treatment settings (a traditional storytime room and the LIT ROOM); (2) we conducted usability evaluations via facilitated questionnaire with all children participants; and (3) we conducted a focus group with the children's librarians focused on measures of usability.

In order to better understand the efficacy of the LIT ROOM as a context for children's literacy, we also conducted an initial analysis of children's literary understandings during picturebook read-alouds in the LIT ROOM. To report on how the multi-media effects were influencing children's meaning-making in the LIT ROOM setting, we categorized children's response initiations guided by seminal research in children's literary response [18, 32]. Maloch and Beutel's study on meaning-making strategies framed our coding of instances where children seemed to be leveraging the environmental effects: to make *connections* between their personal experiences and the picturebook being read; to make *predictions* about the text; to clarify information in the text; to make *observations* about the text; and to *enter the story world* as co-participants or co-authors [18]. These meaning-making strategies built upon Sipe's seminal study identifying five primary categories of initiations for children responding to fiction texts: the *analytical* response, the *personal* response, the *intertextual* response, the *transparent* response and the *performative* response. [32]. While a comprehensive, descriptive statistical analysis was conducted to determine the frequency and percentage for each category of response, we focused on two of Sipe's five categories of literary understanding [32] – the *transparent* and *performative* – in order to consider how the LIT ROOM multi-media and architectural robotics effects might influence children's *aesthetic* responses. Finally, we conducted an initial descriptive analysis of the differences between the children's literary responses (and specifically, their *aesthetic* responses) in two settings for two of the small groups (N=8), comparing those observed in the LIT ROOM to those observed in the traditional storytime room. For these analyses, the discourse was transcribed according to a methodology devised by [32] in his seminal study of children's literary responses.

Overview of Results

From the summative usability testing, we learned that the LIT ROOM functioned largely as expected. We therefore focus the reporting of results on our summative efficacy evaluation – far more illuminating – for three main areas: (1) an analysis of children's responses to two picturebooks within the LIT ROOM installation to describe how the environment and its multi-media, architectural robotics [15] effects were influencing the strategies the children utilized for connecting to the text; (2) an analysis of the frequency of responses mediated by the specific effects deployed in the LIT ROOM environment, including elaborations on

how the lighting, sound, and moving panels were influencing their strategies for making connections to the text and their aesthetic response initiations; and, (3) a comparative analysis of the children's aesthetic responses (*transparent* and *performative*) observed in the traditional storytime room and in the LIT ROOM for one of the picturebooks. Our analyses of the efficacy studies are far too detailed to present in the limited space of this paper; we therefore present the key results in the form of a narrative.

Results-1: Impact of LIT ROOM on connecting with text

Children exhibited a wide range of strategies for making connections to the text while the LIT ROOM environmental effects were activated [18]. Some children leveraged the effects to make *connections* between their personal experiences and the picturebook being read, while others made *predictions* about the text, *clarified* information in the text, made *observations* about the text, or *entered the story world* as co-participants or co-authors [18, 32].

The initial analysis of children's responses suggests that the LIT ROOM effects figured prominently in the discourse and influenced the strategies and response types exhibited by the participants. Nearly half (48%) of the children's responses were identified as having been mediated by the effects of the LIT ROOM. A "response" was identified as being influenced by the LIT ROOM if the child mentioned the specific effect in his/her response (such as by saying "blue," in reference to the lighting); if the comment referenced a transformation in the space but did not name a specific effect (such as "It looks like he's going to come at all of us!" when a child referred to the "gorilla" wall-mounted robotic panel); and for responses where no specific effects were named but the child was gesturing towards or visually attending to a specific area of activation (such as "To the forest," where a child was predicting the actions of Mr. Tiger while gesturing to a wall robot). Non-specific verbal utterances where children were reacting to the effects (such as "Oh!" when a child reacted to the ceiling robot immediately upon activation) were also included as an example of an effect-mediated response.

The results also indicate that for the instances where a response was associated directly with the LIT ROOM effects, children exhibited a wide variety of strategies [18] while transacting with the picturebook in this setting. Some children leveraged the effects to make *connections* to the text (such as "I play around in water sometimes," a *personal* response to the ceiling robot evoking waves), while others made *intertextual* connections (such as a child sing-talking "Superman!" while the ceiling robot above resembled a red, flying cape and played movie-music sounds). An example of the *analytical* response, other children made *predictions* about the text using the LIT ROOM effects, (evidenced by a child pointing at the "wilderness" wall-mounted robotic panel while answering, "To the forest" when the librarian reader asked where Mr. Tiger was going to go next). Many children made

observations about the environment while relating to the picturebook (evidenced by a child stating: "I notice the lights—the lights is [sic] acting like, when, uh, the tiger is swimming in the water"), and others clarified and extended the effects and how they relate to the inner life of the characters (such as the comment: "It sounds like he's lonely and it's raining," referring to the scene where Mr. Tiger is in the wilderness, alone). The LIT ROOM effects also served as a conduit for children to *enter the story world* [18, 32]. During an interactive read-aloud for *Gorilla*, for instance, one child repeatedly monitored the "gorilla" wall-mounted robotic panel behind him as if it was alive. Sipe [32, 33] would identify this instance as a *transparent* response, an example of Rosenblatt's "lived through experience" [28] where a child becomes one with the story world. This initial analysis of the children's responses suggests that the LIT ROOM effects created a threshold between the imaginary and the real, and allowed the world of the picturebook to become transparent to the children's world, if only momentarily [32].

Results-2: Frequency of responses mediated by LIT ROOM
Following Sipe's elaboration of "aesthetic impulses" [32, 33], we counted the frequency of both *transparent* responses (where children enter the world of the book, even responding to characters from the book as if they were sharing the physical space with them), and *performative* responses (where children leverage the text to express their own creative impulses, often evidenced by dramatic interpretations, characterizations, embodied gestures and vocal intonations [1]). Among the children's response initiations that were identified as being directly influenced by the LIT ROOM effects during scene activation, approximately 38% of them were categorized as transparent responses, while approximately 20% of them were categorized as performative responses. The instances of aesthetic impulse therefore comprised over half of the responses analyzed for this study. By comparison, in Sipe's seminal study of first and second-grade children's literary understanding during interactive picturebook read-alouds in traditional classroom settings [32], the aesthetic impulse comprised only 7% of children's responses: 2% categorized as transparent responses, and 5% categorized as performative responses. This comparison suggests that the LIT ROOM, as compared to a traditional storyroom, could hold promise for facilitating more diverse categories of children's literary responses by providing opportunities for children to explore the text as a launching pad for their own creative and aesthetic expression.

Results-3: Children's responses in LIT ROOM vs storyroom
While in Sipe's seminal study, as just considered, the aesthetic impulse in a traditional story room comprised only 7% of children's responses, the interactive picturebook read-alouds analyzed for this study resulted in higher frequencies *for both* the traditional story room setting *and* the LIT ROOM setting (28% and 29%, respectively).

Moveover, while the results indicate no significant difference between the overall frequency of aesthetic response initiations across the control and treatment settings, children's *transparent* response, where they entered the story world, was observed at greater frequency in the LIT ROOM installation. Further, there were also differences in the nature of transparent responses in the two settings. In the traditional storytime setting, children were observed entering the story world through primarily verbal responses, by speaking directly to a character (such as "What are you doing, mister?" when a child confronted Mr. Tiger about being wild), or spontaneously assuming the role of the character (such as "I'm free!", when a child expressed Mr. Tiger's feeling of being in the wilderness). In comparison, children in the LIT ROOM were more likely to "act out" Mr. Tiger's transformation by crawling around the installation and roaring like tigers. This suggests that the LIT ROOM may encourage more full-bodied (*embodied*) performative response styles.

Sipe argues that interactive read-aloud settings, such as the multi-sensory LIT ROOM, should be designed to facilitate the entire range of dialogue, and in particular, children's aesthetic responses [32, 33]. By blurring the lines between the picturebook and the real world, the LIT ROOM may even support a transformation in the way we think about children's performative and transparent responses to picturebooks, resulting in a "blended" aesthetic response category – the "transformative response."

CONCLUSION
While there is evidence that public libraries effectively leverage technologies – physical and digital – to reduce illiteracy in their communities [17, 22], there are significant gaps in the research on effective interventions in children's libraries, especially in the realm of employing interactive technologies for early literacy skill development [16]. This research sought to fill this gap through a reconfigurable, cyber-physical environment in which *words become worlds*. In the LIT ROOM, children leverage cognitive, embodied processes to foster early literacy skills.

Supporting a variety of programming beyond that reported here, the LIT ROOM proved robust and engaging to library patrons for over one year following the conclusion of our formal studies. We recognize such cyber-physical systems at room scale, like the LIT ROOM, as a new frontier for designing interactive systems. As offered in this paper via our RtD reporting, the LIT ROOM represents an exemplar for designing and studying interactions within interactive systems at habitable scale – an inevitable future for the field.

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