Examining Actual Effects of a Tangible Tool on Children's Collaboration

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Figure 1: *SpellBoard* for children learning German spelling: a) The whole setup with 20 letter blocks, a board with six positions to put letter blocks, and a laptop for showing spelling tasks; b) Two children in our study were spelling "Truhe" (i.e., chest in English).)

Abstract

Tangible user interfaces create a novel collaborative environment for children to interact with physical objects with augmented computing technology jointly. However, most previous studies only did short-term experiments. Moreover, we still need to examine the actual effects of tangible tools on children's collaboration. Thus, we designed, developed, and evaluated a tangible collaborative tool called *SpellBoard*. We conducted user studies for two weeks to see the actual effects. We dug out three key findings: 1) Interactive constraints can be specially designed to allow children to coordinate their collaborative actions; 2) From an actual usage effect, we need to redesign *SpellBoard* to consider children's cognitive engagement and interdependency in collaborative activities; 3) Children need time to understand the tangible design fully. Thus, we need a framework to add new learning content to sustain their engagements. Our findings could improve the future tangible design and make it have a good long-term impact on children's collaborative learning.

Index Terms: Human-centered computing—Human computer interaction (HCI); Applied computing—Education

1 Introduction

Computer-Supported Collaborative Learning (CSCL) is an essential field within learning science [18], which studies how computers can facilitate collaborative learning with technological and pedagogical strategies [12]. Tangible user interfaces (TUI) create a novel CSCL environment for children [22, 29] to interact with physical objects with augmented computing technology. TUI has been used for children's exploration [3], problem-solving [10], skill development [20], and communication [8]. However, previous studies have two limitations [22, 29]: First, study findings were inconclusive because most of the experiments were conducted once, and their experimental time was short; Second, their main evaluations were social interaction and enjoyment. To have an actual learning effect beyond playfulness and fun, we need new evaluation methods to help future studies focus on the right direction.

Our study intends to explore the practical effects of a tangible tool on children's learning. First, we designed and built a tangible tool *SpellBoard*, which is for two children to learn German spelling collaboratively. It had five iterative design phases: designing and refining the concept idea, envisaging natural and interdependent interactions with the paper prototype, testing such interactions with the initial technical prototype, examining the actual user experience with the final prototype, and improving the user experience. Then, we examine its practical effects on children's learning performance, collaborative behaviors, and learning engagement using two weeks. Our findings provide useful insights and practical considerations for designing a tangible collaborative tool for children learning.

Our investigation revealed three main findings. First, interdependent collaboration and cognitive engagement must be improved from a long-term effect perspective. Second, we should consider design interaction constraints allowing children to coordinate their actions. Finally, we need a flexible content framework to customize the learning tasks. Overall, *SpellBoard* was a good tangible collaborative tool to promote children learning.

2 Related Work

To conjure the research questions, we need to recognize: 1) Previous studies of CSCL to see the benefits of children using "computers"; 2) How tangible tools have specifically benefited children's collaborative learning; and 3) The evaluation of effective collaboration from learning engagement perspectives.

2.1 Computer-Supported Collaborative Learning

Computer-Supported Collaborative Learning (CSCL) refers to "how collaborative learning supported by technology can enhance peer interaction and work in groups, and how collaboration and technology

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facilitate sharing and distributing knowledge and expertise among community members" [21]. Good collaboration needs a process-oriented consideration [12] and requires tools to create a productive learning environment. CSCL tools try to support constructs for an effective collaboration [17], e.g., designing awareness and negotiation for sustaining positive social interaction.

Collaboration has various forms [28], e.g., peer-peer, child-mentor, and computer-child. Peer-to-peer interaction makes collaboration facilitate cognitive restructuring [26]. The child-mentor has a more *able* peer and benefits from "mentoring" collaboration [33], which provides a "scaffolding" way of interaction [25]. CSCL tools allow children to collaborate more actively and interestingly within the physical context [28]. Designing them creates an opportunity to design natural collaborations to support learning, where the children could obtain a new learning experience through, e.g., mobile [31], and embodied learning. There are many CSCL applications designed for children, e.g., knowledge forum [30], Logo [5], games [31], and tangible tabletop [34]. By interacting with technology, children can enhance their cognition, motor skills, language, and social skills, intelligence, reasoning, and personality [23]. However, only a few studies addressed designing interactive, collaborative play or methods for children [2, 34]. Most instances of collaborative interaction techniques are from the game industry, which focuses on enhancing traditional input devices (e.g., game controllers) of on-screen applications for a single user. In addition, we need to know whether promoting true collaborative learning is a realistic ambition for young children [11, 34].

2.2 Tangible Collaborative Tool

Tangible technology provides opportunities to design collaborative interactions, allowing learners to engage in highly collaborative activities [27]. For children's education, the physical world has an essential effect on coordinating learning activities and creating a shared collaborative space. Prior CSCL studies did not sufficiently consider the influences or potentials of the physical world interaction for facilitating such shared goals and mutual understanding of collaboration [21,31]. However, the physical world offers a rich experience to facilitate collaboration [32]. Piaget [26] found that children did not passively obtain ideas from the external world but had to construct concepts or knowledge through active experimentation and observation. Children learn by playing and exploring [31]. TUIs can offer such an "actual" learning experience, where children can play with the physical learning tool to explore their understanding [24]. Thus, they obtain new skills and learn to collaborate through social interaction or imitating others' behavior.

Tangible tools have been applied in many domains for children [29], e.g., programming, communication, mathematics, and storytelling. The uniqueness and benefits of using tangible tools for collaboration are: 1) Tangible objects help children have joint control of the interface, which builds a shared space for them to communicate and discuss [1]; 2) Physical object is easy and fun to embed embodied interactions, which creates interdependent reliance for children to achieve the same goal [34]. Thus, TUI is a natural way for children to interact with technology, especially in collaborative learning. There are many good examples that could help us understand how tangible tools have been designed and developed to help children learn. For example, *PhonoBlocks* [13], a tangible system to support children learning English letter-sound correspondences, achieved significant learning gains. *BlackBlock* [4] promoted children aged 4 to 8 to learn through embodied experience and positive mood. *Towards Utopia* [7] enabled children (7-10 years old) to construct knowledge about land use and sustainable development. *TurTan* [15], a tabletop interface with tangible objects, helped children creatively explore tangible programming language.

However, previous studies have three problems [22, 29]: 1) Majority of the studies experimented only once, e.g., 18 mins user tests [16]). Thus, it was hard to believe their empirical findings on the TUI effectiveness; 2) We still lack guidelines to design and develop tangible tools which could have an actual effect on children's long-term learning. For example, what are the primary considerations for children who use a tangible collaborative tool? How to evaluate the effectiveness of such a tool? 3) The primary evaluations were user experience and enjoyment [35]. Findings in the CSCL field are mainly obtained by "after collaboration" measurement and lack measures for examining learning processes [17]. However, when envisaging an environment for collaborative learning, we need to consider creating an experience arising where children are aware of communal purpose [34].

2.3 Learning Engagement

Engagement is a critical criterion for measuring or evaluating collaboration effects. Learning engagement has multidimensional constructs, including behavioral, emotional, and cognitive learning experience [14, 19]. Behavioral engagement refers to involvement in learning and includes factors for intrinsic motivation, e.g., effort, persistence, concentration, attention, and asking questions. Emotional engagement means individual affective reactions such as interest, boredom, happiness, sadness, and anxiety. Cognitive engagement indicates strategic and self-regulated behavior, e.g., when using meta-cognitive strategies for planning, monitoring, and evaluating cognition while accomplishing tasks. Learning has always centered on cognition, which is concerned with skills and processes such as thinking and problem-solving. However, behavior and emotion should be equally considered, especially for young children. TUI changes traditional learning methods, which creates an active learning environment for young children to explore their understanding by interacting with physical objects. In this situation, the nature of cognition has been re-considered. Unlike focusing on abstract symbols, the tangible approach proposes the fact that cognition is, instead, a situated activity [6].

3 Research Questions

TUIs give children an active and engaging collaborative experience within the physical context. However, it is unclear what are their principle design deliberations [31] and what are their actual effects [11]. Therefore, we designed and developed a tangible tool named *SpellBoard* to examine the following three research questions:

- **RQ1:** How could *SpellBoard* actually affect children's learning performances and collaborative behaviors?
- **RQ2:** How could *SpellBoard* actually affect children's behavioral, emotional, and cognitive engagements?
- **RQ3:** What are the primary considerations for designing a tangible tool for children's collaborative learning?

4 *SpellBoard* Design

We used twenty German words from the discussion with two primary school teachers (see Table 1). Meanwhile, we created twenty letter blocks. To help children naturally collaborate, we made an interdependent design:1) There were blue and orange colored letters with similar usage percentages, and 2) All words had to be spelled with blocks of both colors. The color of the letters was determined according to the frequency table of German letters [9]. Then, as shown in Table 1, we balanced the blue letters and orange letters with similar frequency.

More specifically, participants could naturally interact with the *SpellBoard* by putting letter blocks in sequence on the board. The *SpellBoard* tablet system would automatically give feedback to the participants. The interdependent constraint is that each word needs letter blocks from both colors: blue and orange. Thus, children will naturally work together to finish the tasks because each child only has either blue or orange letter blocks.

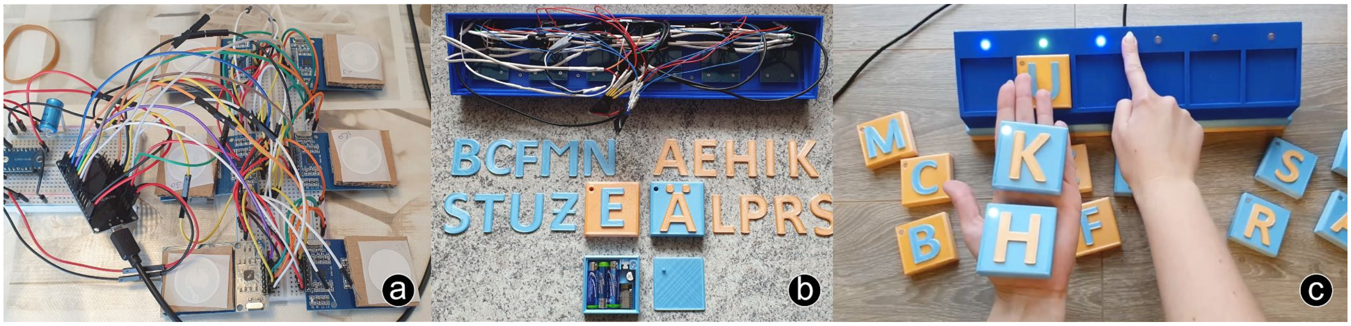

Figure 2: *SpellBoard* hardware: a) Connect six RFID readers, b) Inner structures of the prototype, and c) Use the help function by pressing the help button in the middle of the board.

Table 1: Twenty German words for spelling in the first user study (orange letters are for one child, blue letters are for the other child).

BÄUME	BEUTE	ECHSE	FERKEL	FEUER	MÄUSE	MEER	MESSER	SCHULE	SIEBEN
INSEKT	KARTE	KATZE	KUH	LUPE	STUHL	STURM	TRUHE	ZAHL	ZUCKER

5 *SpellBoard* DEVELOPMENT

There were an ESP32, six RFID readers, six reed connectors, six RGB LEDs, a button, and the associated cabling in the game board (see Fig. 2a). The RFID readers were attached to six positions, and among them were the reed connectors. The reasons were to reduce power consumption and make readers read only when the circuit at the magnet connector was closed. This design is necessary because six simple and closely positioned readers strongly interfere with each other (see Fig. 2b). The main functions of *SpellBoard* were: 1) The board block could recognize the correct letter blocks. If the top LED light on the board shows red, the child puts a wrong letter block; Green means placed correctly; Blue indicates a letter block must be placed there. 2) As shown in Fig. 2c, if the child presses the help button, the LED light on the top left of the missing letter block will flash. This function helps children learn independently.

We also developed a tablet learning application with the cross-platform game engine Unity to engage children in the learning content. It mainly had four functions: 1) It gave children gamified roles. For instance, the child could add his or her name and choose an avatar (see Fig. 3a); 2) It shows which word to spell and plays word pronunciation automatically (Fig. 3b), which is essential for German language learning; 3) To keep their learning interests and motivations, we design three difficulty levels by using themes to gather the words. 4) Incorrectly spelled words would be summarized for further practice; 5) New words could be added, especially by parents and teachers (Fig. 3c). Overall, the tablet application was understandable for children.

6 METHOD

We designed 20 German words for the initial experiment. Each word needs letter blocks with both orange and blue colors. We implemented functions of letter block with hardware such as ESP32 and RFID. Later, we conducted user studies with four children for four sessions.

6.1 Participants and Setup

The user study was conducted with four children (3 girls, 1 boy, M(age) = 8.25). It consisted of two pairs, one pair with 7-7 yo and the other one with 9-10 yo children. Each pair attended our user study four times within two weeks with the same experimental interval. All children were recruited from local families who were willing to participate. The user studies were conducted at children's homes. Their parents were present during all the activities but just as observers. Parents signed a written consent before their children's participation. Children were voluntary to attend and were free to stop at any time. As shown in Fig. 1, the study setup contained an Apple MacBook Pro (16 GB, Intel Core i7, 13.3 inch with 2560×1600 px), a computer mouse, *SpellBoard*, a tablet for video recording, and a smartphone for taking pictures.

6.2 Procedure

Children played *SpellBoard* in pairs for around 25 minutes with video recording. Two different authors conducted in-field observations with a structural observation form for each pair. The observation form consisted of five dimensions: understanding of the system setup and design (5 items), behavioral engagement (3 items), emotional engagement (5 items), cognitive engagement (5 items), and collaboration (4 items). For example, "*The kids are having fun.*" (emotional engagement) "*The children were attracted by the task.*" (cognitive engagement) "*The children help each other.*" (collaboration). The after-study interview was conducted with each child for about 10 mins with audio recording. In all, it had 22 items from 1 (*strongly disagree*) to 5 (*strongly agree*). Eight questions were prepared to ask about their feelings of engagement and collaboration, e.g., "*Did you have fun?*" and "*Did your partner help you?*." All interview audios were transcribed and coded by the second and third authors. We obtained five analysis themes: system understanding, collaboration, behavioral, emotional, and cognitive engagement. The results of these themes were translated from German into English by authors who were native German speakers and fluent in English. Finally, system log files had children's behavior data, e.g., how often one letter block per word was misplaced and how often the help button was pressed.

As we mentioned, each pair of children attended our experiment four times. In the initial session, the children's parents signed the consent form and got a study code. Before the experiment, we first asked participants' age and recorded their gender, and then we briefly introduced how to interact with *SpellBoard*, such as where was the help-seeking button. During the experiment, participants learned the new German words independently. Meanwhile, we conducted the observation with an observation form. After the experiment, we interviewed individual participants. Regarding the three subsequent sessions, we only did observations and interviews. To keep their interests, we updated 20 new words in each new session.

7 RESULTS

To answer the research questions, we analyzed children's understanding of the design, learning performance, and learning engagement.

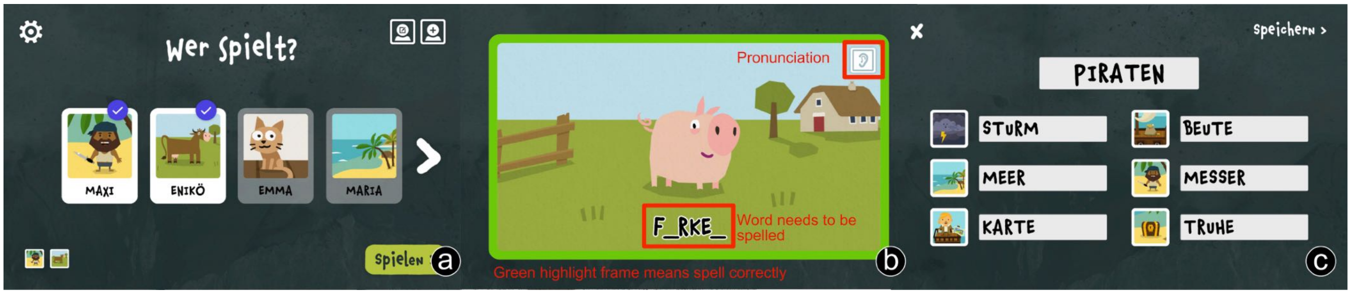

Figure 3: *SpellBoard* tablet application: a) Choose players, b) Interaction feedback, and c) Framework to add customized contents.

Table 2: Learning performance (WToS = Which Time to Spell, ToM = Times of Mistakes, ToPHB = Times of Pressing Help Button).

Word	WToS	ToM	ToPHB	Time (min)
ALIEN	1st	3	1	1:03
	4th	0	0	0:32
ECHSE	1st	0	0	0:26
	4th	3	1	0:28
MÄUSE	1st	1	1	0:59
	4th	2	0	0:37
MESSER	1st	4	0	0:37
	5th	0	0	0:14
RÄTSEL	1st	5	0	0:34
	6th	4	1	0:36
SHRIMP	1st	10	1	1:42
	4th	4	0	1:11
TRUHE	1st	1	0	0:30
	4th	1	0	0:16

In addition, we transcripted and coded the interview results to show insightful actual use experiences of the *SpellBoard*.

7.1 Understanding the Design

From the observation, we found that all children understood what to do at the beginning and immediately did their spelling tasks. The LED notifications on the board were understandable for them. Regarding the help button, both groups were aware that it could be pressed. During the first two experiments, it was rarely used. However, when the spelling of words became more complex, children started using them. In addition, to avoid children misunderstanding some letters, e.g., "M" and "W", we implemented a LED at the top left of each letter. Therefore, although sometimes letter blocks were placed incorrectly, children would quickly notice it, e.g., children said *"Wait, you have to put it the other way around." "Was it upside down?"* As shown in Fig. 4, all children had similar understandings of the design throughout our four study sessions. In the initial two sessions, their understandings were unstable and had an evident increase. However, starting from the third one, all children had complete knowledge and remained constant.

7.2 Learning Performance

The system recorded the time spent spelling each word. We selected seven words that appeared many times to show the performance difference. As shown in Table 2, except "MESSER", all other words used less time in the last time. Meanwhile, the overall frequency of misplaced letters decreased from 13 to 6. Children made fewer mistakes in the final session for the same spelling words. However, the help-button press frequency was similar.

7.3 Interdependent Collaboration

Children talked with each other since the game started. In each session, there were always situations where a child was slightly more dominant and said something like *"Wrong, a Z belongs there." "*Name of ID3*, do not smash that around!" "This is not a wolf, this is a fox."*. However, they were also switching roles from a leading *wise person* to the other who followed the instructions. When they worked together, they had many collaborative conversations, such as *"Wait, you have to do it this way." "Wait...no, that does not belong there." "Ah misspelled, right?" "And now you can choose." "No, you have it the other way around." "So, which one do we choose? The bird, right?" "What should we take? The mice?"* and *"That is an M, we need an N."*. As shown in Fig. 4, their collaborations increased until Session 2, then started to decrease.

7.4 Learning Engagement

In all four sessions, children showed good behavioral engagement, even though it was not stable (see Fig. 4). From the video analysis, we could see they were highly motivated to solve the spelling tasks without help or encouragement from external persons (e.g., their parents or experimenters). They had many hands-on interactions, e.g., *"So, we already had that before." "Bee? No, we already had that. Or the rattle? Or the next one. - We already had that."* However, their concentration slowly decreased during Session 3 and 4 by 18.75%.

All children's interests in solving the tasks (i.e., emotional engagement) were high and stable after Session 3 with above 4. Sometimes, when they finished the task, they would say: *"Are we already finished?" - "Yes." - "Oh, a pity."* When placing the letter incorrectly or having to press the help button, their perceptions of frustration was low; Only Child C sometimes said *"Where is the *** R?"*. However, children were more likely to be motivated to find the correct letter blocks if they put the wrong one. For example, they motivated each other very often with *"Well done." "Great!" "We can do that really well!" "I like to write that down." "The bee looks the most beautiful!"* and *"Ah, the one is there! It is cute."*.

The average percentage of whether the children worked on the tasks due to intrinsic motivation is 90.63%. Video analysis of Group 2 showed that one child always told his partner not to use the help button. He said: *"- Do not push it. - I do not like that. - Stop. I still know how to spell the word!"*. Sometimes, the children also would say: *"No, let's take something else. We have already had it." "Or let's do the difficulty again ..." - "Yes, more difficult. Difficult! "* However, it must be mentioned that distractions were high during Session 4 (see in Fig. 4-cognitive engagement). High cognitive engagement indicated learners could realize a knowledge link between school learning and everyday life [14]. This was also found in our user study. When one of the participants needed to spell the German word "SHIRT," she immediately noticed that she learned it in her English lessons and said: *"We had that in English."*

In sum, participants had unstable behavioral and cognitive en-

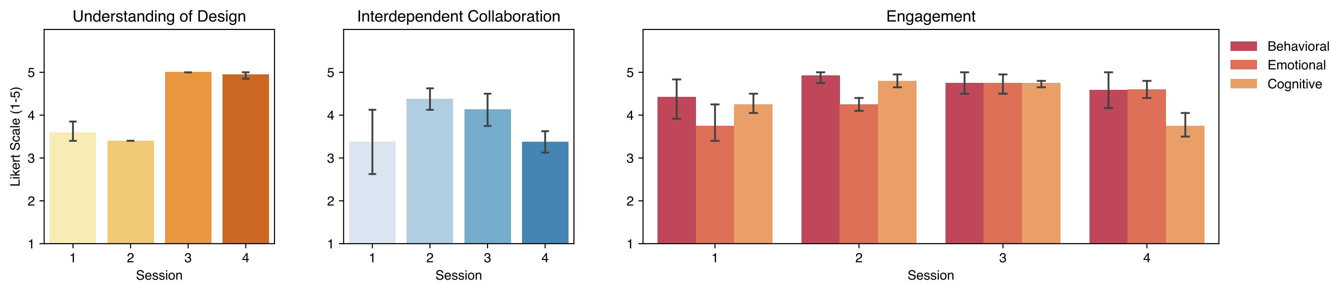

Figure 4: Children's understanding of design, interdependent collaboration, and (behavioral, emotional, and cognitive) engagement from Session 1 to Session 4.

gagements between 4 and 5. However, their emotional engagement slowly increased and kept stable above 4.5 from Session 3.

7.5 Interview Results

After each session, we interviewed children and asked them eight questions. Their answers were mainly limited to "yes" or "no." Only when asked about *What did you like?*, they made some concrete examples: *Letter blocks' light* (12.5%), *choosing the pictures [when creating avatar]* (25%),*choosing the topics [for practices]* (12.5%), *everything* (50%). From the interviews, we found that children had fun and liked *SpellBoard*. They helped each other when doing exercises. In addition, although formal interviews with parents were not conducted, Child A and C's parents told us that their children were always looking forward to attending our next experiment and asked many questions about *SpellBoard*.

8 Discussion

From a practical user experience perspective, children have a better learning performance and behavioral and emotional engagement. However, interdependent collaboration and cognitive engagement were not sufficient. Therefore, we discuss how to improve the design and what we need to consider.

8.1 Simple and Intuitive Interaction Design for Children

Most children understood our interaction designs, e.g., how to start the game and put letter blocks on the board, but it might take some time. As we could see from Fig. 4, until the third session, children could have a good and stable understanding. Thus, designing intuitive and simple interactions for children to work together effectively is essential. Tangible has the advantage of "force" interdependence because it makes the task-solving processes easy and intuitive. However, we found that children might not always comply with the interdependent design from in-field observation. For example, Group 1 always ensured that letter blocks were returned to the original owner after each exercise. When doing the exercise, they often said something like *"Where is my A?"*, *"This is my S."*. However, Group 2 decided to mix all letter blocks and search together from the beginning. Thus, they often asked *"Where is the Ä?"* or *"SS, two S. There is another one back there."*. Their communications were different but still worked together well. Overall, we could see the importance of having simple and intuitive interactions with children.

8.2 Increasing Long-term Effects on Interdependent Collaboration

The results showed that participants had the highest interdependent collaboration in Session 2 but could not maintain it. Their cognitive engagement started to decrease in Session 3. Behavioral engagements constantly changed. However, emotional engagement rose steadily. Therefore, we should especially consider improving children's interdependent collaboration and cognitive engagement for better long-term learning effects. In our study, we designed the interdependent collaboration in a way that all spelling tasks required both children's blocks. We told them not to share the blocks at the beginning. However, one group did not obey this rule based on our observations. Meanwhile, children's previous knowledge of our chosen words might also influence the effects of our design purpose. Therefore, we should find multiple interdependent collaboration methods. In addition, we evaluated children's collaborations mainly by analyzing their helping conversations, help-request, and help-seeking behaviors. However, experimenters felt that sometimes even when children did not show many such behaviors, they were still collaborating well, but more with a tacit agreement. Thus, it proposed a reflection on how to measure and evaluate children's collaborative behaviors in the future. Should we value verbal or embodied behaviors more?

8.3 Providing a Flexible Content Framework to Sustain Cognitive Engagement

The results demonstrated that children did not have a high cognitive engagement. However, we had two design strategies to improve children's cognitive engagements in the study: learning tasks with different difficulty levels and an open frame for teachers or parents to add new tasks for an actual learning requirement. Cognitive engagement evaluates the effort children are willing to invest in working on the tasks and how long they persisted. Thus, the study results might have two reasons: 1) As we know, children have a short concentration span, resulting in an unstable behavioral engagement. If it were hard to keep children focusing on the tasks for a long time, they would tend to have low cognitive engagement; 2) Our participants did not have enough motivation to put too much effort into the tasks because they attended our study only as volunteers. If our tasks were a gamified competition or associated with teachers' homework, children might put more effort. Thus, we concluded it was crucial to have a framework to add contents autonomously for a long-term experiment.

9 Conclusion and Future Work

To examine the actual effect of TUIs on children's collaboration, we designed and developed a tangible collaborative tool named *SpellBoard*. We conducted user studies for four sessions. The results showed that *SpellBoard* had actual sound effects on children's collaborative experiences and behavioral engagement. We recommended simple and intuitive interaction design for children, increasing long-term effects on interdependent collaboration, and providing a flexible content framework to sustain children's cognitive engagement. In the future, we plan to: 1) Build more letter blocks because we only have 20 ones in our experiments; 2) Collaborate with teachers and use *SpellBoard* in an actual kindergarten classroom. Because we want to see long-term effects from at least one semester; 3) Use more dimensions or methods to evaluate the effects.

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