Cuby and His Shadow Friend: A Game-Based STEAM Learning Book for Kids Ages 6-9

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摘要：

With the increasing emphasis on STEAM education globally, there is a growing demand for educational resources that make complex scientific concepts understandable and engaging for young learners. Despite the rise in extracurricular STEAM resources, many existing books are either over-complex or prioritize aesthetics over substantive content. Additionally, less science books consist features that enable effective parental involvement in facilitating young learners' enjoyable reading experience. This study introduces *Cuby and His Shadow Friend*, an embodied, game-based STEAM learning book designed to help children aged 6-9 exploring concepts of light and shadow through interactive, parent-child co-reading. By using embodied learning principles, Cuby and His Shadow Friend engages multiple senses, enhancing cognitive and emotional development through tactile, auditory, and visual interactions. Developed using a participatory design approach informed by interviews

with teachers, academics, and parents, this book combines narrative with interactive features such as a UV lamp for uncovering hidden story elements and a prism for experimenting with light refraction. User feedback shows that these multi-sensory features effectively foster curiosity and understanding, although some elements require further refinement for independent use. This innovative, low-cost design promotes long-term engagement, encouraging repeated exploration and continued learning.

Keywords： Embodied Learning, Tangible interaction, STEAM education, Game-Based Book.

1. Design Background

Science, Technology, Engineering, Arts, and Mathematics (STEAM) education has gained significant attention for its role in fostering creativity, critical thinking, and problem-solving skills among primary students (Khine & Areepattamannil, 2019). Integrating these disciplines offers a multidisciplinary approach that encourages students to connect theoretical knowledge with real-world applications, providing a holistic educational experience (Papadakis et al., 2023). With growing need in supplementing school STEAM curricula, extracurricular STEAM books are becoming more popular among educational settings (Yen et al., 2024).

However, existing extracurricular STEAM books for younger students still face challenges -- many of them are written in a complex language that is difficult for younger readers to understand (Sun & Zhong, 2023). Moreover, while there are more and more interactive books and multimedia resources attracting children's attention through appealing aesthetics (Figueiredo, 2013), they prioritize aesthetic elements over substantive educational content (Bu, 2018). Another limitation is the lack of instructional support for parents and educators, who may need additional guidance to

explain STEAM concepts effectively to young learners. These problems make books less engaging and educational.

Embodied learning approaches use tangible technologies to enhance understanding of complex concepts through gestures and physical actions (Weisberg & Newcombe, 2017; Manches & Price, 2011). This method is particularly beneficial for children aged 3-9, who are in a developmental stage where sensory learning plays a critical role in their cognitive and motor development (Kim & Bacos, 2023). Imagine a primary student learning about how shadows are formed by light. In many traditional educational settings, students typically learn about this concept through textbook explanations and diagrams. They encounter the idea of shadows in a way that feels disconnected from their personal experience. As a result, this knowledge is often stored as abstract, symbolic information—students may understand the theory but struggle to relate it to real-world situations (Black, 2010). In an embodied learning setting, however, students observe firsthand how a shadow appears when an object blocks a light source and disappears when the light is removed. By linking real-life physical interactions to abstract concepts, embodied learning fostering a more intuitive and concrete learning process (Weisberg & Newcombe, 2017).

Principles of light and shadow particularly requires extensive spatial reasoning skills, making it especially suited for embodied learning approaches (Pallrand & Seeber, 1984; Castro-Alonso, Ayres, & Paas, 2015). For example, observing the physical interactions of light and shadow not only deepens understanding but also builds the spatial reasoning necessary for more complex scientific learning.

Some educational materials have been designed to incorporate embodied learning in STEAM education, such as tangible games for training visual perspective-taking skills (Geurts, 2014) and mixed reality game systems using role-play to enhance social and collaborative skills (Wu, 2023; Baldassarri, 2018). However, most of these approaches depend on electronic screen, which limits accessibility, particularly for students in remote areas.

2. Design Process

2.1. Participatory design with children, parents and teachers

In order to ensure that educational resources effectively meet the needs of children, it is essential to engage them in the design process. Participatory design seeks to democratize the design process by actively engaging users in the development of products and services that affect them. According to Schuler and Namioka (1993), this approach not only enhances the relevance of design outcomes but also empowers users by giving them a voice in decision-making processes. Participatory designs has emerged as an important design methodology in developing interactive picture books. Drawing on existing literature on participatory design, we established an interdisciplinary team of experts who, in collaboration with students, parents and teachers, obtained direct insights into children's needs, preferences, and experiences through interviews.

2.1.1. Participatory Design Methodology

A total of three children were recruited to provide insights into their reading habits and comprehension of scientific concepts. Each child's parent was also invited to participate in the interviews to share their observations regarding their child's learning processes and their expectations for educational materials. Additionally, we recruited two teachers, particularly those with backgrounds in science education, to discuss their experiences with educational materials and the challenges they face in the classroom.

The interviews followed a non-intrusive semi-structured format. This methodology facilitated a deeper exploration of participants' perspectives and experiences. Key interview questions focused on the children's reading habits, such as

the types of books they preferred, the duration of their reading sessions, and the difficulties they encountered. Parents were asked about their observations of their children's attitudes towards reading and their engagement levels, while teachers provided insights regarding using multimodal materials and the challenges they faced when teaching science to children aged 6-9.

2.1.2. Insights

The analysis of the interview content revealed several critical findings from the different stakeholders. Children commonly expressed difficulty with text in games and extra-curricular reading materials, particularly with longer passages, often opting to skip over dense-texts and focus on images or interactive elements. They exhibited a pronounced interest in game-like and interactive content.

Parents generally expressed a desire for materials that enhance their children's learning motivation through engaging stories and interactive elements. Parents also anticipated that the picture book would provide simple and comprehensible narratives along with captivating scientific concepts to help bolster their children's confidence in reading.

The findings from teacher interviews emphasized the need to enhance the depth of scientific reading materials to provide students with greater intellectual stimulation, while encouragingstudents to creatively apply their knowledge through hands-on projects. Teachers highlighted the importance of providing clear activity guidelines to improve understanding and recommended engaging formats, such as comics featuring captivating characters, alongside educational aids like globes, prisms, and multimedia resources. They stressed the necessity of creating enjoyable learning experiences through interesting narratives and reducing text volume. Additionally, practical solutions were suggested, such as standardizing irregular shapes to cylinders for easier measurement, and integrating arts and technology to foster greater creativity among students.

2.2. Persona

Drawing on insights from participatory design, we developed a persona to better understand our target users.

table 1 Persona of target user.

Name	Jane
Age	7
Grade	2nd Grade, attends a public elementary school
Current Situation	Like many children her age, Jane shows reluctance toward reading text-heavy, extra-curricular science materials. She is more engaged by hands-on, interactive activities that spark her curiosity and help her understand scientific concepts in a practical way. This preference for interactive learning can sometimes lead to disengagement with reading-focused tasks, impacting her confidence and participation, especially in areas where she feels less proficient.
Family Environment	Jane's parents are supportive and invested in her education, but they find it challenging to connect with her over traditional reading materials. They believe that shared learning experiences can strengthen their bond and enhance her comprehension.
Habits	Short video games with imaginative stories and characters.
Goals and Needs	**Goals:** Jane wants to understand science concepts through engaging experiences that allow her to learn by doing. **Needs:** Learning materials that incorporate hands-on elements, visual storytelling, and interactive feedback to support her curiosity and encourage active participation in learning.
Challenges	Limited engagement with text-heavy resources. Needs learning experiences that build confidence and make science approachable.

3. Design Overview

Cuby and His Shadow Friend is a Game-Based Learning Book which guide children through the exploration of light and shadow principles, sparking their curiosity and

interest in these scientific concepts. The main storyline follows Cuby and his shadow on an adventure, structured around three main themes: Shadows in Daily Life, Playing with light and shadow, and Design-it-yourself (DIY) shadow creation. On each spread, the left page is filled with instructions and the right page is designed to conduct the activities aligning with the instructions. Through playing this book along with their parents, children actively participate, observe, and experience the fascinating world of light and shadow.

Our primary audience is children aged 6-9, who are in Piaget's 'Concrete Operational Stage' (Piaget, 2003). At this stage, children start thinking logically about tangible objects but remain closely tied to hands-on experiences (Wadsworth, 1971). Introducing scientific concepts now can aid their cognitive development and ease the shift to the Formal Operational Stage, where abstract thinking grows (Börnert-Ringleb & Wilbert, 2018).

3.1. User Scanrio

To illustrate how the book is used, we follow Bruce, a 7-year-old child, as he explores *Cuby and His Shadow Friend* with his mother, Linda (the names of participants have been altered to maintain confidentiality).

3.1.1. Shadows in Daily Life

In the first section, Bruce opens the book and sees Cuby and his soft, fuzzy shadow. Drawn to the tactile quality, he reads, "Cuby and his shadow are inseparable friends." Linda then guides him to use the UV light discover hidden secrets under the book. Using a UV light, Bruce excitedly searches for hidden dialogues and finds lines like, "Where you go, I go! We'll always be together, Cuby!" To which Cuby replies, "Not when it's dark! When I turn off the light, you hide away!"-- A hint that the shadow disappears without the light being prensent. A question on the page margin

asks, “When do you see shadows?” prompting Bruce to think of the appearance of shadows in daily life. This helps Bruce emerge to the light-and-shadow world. As Bruce turns the next few pages, he sees how shadows can change in different shape, quantity, and texture, varying with different light sources and angles from the left side of the book.

3.1.2. Playing with Light and Shadow

（1） Hide and Seek: The Formation of Shadows

As Bruce progresses, he reaches a page that mimics a rainy scene with sound effects and a pop-up cloud. Linda holds a flashlight behind the cloud and asks Bruce to observe how the shadow gradually fades as the light source is blocked. This observation makes Bruce think of familiar moments, like cloudy days when shadows seem to disappear, guiding him to understand that light is essential for shadow formation.

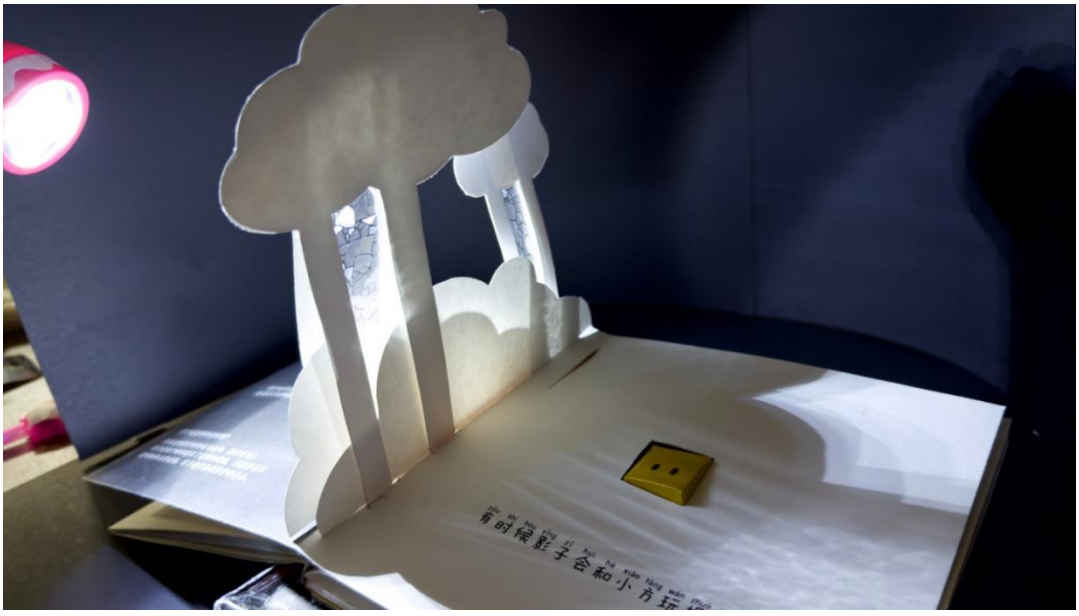

fig. 3.1 Bruce positioning the flashlight on the left to observe how clouds obscure Cuby’s shadow.

（2） Dancing Shadows: Shadows and Movement

On the next page, rhythmic music starts to play. Bruce, caught up in the rhythm,

moves his flashlight along to the beat, watching how his shadow dances with him. This interaction illustrates the connection between light direction and shadow positioning, letting Bruce experience firsthand how shadows change shape with the movement of light.

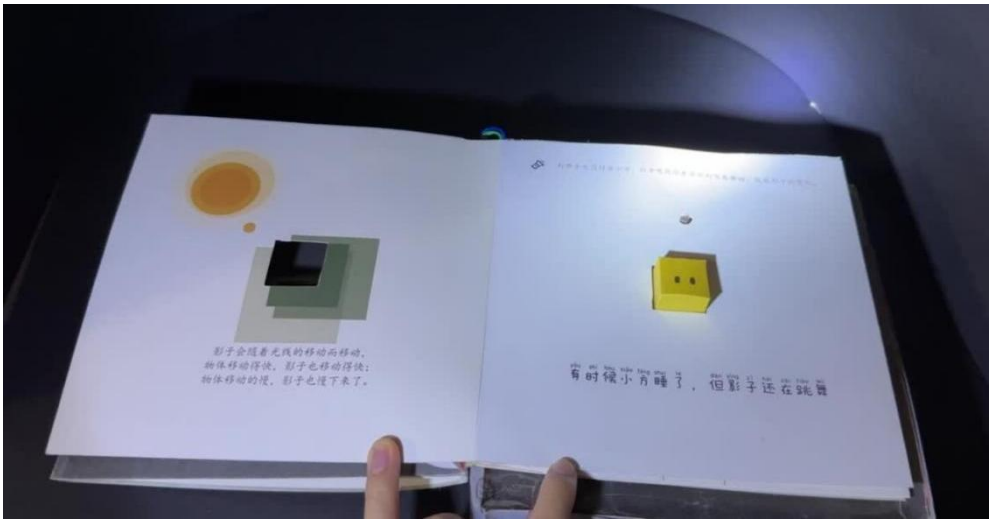

fig. 3.2 Bruce moves his flashlight to the rhythm, watching his shadow dance along with him.

（3） The Shadow Theater: Light Travels in Straight Lines

On this page, unfolding the pop-up structure reveals a small theater curtain in front of Bruce. Linda places a flashlight firmly on the page, pointing directly at the curtain. She says, “Cuby is watching a shadow play! Can you create a shadow of a little cat?” Bruce selects some geometric shapes from the pre-cut cards and inserts them into the slots on the page. As Bruce moves the slider below the cards, the shadows on the curtain shift accordingly. “It’s amazing!” Bruce exclaims. Linda explains, “This happens because light travels in straight lines. When the light shines directly through these shapes, it projects their exact forms onto the curtain.” Through this interaction, Bruce learns how shadows change in relation to light traveling in a straight path. Bruce then looks at the different shapes on the left page and tries to recreate them using the available inserts.

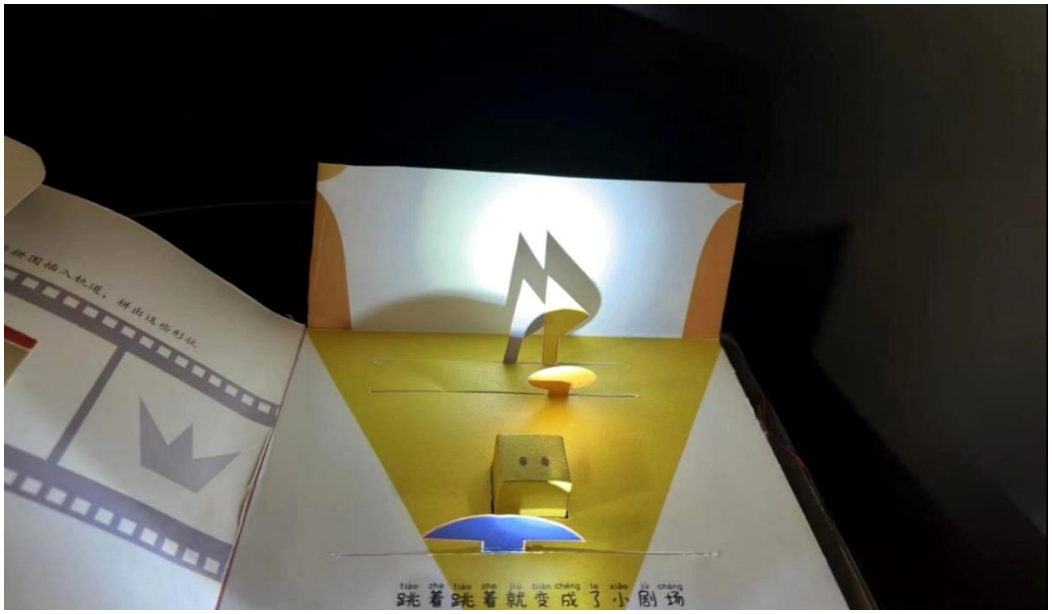

fig. 3.3 Bruce creates unique shadow effects on the curtain and showcasing the fascinating interaction between light and shadow.

（4） Sun Bathing:

In this section, a pop-up structure allows Bruce to follow the sun's path across the sky by moving his flashlight along a track. Bruce observes that Cuby's shadow is changed during a day. On the left page, a simple explanation is provided, and Linda explains, "The changes in shadow length are due to the Earth's rotation, which changes the sun's position in the sky." This helps Bruce understand how light direction affects shadow length over the course of a day.

fig. 3.4 Bruce moves a flashlight along a track to mimic the sun, observing his shadow's changing length.

（5） Cuby's Colorful Friends: Light Composition

The background of the page turns to gold as Cuby is bathed in sunlight. Bruce notices six colorful beams on the right side that appear to be Cuby's friends, though they're different—they're made of light, not solid objects. Intrigued, he guides Cuby along a track, where Cuby merges with the six beams of light. On the next page, an illustration shows how these seven beams come together to create a single white light. This interaction helps Bruce understand how multiple colors combine to form white light, engaging him in a fun exploration of light composition.

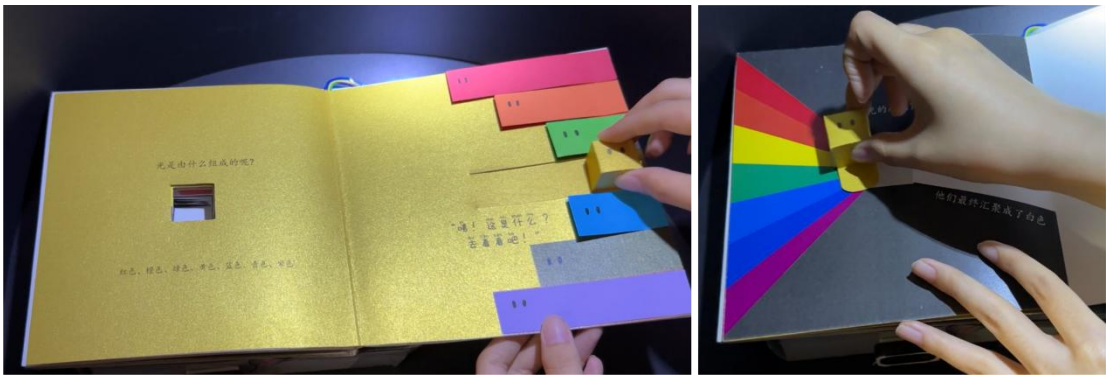

fig. 3.5 Bruce moves Cuby and merge with six colorful beams, discovering how different colors combine to create white light.

（6） Cuby's Transformation: Discovering Color Refraction

In a climactic part of the book, Bruce discovers a hidden prism inside Cuby when he unwraps a part of the book. Linda encourages him, saying, "Wow, Cuby has transformed!" Placing the prism on the page, Bruce shines his flashlight through it and watches as white light disperses into a rainbow on the paper. The illustrations benethe the prism further explain the concept, giving Bruce a visual understanding of how light refracts into colors, making abstract scientific ideas tangible and playful.

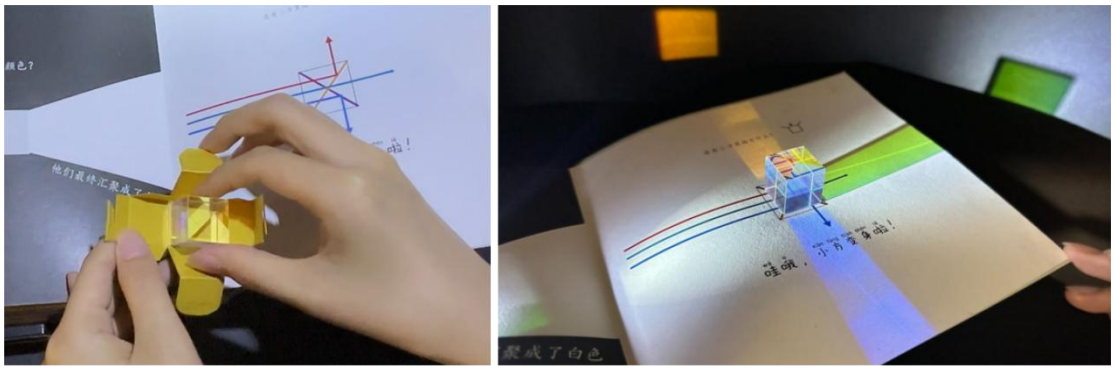

fig. 3.6 illustrates Bruce unwraps the Cuby and shines a flashlight through Cuby's hidden prism, discovering how white light separates into colors.

3.1.3. Create Your Own Cuby Family

Towards the end of the book, Bruce is encouraged to create new shadow characters using DIY cutouts of Cuby's family members. He takes out flat, perforated templates of Cuby's family members from the materials kit and carefully assembles them along the dotted lines. As he shines his flashlight on each one, he notices how the shadows vary in color and density depending on the material and structure. This activity allows Bruce to apply his creativity, reinforcing the concepts he has learned throughout the book and exploring how different materials affect shadow density.

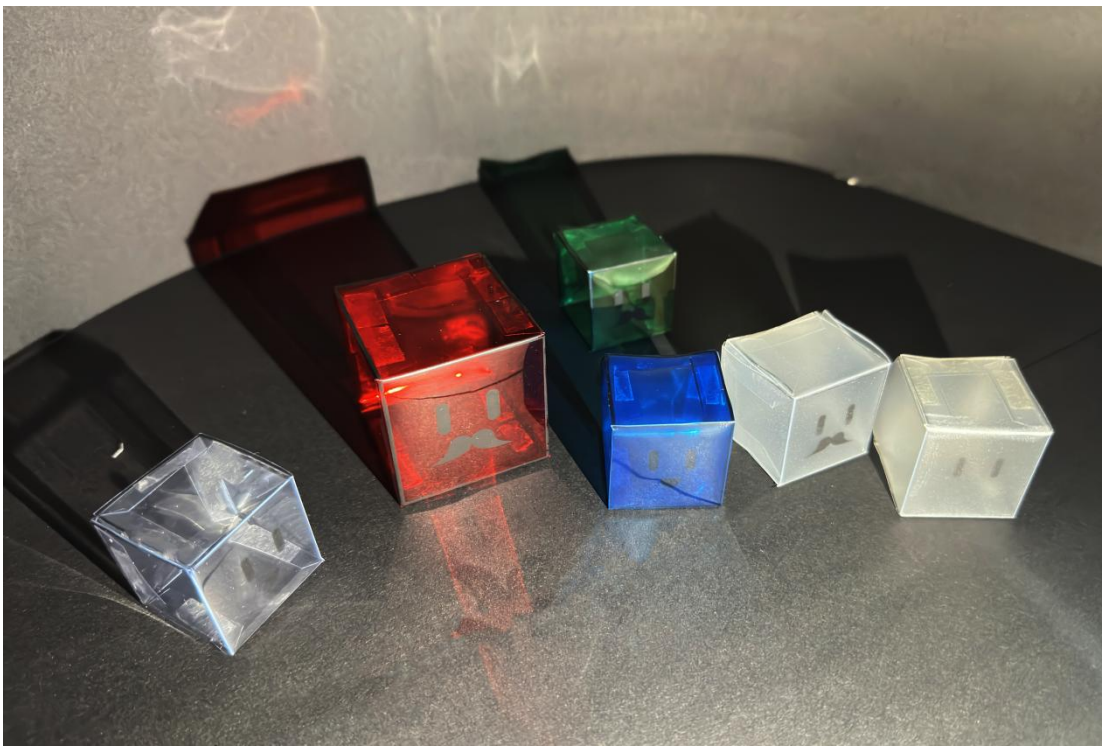

fig. 3.6 Bruce assembles Cuby's family cutouts and uses a flashlight to observe unique shadow effects.

3.2. Technical Implementation

In order to realize the interaction between visual and aural elements in various scenarios, we used Arduino along with supplementary components to automatically playback and pause sounds under various light conditions. When Shadow and Cuby play hide-and-seek, a soft rainfall sound effect is triggered, creating a rainy scene and aiding children in understanding how shadows are created. Children can investigate the relationship between light and shadow by listening to the rhythmic music on the other page, which mimics the shadow "dancing" as the light source changes.

The hardware utilised includes the Arduino Uno, two photoresistors, an MP3 module, and a speaker. The Arduino consists of a microcontroller-based, open-source hardware platform and a development environment for programming, and it aids sensory perception and control in the physical environment. The components chosen for this project are affordable, compact, and easily accessible on market, making

them well-suited for integration with picture books.

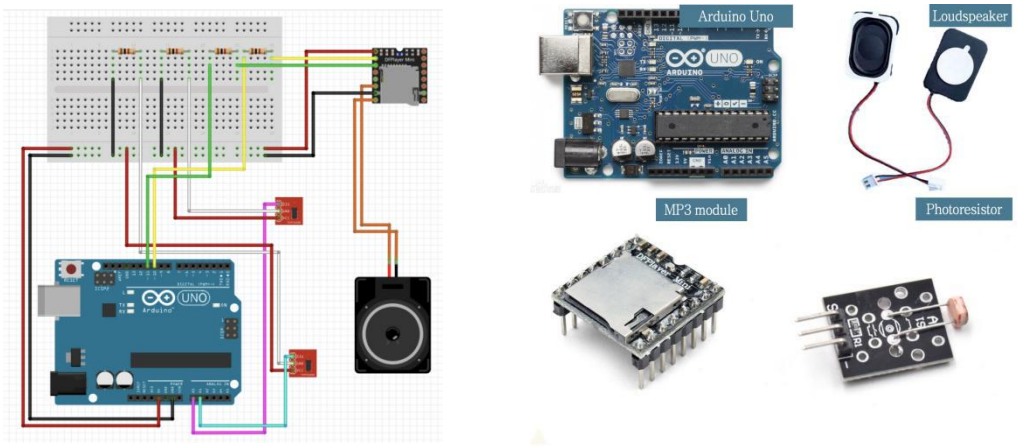

fig. 3.7 Left: Wiring diagram; Right: Components used, including Arduino Uno, photoresistors, MP3 module, and speaker.

We developed the program in the Arduino IDE and uploaded it to Arduino Uno. When powered on, the Arduino can detect light intensity in our book via the photoresistor and control the output music from the MP3 module. The photoresistor continuously senses the light intensity. When particular page is opened, the MP3 module begins playing the corresponding scene's sound. When the page is turned away, the photoresistor detects the dimming light, and the MP3 module pauses playback.

	LDR_A val>500	**LDR_A val<=500**
LDR_B val>500	Play musicA	Play musicB
LDR_B val<=500	Play musicA	Pause

fig. 3.8 MP3 player all conditions and execute commands

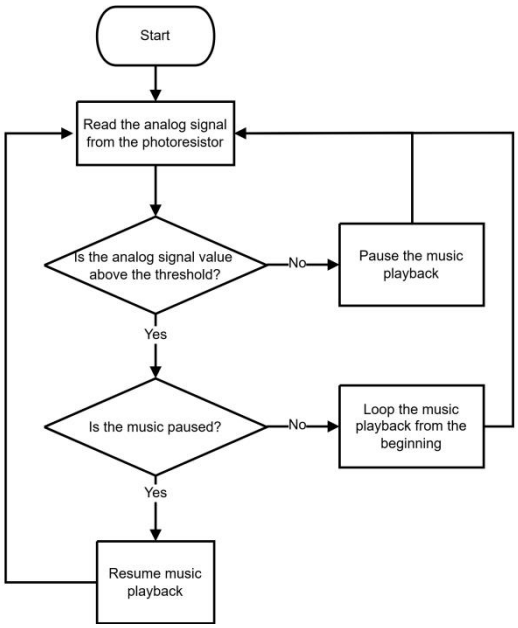

fig. 3.9 Procedure flow for single photoresistor.

4. Main Innovations

4.1. Multiple Embodied Interactive Designs

The book employs embodied learning approaches, connecting children's real-world experiences to abstract light and shadow concepts (Antle, 2007). This intuitive, hands-on method helps children understand complex knowledge concretely. By facilitating interaction with light and shadow changes and incorporating multimodal interactions and DIY activities, the book transcends the limitations of traditional text-based picture books, enhancing engagement and learning efficiency.

4.1.1. Interactive Contextual Learning

In the book, children actively control the position of a flashlight to directly observe shadows. This design imbues the shadow with functionality, transforming it

from a mere visual experience into a medium of interactive learning trigger. For example, the “formation of shadow” page simulated cloudy-day scenario, children use a flashlight to observe the disappearance of shadows of the Cuby when light is blocked by clouds. This realistic scene simulation helps children connect daily observations with scientific knowledge, enhancing their understanding of optical phenomena -- light propagation and shadow formation.

4.1.2. Multimodal Interactive Design

This embodied learning book integrates tactile and auditory modalities to enrich the learning experience.

(1) Tactile Engagement with Shadows. In the first part, we incorporate diverse materials such as felt, plastic sheets, and sandpaper to represent shadows, engaging children's sense of touch and focusing their attention on shadows from the outset. This tactile approach subtly introduces the concept that shadows can vary under different conditions: sandpaper represents shadows with sharp edges, felt illustrates blurred edges, and plastic sheets convey semi-transparency (See Figure 4.1). This reflects real-world observations where shadows can have varying sharpness and opacity, aligning with scientific principles and enhancing embodied learning.

(2) Auditory modules enhance immersive experience. On the page "Fromatuion of Light," opening the page triggers the sound of rain, helping children recall rainy-day contexts and the characteristics of light and shadow in such conditions. On the page "Movement of Light," children swing the flashlight along with music to explore shadow variation according to the light movement. This design combines visual, auditory, and physical interactions , allowing children to experience the relationship between light and shadow through synchronized movement and sound,

4.1.3. Multi-Material Handicrafts

The book includes multiple handicraft sections that strengthen the emotional connection between children and the protagonist Cuby while promoting a vivid understanding of light and shadow principles.

(1) Interactive Exploration in the "Shadow Theater"

In the "Shadow Theater" page, children can select and insert different geometric shape cards into designated slots, creating various shadow patterns. By moving a sliding mechanism, they adjust the positions of the cards, observing how shadows change correspondingly. As they manipulate elements, they gain insight into how light direction and path affect shadow formation, reinforcing the principle of light traveling in straight lines.

(2) DIY Your Own Cuby Family.

In the final section, children use provided materials to craft members of the "Cuby Family." Each character uses different materials--Cuby's Dad is made from red transparent plastic, Cuby's Brother from blue transparent plastic, and Cuby's Friend from fully transparent plastic. By illuminating these characters with a flashlight, children observe how different materials affect light transmission and shadow appearance. For example, shining light through the red transparent plastic of Cuby's Dad results in red-tinted light, and the shadow may exhibit a colored hue due to selective wavelength transmission. This embodied interaction enhances understanding of optical phenomena such as color filtering, translucency, and material effects on light and shadow.

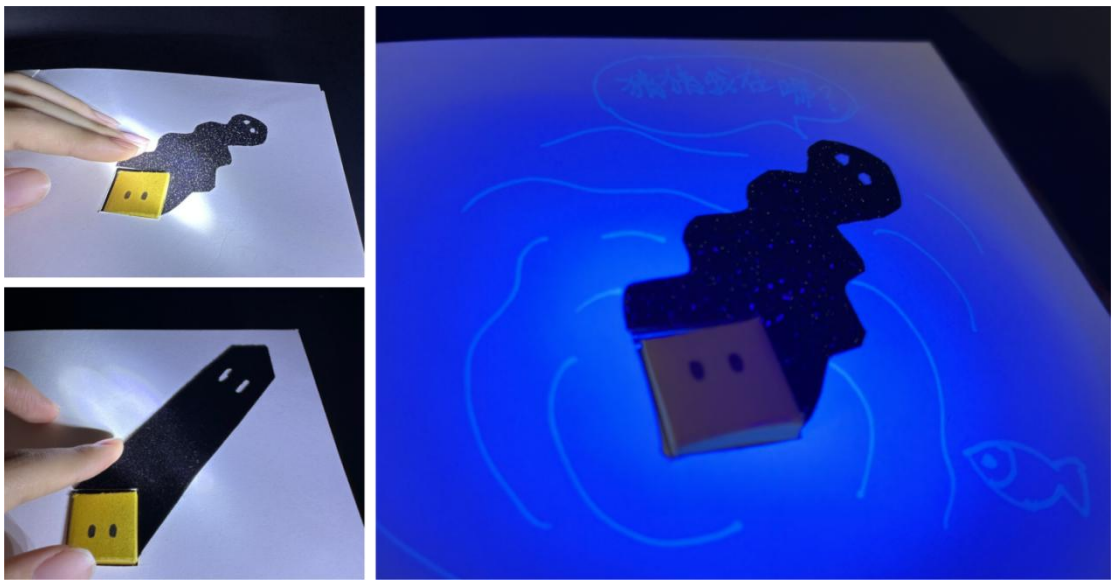

fig. 4.1 Left:Design of the shadow textures; Right: Hidden plots revealed by UV light.

4.2. Narrative Design: Learning Guided by Plots

4.2.1. Emotional Engagement through IP design.

The book effectively integrates plots with educational content, ensuring the narrative storyline aligns closely with learning objectives.

We have designed the protagonist Cuby as an abstract cubic character with minimal details. This three-dimensional, minimalist design directs children's attention toward observing the changes in light and shadows rather being distracted by the detailed character aesthetics. The minimalist character appearance provides flexibility in material and shape, allowing us to effectively convey various light and shadow phenomena. The simplicity of Cuby's design not only enhances the educational focus but also makes the character easily recognizable and endearing. This facilitates emotional resonance with children, thereby increasing their engagement and motivation to learn.

4.2.2. Progressive Integration of Storyline and Knowledge Acquisition

Secondly, The complexity of knowledge on each page aligns with the storyline's development. The first part (pages 1-4) introduces simple concepts by showcasing everyday shadow phenomena, sparking curiosity about light and shadow relationships. Correspondingly, the plot is straightforward, focusing on introducing Cuby and his shadow. In the second part (after page 5), more complex knowledge is introduced, along with engaging activities like exploring light color changes. Correspondingly, the storyline advances to Cuby and his shadow embarking on adventures in various environments-rainy days, theaters, and transformations. This alignment synchronizes narrative progression with increasing knowledge complexity for a cohesive learning experience.

4.2.3. Hidden Narrative Layers Enhancing Engagement.

Beyond the explicit storyline, a hidden narrative layer is accessible through an UV lamp. Children use the UV light to discover concealed dialogues, facilitating curiosity and exploration. These hidden messages hint at specific scientific concepts, making abstract ideas tangible through active participation (See Figure 4.1). For example, in a plot designed to illustrate the light-dependent nature of shadow formation, the shadow expresses its intent to always follow Cuby, but Cuby points out that this only happens when the lights are on, hinting that shadows disappear in darkness.

4.3. Low-Cost and Long-Term Utilization

4.3.1. Practical and Low-Cost

The practical and low-cost design of this pop-up book optimizes space through a strategic structural layout. The embedded structure of Cuby enables light and shadow exploration within the limited surfaces of each page--the hollowed sections position Cuby centrally, with each page featuring interactive games that involve him. As children progress through the book, Cuby transitions from being partially covered to gradually revealed, ultimately becoming a removable and transformable prism. These physical transformations provide varied content and interactions, allowing children to gain a vivid understanding of how light and shadow interact with objects of different sizes and materials. Furthermore, Cuby serves as both a character and a teaching aid, which children can repeatedly play, reinforcing knowledge aquisition and extending the book’s lifecycle. The games, designed for repeated engagement, include features like the "Shadow Theater," where children can swap geometric cards to create different shadow effects, encouraging ongoing exploration.

5. Discussion

5.1 User Feedback and Educational Value

fig. 5.1 Left: The interactive picture book used in the experiment alongside a non-interactive version for comparison; Right: A photo from a user study session.

We conducted a user study to gather feedback by comparing an interactive picture book with a non-interactive version during a children's market event. The children and parents feedback showed that the book's multi-sensory, interactive features were highly engaging, particularly for younger readers. The UV light feature was especially popular, sparking their curiosity and excitement. The prism cut-out feature also intrigued children, as it let them explore light refraction in an engaging way. Overall, the 3D format was preferred over traditional flat books, with children finding the immersive, tangible design more enjoyable. For instance, younger readers like A5 described the shadows created in the pop-up book as "real," highlighting the emotional engagement and hands-on interaction the book provided. Additionally, the music-accompanied flashlight activity offered a unique way to explore light and movement, though some children needed guidance to match their actions to the rhythm.

The book also proved effective in helping children understand scientific concepts. Some older children, like B7, showed particular interest in the principles of UV light,

using it to experiment with different materials and enhancing their engagement with scientific inquiry. Activities like assembling geometric shapes and combining elements to observe light effects further reinforced learning, making scientific concepts more accessible and fostering a sense of discovery.

Additionally, the book promotes STEAM education by integrating art with physical science. As children engaged with the visual aspects of light and shadow, they not only learned scientific principles but also sparked their creativity, supporting the development of both cognitive and artistic skills.

6.3 Limitations

The user study highlighted a few design limitations. Certain interactions required specific techniques, such as positioning the flashlight at a particular angle or timing it rhythmically, which some children found challenging. Although children displayed strong interest and curiosity, many required adult guidance to achieve the intended effects, which may impact the book's suitability for independent learning. For instance, children often struggled to angle the flashlight correctly, and some, like C6 found it difficult to match the light's movement to the background music.

Additionally, while the prism and embedded light elements captivated children, the complexity of these materials may lead to increased production costs, which could limit the book's affordability and accessibility in some educational settings.

6.4 Future Work

To further enhance the book's learning potential and address current limitations, integrating augmented reality (AR) could enable children to explore scientific concepts independently. For example, we could use 3D models to illustrate light

source direction for better understanding of how to play this book. Refining the prototype for market readiness, with optimized production and smaller Arduino components, could also reduce costs and improve visual appeal. Additionally, expanding the character of Cuby into a broader IP with age-specific textbooks and books on topics like forces, coding, and mathematics holds promise for supporting diverse educational needs.

6. Conclusion

Our work introduces Cuby and His Shadow Friend, a game-based learning book designed to enhance children's understanding of STEAM concepts, with a focus on light and shadow through hands-on, embodied learning. Insights from interviews with teachers, academics, and parents revealed that children prefer interactive elements, parents value content that boosts reading confidence, and teachers seek clear narratives to simplify complex ideas. To address these needs, the book includes embodied interactive designs to engage children with light and shadow, a layered storyline with UV light-revealed elements for progressively complex learning, and a durable, low-cost design with pop-up structures and reusable games. Feedback from primary students and parents indicated strong engagement and improved understanding, though some children required guidance for more independent exploration.

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