Tangible Interfaces Support Young Children's Goal Interdependence

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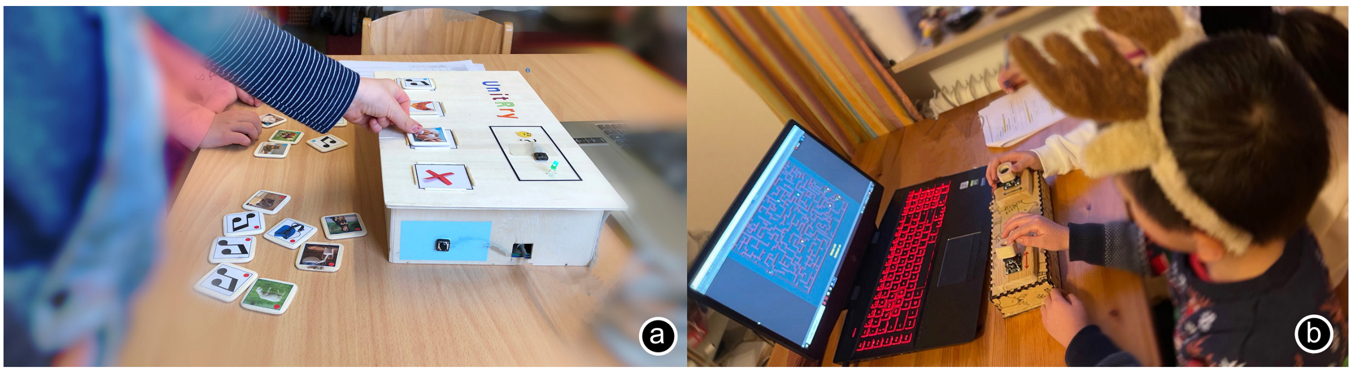

Figure 1: The tangible prototypes *UnitRry* and *CollabMaze* we developed and evaluated. a) Two children put knowledge cards on *UnitRry* to learn relations of chicken, egg, and chicken cluck. b) One child controls left-right, the other controls up-down of the *CollabMaze* to move the character out of the maze.

ABSTRACT

Understanding how to contribute to group work is challenging, especially for young children. To have a productive group process, we need to know the mechanism of positive interdependence, which is a fundamental element of successful collaboration. Unfortunately, although there are many suggestions for promoting positive interdependence with tangible technologies, there are few guidelines for structuring children's interdependent collaboration. Therefore, we designed two tangible games, *UnitRry* and *CollabMaze*, using weak and strong goal interdependent designs. We conducted two user studies with 32 children. Our investigation revealed three main findings. First, weak and strong goal interdependent interfaces had high enjoyment and interdependence. Second, tangible interfaces help young children have more idea communication and need less time to solve the tasks. Finally, young children using tangible interfaces were more engaged in the tasks. In the long run, our results can improve the design of tangible interfaces for young children's collaboration and help them have a better collaborative experience. Furthermore, our findings showed the value of tangible technologies compared with tablet applications in facilitating children's collaboration.

CCS CONCEPTS

• **Applied computing → Education**; • **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

tangible learning, goal interdependence, collaborative learning, young children, tangible interaction, tangible user interface, TUI

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1 INTRODUCTION

Collaborative activities transform traditional teacher-centered teaching into student-centered learning [33]. Collaboration facilitates idea exchanges and builds students' self-esteem and confidence. In addition, it helps to reduce anxiety and keep children active in the learning activities [17]. However, it is challenging to know how to contribute to group work [15, 18], especially for young children [39]. To have a productive group process, we need to know the mechanism of positive interdependence [11], which is a fundamental element of successful collaboration. Positive interdependence is an essential element for group members perceiving that they are interconnected and that one person's success is inseparable from the achievements of others in the group [12, 16, 34]. It encourages children to work together rather than competing or individually, promoting more negotiation and communication to resolve conflicts together rather than unilaterally [39]. If there is no positive interdependence, there is no collaboration. As we can see, it is essential to structure children's goal interdependence, but currently, there are few studies on how to design this interdependent strategy [3]. One possible reason is that without suitable technologies for supporting the design.

Tangible User Interfaces (TUIs) are a promising solution [3, 19]. TUIs are novel interactive interfaces using the control of the physical object to build a bridge between the physical world and the digital world. TUI provides particular affordances for fostering positive interdependence because the distributed work with particular duties brings object ownership and also because children have more desire to manipulate physical objects [35]. In addition, it helps children who do not have computer skills in particular because it is intuitive to know how to interact with [22]. Many studies [3, 7] have compared TUI with other interfaces, such as physical user interfaces and Graphical User Interfaces (GUI). *Youtopia* [39] is a tangible and interactive tabletop application that allows students to plan for sustainable land collaboratively. They compared the pairs of children assigned particular roles in positive interdependence conditions and the other pairs not assigned roles in the control condition. The results showed that groups assigned specific roles spent more time explaining their thinking or reasoning to the partner than groups not assigned roles but had fewer conflicts. In addition, it found that the assigned roles provide a positive effect on collaborative working. Fan et al. [7] compared the differences between codependent and independent access points among university students. Even though there are many suggestions for promoting positive interdependence, there are few guidelines on structuring children's interdependent collaboration with tangible technologies and their actual effectiveness.

We guide this work by asking whether TUIs can help support children's goal interdependence. Therefore, we designed and developed two tangible prototypes, named *UnitRry* and *CollabMaze*. Here, one with weak and the other with strong interdependent designs. To the best of our knowledge, we are the first study to explore TUIs that support different degrees of goal interdependent for young children. For both prototypes, we also designed and implemented a tabled based GUI for a baseline comparison. We conducted two user studies with overall the same goal and measurements for engagement and goal interdependence. In the first study, we use one with *UnitRry* and paired twelve children to play with it. In the second study we used *CollabMaze* paired twenty young children to play with it. Using our two prototypes, we found that both weak and strong goal interdependent interfaces had high enjoyment and interdependence. We further found that the tangible prototypes made young children have more communication and at the same time need less task time. Finally, young children using TUIs were more engaged in the task.

2 RELATED WORK

To get an insight into tangible technology for supporting children's goal interdependence, we need to understand (1) how previous studies have explored the collaboration for young children, (2) goal interdependence, and (3) how tangibles have supported children's goal interdependence.

2.1 Collaboration for Young Children

Physical object manipulation has an essential influence on young children's cognitive development [27]. Children explore the world by acting, arranging, structuring, and counting objects [29]. In other words, play promotes children's development [27]. Furthermore, when children interact with their surroundings, e.g., by grasping objects and giving them a name, they can learn to think and act logically [29]. We want to support this process, but most traditional interfaces are not suitable for children's underdeveloped motor skills or the two-dimensional information representation [27]. Moreover, they do not support children's social interaction or collaboration. To learn and develop collaborative skills, children need a physical space for having the opportunity to communicate with peers, such as grasping and interacting with physical objects together [27, 29].

TUI benefits children's visual-spatial thinking. Verhaegh [38] investigated whether visual-spatial reasoning tasks were more manageable for 5-7 years old children when we presented them in the tangible format, not virtual. He compared twenty-five children and found that the tangible group solved the tasks doubled faster and showed significantly more visible problem-solving behaviors. Many children have difficulty visualizing abstract functions, such as sine, cosine, and tangent. One approach to promote algebraic, geometric, and visual thinking are TUIs. For example, Urrutia et al. [36] found that students performed significantly better on trigonometry tests after using a tangible tool for representing the geometric concepts. Therefore, many studies have explored how TUI could collaboratively help children learn visual-spatial thinking. For example, *Tangicons* [29] used games to help children have their first experience of programming and algorithmic thinking together. *Flow-Blocks* [42] taught children mathematical and computer science concepts by letting them manipulate abstract structures. With *Ely the Explorer* [1], three children could learn about new cultures while practicing reading, writing, and counting together. It encouraged collaboration because each child must complete their task to contribute to the group goal. *Utopia* [39], a tangible and multi-touch tabletop interface, allowed children to create their world where they see the impact of their choices on the amount of food or energy for the population. Finally, Horn et al. [8] conducted a study to examine the differences between using a tangible and a graphical programming language. They found tangible conditions children showed significantly higher collaborative behaviors.

TUI builds on basic skills people have in the physical world. By interacting with real objects in a variety of ways, including touch, press, and grasp, TUI establishes a new possibility of connecting with digital worlds [31]. Therefore, the core idea of TUI is to make digital information show and perceived in a physical form, which could make information immediately graspable and manipulable through haptic feedback [10]. For children in the early stages of cognitive development, the primary way they explore new knowledge is through the intuitive and straightforward way of touching and manipulating objects [41]. Concrete objects are crucial for children's learning because when they can solve problems without symbolically imagining the rationale [23].

2.2 Goal Interdependence

Interdependent collaboration provides a context where promotive interaction occurs so that interpersonal interaction produces a high achievement [5]. In order to achieve a good collaboration, it is essential to structure collaborative activities, e.g., design collaborative tasks, interdependent roles, and interactions. From Human-Computer Interaction (HCI) perspective, we need to consider how to design interdependent interaction mechanisms to make learners influence and rely on each other to achieve the same goal. Wise et al. [39] found social/technological interdependence helped children produce more in-depth explanations and have fewer but longer cases of resolving conflicts jointly. Collazos et al. [5] claimed interdependent collaboration could motivate students to work hard and also facilitate the explorations of new insights and understandings.

Interdependence has three types: positive (cooperation), negative (competition), and none (individualistic efforts) [14]. Positive interdependence, a basic element of collaborative learning [16], refers to the success of one learner being constrained by the success of others in collaborative learning activities [5]. There are some different kinds of positive interdependences [5, 16], for example, positive goal interdependence, positive celebration/reward interdependence, positive role interdependence, and positive task interdependence. Designing such positive interdependences could encourage children to negotiate, solve, and discuss tasks collaboratively [39]. In other words, interaction results should be purposely designed to have children engage in the collaborative environment. Therefore, they could have an interdependency to improve children's collaborative experience [25].

Even though there are many suggestions for promoting positive interdependence, there are few guidelines on structuring children's interdependent collaboration with tangible technologies. However, TUI has an affordance to create an interdependent environment, where children have a physical embodiment of distributed control and social engagement around the interactive object [35]. It has a technological benefit, which can be employed to facilitate face-to-face (F2F) collaboration [6] and its social interdependence [35]. It is essential to explore the design space of goal interdependence with tangible technologies to understand how could design TUI for a better collaboration. Therefore, we investigate different embodied constraints for achieving the same goal. In this paper, we had two key concepts: weak goal interdependence and strong goal interdependence. We created them to understand the different levels of goal interdependence easier. **Weak goal interdependence** refers the interaction and output feedback do not have to rely on two or more users synchronously. However, **strong goal interdependence** means that users have to interact with their own tangible objects almost at the same time to understand the interaction output.

2.3 Tangibles to Support Goal Interdependence

TUI is well-suited for children's collaborative learning [21, 30] because (1) it provides particular affordances for fostering positive interdependence; (2) The distributed work with particular duties brings object ownership; (3) Children more prefer to manipulate physical objects [35]. "Affordance" describes the specific physical characteristics of objects "naturally" reveal what they might be used for [23]. To better design TUI for supporting collaboration, Antle and Wise [3] summarized twelve guidelines for designing tangible learning interfaces. In addition, they mentioned the significance of creating codependent access points, which can force learners to negotiate with others [7, 39].

Compared to other interfaces, TUI compensates for using human spatial abilities. It helps exploit our natural ability to interact with physical objects [32]. GUI such as tablets can add multiple inputs, but similar TUI is not confined to visual and auditory senses and could use the sensation of touch [31]. Some researchers believe that TUI can compensate for GUI. However, some argued that although TUI provides haptic feedback and intuitiveness, it lacks the portability and flexibility [4].

As seen in Table 1, there were various comparative studies with TUI and GUI for children's goal interdependence. However, different and even contradictory findings are often found [43]. For example, Xie et al. [40] compared pairs of children playing puzzles between physical, GUI, and TUI. The results showed that TUI and physical outperformed GUI in terms of finishing time and engagement, but not about enjoyment. They also observed parallel and independent collaboration strategies in TUI and physical, while children took turns in sequence in the GUI condition. Horn et al. [8] also conducted a study for comparing TUI and GUI, using a programming language to control a robot in a museum. They found that TUI promoted more active collaboration and was more child-focused than GUI. However, they uncovered opposing findings to Xie et al. [40] regarding performance and engagement. Sapounidis and Demetriadis [28] had three different age groups of children in a robot programming task and found that TUI was more enjoyable and easier to use for younger children. Cheng et al. [4] compared the difference between GUI and TUI for primary school students without prior computing experience to learn 3D modeling. It found no significant differences in engagements. However, they highlighted the importance of prior experience and the idea that prior experience is one of the essential factors in assessing performance. Finally, Almjally et al. [2] indicated that GUI was better than TUI for performance, but the TUI showed a more significant improvement in attitude.

Table 1: Good examples of previous comparative studies (Collaboration studies are marked in bold font).

Reference	Interfaces	Task	Evaluation	Findings
Xie et al. [40]	GUI TUI Physical	Puzzles	Performance Engagement Enjoyment Collaboration	Performance: TUI & Physical Engagement: TUI & Physical Enjoyment: no difference
Horn et al. [8]	GUI TUI	Programming Robot	Performance Engagement Collaboration	Performance: no difference Engagement: no difference
Cheng et al. [4]	GUI TUI	3D learning	Engagement	Engagement: no difference
Sapounidis and Demetriadis [28]	GUI TUI	Programming Robot	Enjoyment Easy-to-use	Enjoyment: TUI Easy-to-use: TUI
Loparev et al. [20]	GUI TUI	Bio-design	Enjoyment	Enjoyment: no difference
Pollalis et al. [24]	GUI TUI	Archaeological artifacts	Enjoyment	Enjoyment: no difference
Almjally et al. [2]	GUI TUI	Programming	Performance Attitude Enjoyment	Performance: GUI Attitude: TUI Enjoyment: no difference

3 RESEARCH QUESTIONS

As we can see from related work, previous studies got conflicting results using tangible and graphical interfaces. Some interfaces were designed for collaborative activities, but the collaborative mechanisms were unclear. In other words, users do not know their role and have no codependent access, leading to a negative collaboration, such as parallel and independent collaboration. Furthermore, the most critical element of collaboration – positive interdependence – was not mentioned. None of these studies compared different interfaces to support positive interdependence. Therefore, we propose two research questions:

- **RQ1:** What are the effects of the tangible interface with weak or strong goal interdependence design on young children's collaboration, enjoyment, and performance?
- **RQ2:** Compared to touchable tablets, what are the characteristics of tangible interfaces to support young children's goal interdependence?

To explore the above research questions, we designed two tangible prototypes: *UnitRry* with weak goal interdependence design and *CollabMaze* with strong goal interdependence design. Correspondingly, we conducted two studies, which aimed to: (1) explore an iterative design method to develop tangible prototypes with weak or strong goal interdependent design for young children; (2) evaluate the effects of such design on children's collaboration and enjoyment; (3) investigate the characteristics of such designs on supporting young children's goal interdependence compare to GUI with the same tasks.

4 TANGIBLE PROTOTYPE DESIGN

There are two conditions for creating positive goal interdependence: set a clear group goal and design constrained or codependent accesses. Such designs aim to motivate group members to commit to working together and let everyone realize the responsibility for the group's success. More specifically, we need an embodied facilitation design [9, 31], which contains three concepts: (1) *embodied constraints* means to favor some actions and restrict others, (2) *multiple access points* means to ensure that users can interact equally and simultaneously, and (3) *tailored representations* refer the interaction depends on the knowledge of the users. As shown in Table 2, we chose two contexts for designing *UnitRry* and *CollabMaze*.

To get the idea of *UnitRry*, we interviewed a kindergarten teacher (61 years old, female) who had worked in the kindergarten for over 25 years. She told us different exercises they did with the children and particularly mentioned a card game. This game has many pictures, and the children need to find two different cards that could match (e.g., hand and glove, garden and house). We used a similar idea for designing *UnitRry*, where two children need to find cards that have some relationships. If the children put the cards on a common board (see Figure 2b), *UnitRry* will give them an automatic feedback. Therefore, we could see how the actual effects of our design on helping children work together without external help. Two children of similar age work together. Before the game, we told them that each had a box of cards and was only allowed to use their cards when solving the tasks.

CollabMaze came from the brainstorming of "strong goal interdependent design", where children have to rely on each other, immerse themselves, and have fun. It is well known that games are natural and favorite activity for children. After investigating the

Table 2: Goal interdependent design of *UnitRry* with weak interdependence and *CollabMaze* with strong interdependence.

	UnitRry	*CollabMaze*
Context	Learn daily common relations (e.g., honey, bee, and sound of bee)	Move the game character to get out the maze
Group Goal	Find related cards and put them on the board	Move the game character to exit the maze
Embodied Constraints	None	One child controls the movement of left-right, the other controls up-down
Multiple Access Points	Two children have the same amount of cards	Two children have similar opportunities to move the game character
Tailored Representations	Two children are similar years age and have similar cognitive development	The tasks are easy to understand and do not need previous knowledge

current games played by children, we found a traditional and easy-understanding game called "Maze." Maze starts from ancient Greek culture and continues today. As a child-friendly and concentration-enhancing game, we chose the maze as our collaborative context, where two children were "forced" to work together to find the maze exit. It requires both children's active and equal participation to create positive interdependence. The movement of the game character is divided between two children, where one child controls the horizontal movement, and the other is responsible for the vertical one. To move the game character, both children should collaborate and rely on each other. The goal is for two children to work together and find the exit.

4.1 *UnitRry* for Weak Goal Interdependence

When developing *UnitRry* tablet application, we used Unity software. It contains logic and graphic representation. The tablet application receives messages from the buttons or Radio Frequency Identification (RFID) readers connected to the Arduino and sends the LED information to the Arduino. A package called *Ardity*[1] was used for this. It enables serial communication via a communication port between the Arduino software and the Unity software. We programmed a tablet application that could be used with the *UnitRry* and also on the tablet. When starting the application, it displays a menu that the children can select from four task levels. We had two difficulty levels, one for putting three cards and the other one for four cards. If the children use the *UnitRry*, a task explanation animation appears at the beginning to let the children understand how to interact with *UnitRry*. The *UnitRry* system has four levels of tasks. In level one and two, children need to find three common cards, e.g., "barking sound", "dog", and "bones". In level three and four, they require to search four common cards, for instance, "car", "bus", "plane", and "petrol station". Each level has seven tasks.

We also made an animation of how to use the help button. Children can either drag or drop the pictures to place on the specific card fields in the tablet condition. There is a smiley on the right side. It looks sad. Only when the children put all the cards correctly (no matter the order) do its similes. When the children have problems and press the help button, some unrelated pictures will disappear for 30 seconds, which helps the children narrow down the options.

To develop the *UnitRry* hardware, we used an inexpensive technology (i.e., RFID). A 22 mm diameter RFID sticker with a unique identification number was affixed to each playing card. We designed ten 4.5 × 4.5 cm cards with blue and red color for each child (see Figure 2b). In addition, we made a 36 × 20 × 8 cm box with four locations to put the card. Four RFID readers (MRFC 522) were implemented to read the cards. Furthermore, we made a help button. Children could use it only when it is green. This green color shows only after three minutes of each task.

4.2 *CollabMaze* for Strong Goal Interdependence

CollabMaze has two parts: one is the digital maze (i.e., GUI), and the other is the tangible controller. The digital maze was run on an iPad and was made with Unity with the version 2019.3.15f1. First, the children can choose their character from three avatars. Then, they need to choose a maze from six options with a teaching demo. The teaching demo is a setting in which the character can move around without obstacles, i.e., there are no mazes or walls in this space. It contains all the elements of the game: monsters, coins, keys, and the start and endpoints. At the bottom, we designed two sets of control buttons (see Figure 2c), consisting of up-down buttons and an attack button (star). In the middle is an area displaying information on collected and need-to-be collected coin numbers and the current status of the keys obtained. The red wall, in the end, will be opened automatically only when enough gold coins and keys have been collected. There is no such compulsory requirement regarding monsters, but the monsters will block the path in the normal levels and do not allow the player to pass. So the children are forced to kill it to get through. After they reach the destination (pictorial trophy), the "You did it" screen is presented, providing the total time spent and the walking time. One basic design is that all the mazes have two exits as a stimulus for negotiation. From Level 1 to Level 5, the maze size increases, and more coins and monsters appear.

CollabMaze hardware contains two main components: two joysticks and a base box (see Figure 2d). The joystick module that we used was the KY-023 two-axis analog joystick with 4 × 2.6 × 3.2 cm. To accomplish divided movement control, one joystick is designed for up-down movement (y-axis), while the other is for the

Table 3: Apparatus used in the four conditions.

Game	Condition	Apparatus
UnitRry	GUI	Acer Switch 3 Convertible (12.2", 1920×1080 px)
	TUI	Lenovo ideapad 5 Laptop (15.6", 1920×1080 px) + *UnitRry* prototype
CollabMaze	GUI	iPad Pro (12.9", 2732×2048 px)
	TUI	HP Laptop 17-cb1xxx (17.3", 1920×1080 px) + *CollabMaze* prototype

[1]https://ardity.dwilches.com/

Figure 2: *UnitRry* and *CollabMaze* setup. a) Two children are playing in the *UnitRry* tablet condition. b) *UnitRry* tangible condition setup. c) *CollabMaze* tablet condition setup. d) *CollabMaze* tangible condition setup.

left-right (x-axis). In order to prevent other directions' movement, we created wooden rails. By simply moving or pressing the joystick, the children can control the game character left-right, up-down, or beat monsters. To make it easier to grip the joysticks, we drilled a hole in the middle of the wood as a joystick cap (see Figure 2d). In addition, as the control buttons in the GUI condition cannot be moved, we also fixed the wooden joysticks on a base box with a size of $25 \times 10 \times 5$ cm. Furthermore, we drew red and blue arrows on the joysticks' bases to simulate the same directional hints on the control buttons in the GUI condition.

5 METHOD

Both *UnitRry* and *CollabMaze* prototypes contain two parts: tangible objects and tablet application. The tablet application could be used independently. If we use the tablet touch screen as input directly, we call it GUI condition. If we use tangible objects as an input, we call it the TUI condition.

5.1 Participants

In ***UnitRry*** study, 12 children (8 girls, 4 boys) had a mean age of 5.4 years (SD = 0.6) participated in the user study. Six participants (3 girls, 3 boys) with a mean age of 5.8 years (SD = 0.4) played with *UnitRry*. The other six participants (5 girls, 1 boy) with a mean age of 5.0 years (SD = 0.6) played with the tablet.

In ***CollabMaze*** study, 20 children (9 girls, 11 boys) with a mean age of 7.7 years (SD = 1.6) participated in the user study. In the *CollabMaze* condition, we had 10 participants (3 girls and 7 boys) with a mean age 7.8 years (SD = 1.5). In the tablet condition, the other 10 participants (6 girls, 4 boys) with a mean age of 7.5 years (SD = 1.8) used the tablet.

5.2 Procedure

During the user study, two children played together and had the same tasks with our designed tangible prototypes or the tablet (see Figure 2). As shown in Table 3, we used a 12.2" Acer Switch 3 for tablet condition and 15.6" laptop with *UnitRry* prototype for tangible condition in the *UnitRry* study. In the *CollabMaze* study, we used a 12.9" iPad Pro for tablet condition and a HP laptop with *CollabMaze* prototype for tangible condition. We conducted the *UnitRry* study in a German kindergarten and *CollabMaze* at the participants' house.

5.3 Data Resources

Before the experiment, we asked all participants some questions, such as demographic information and previous experience (game experience, tablet, and computer experience). Next, the experimenter asked the questions verbally to ensure that every child understood correctly and gave us a possible opportunity to get acquainted with the child for a subsequent interview session. The children were then assigned one of two different interface types. Finally, through verbal explanations and a simple tutorial, participants were shown how to play the prototype and were told that they needed to work in pairs to solve the problems (i.e., representative relations or exit the maze) without help.

We have four data resources: observation, questionnaire, interview, and system data. First, the experimenters and the kindergarten teacher created and filled out an observation sheet while the children were playing. It contains observations on cooperative, competitive, and individual interdependence. For example, the frequency and verbal and non-verbal interaction, helpfulness, and approach are noted. In advance, possible child behaviors were thought of for each item to facilitate the observation process and later evaluate the results. Second, a paper post-questionnaire measured participants' perceptions of enjoyment, interdependence, and tangible prototype usability. We modified Children Intrinsic Motivation Inventory (IMI) interest/enjoyment scale [37] to measure participants' enjoyment, which has seven items. The Social Interdependence Scales [13] evaluate cooperative, competitive, and individualistic perceptions. All items are 5-point Likert scale (1 = *Strongly disagree*, 5 = *Strongly agree*) and translated into German. We read the questions for the participants, and they used Smileyometer [26] to give their answers. Enjoyment and social interdependence scales' Cronbach Alpha values are 0.7 and 0.7 in *UnitRry* study, with 0.8 and 0.7 in *CollabMaze* study. Third, we asked three open-ended questions after they finished the game with the audio recording. One example of the questions was "*Have you ever helped your partner or your partner played you in the game?*" Finally, we recorded the system data, such as the maze playing time and frequency of pressing the help-seeking button.

6 RESULTS

We have collected qualitative (children and kindergarten teacher interviews, in-field observation) and quantitative data (5-point Likert interdependence and enjoyment questionnaires and system data).

Table 4: *T*-test results of participants' enjoyment, interdependence, and play time.

	UnitRry				*CollabMaze*			
	M	***SD***	***t***	***p***	***M***	***SD***	***t***	***p***
Enjoyment [5-point Likert scale]								
GUI	4.1	0.4	2.514	**.031**	4.2	0.5	-0.152	.881
TUI	4.6	0.2			4.2	0.6		
Cooperative interdependence [5-point Likert scale]								
GUI	4.6	0.5	-0.152	.882	4.3	0.5	-0.830	.417
TUI	4.5	0.5			4.1	0.5		
Competitive interdependence [5-point Likert scale]								
GUI	4.2	0.3	-0.693	.504	3.6	1.0	-1.029	.317
TUI	3.8	1.3			3.1	0.7		
Individualistic interdependence [5-point Likert scale]								
GUI	2.2	0.2	0.473	.646	2.6	0.5	-0.626	.539
TUI	2.4	0.6			2.4	0.6		
Play Time [min]								
GUI	19.3	3.3	-1.882	.073	17.2	5.8	-2.412	**<.020**
TUI	14.0	4.3			11.1	3.4		

6.1 Interdependence

Participants have high cooperative interdependence (above 4) and low individualistic interdependence (below 2.4) in both conditions but without significant differences, see Table 4. However, as shown in Table 4, children in *UnitRry* study had a minor higher competitive interdependence (TUI = 3.8, GUI = 4.2) than in *CollabMaze* (TUI = 3.1, GUI = 3.6).

In the *UnitRry* study, we observed that children in the tablet condition talked only sometimes, but children with TUI talked almost all the time. In both conditions, children took a turn working on the tasks. For example, children SCP005 and SCP008 always laid the first card in each task and helped their partners. Except for group 2, all children discussed with their partners about putting which cards. No child asked for an external person, such as the kindergarten teacher present or the experimenter, for help. In addition, we observed that participants SCP008 (TUI) and SCP011 (GUI) were more dominant than their partners. Child SCP008 always took child SCP007' cards without being asked for help, and later child SCP007 began to resist. We observed less conversation and interaction for children in the tablet condition.

In the *CollabMaze* study, we summarized "non-verbal" and "verbal" behaviors. The average frequency of each non-verbal and verbal behavior for each child was recorded in Table 5. The results demonstrate that the average frequency of non-verbal behaviors per child is higher in tablet conditions than in TUI. In contrast, verbal behaviors are higher in TUI than in tablet conditions.

6.2 Enjoyment

As shown in Table 4, children in the *UnitRry*'s tangible condition has a significant higher enjoyment than in the tablet condition (t = 2.52, p = 0.03). However, *CollabMaze* has no such significant difference. In addition, children in the tablet condition used more time to finish the tasks than with TUI. From Level 1 to Level 4, the playing time difference becomes more and more significant (see Figure 3).

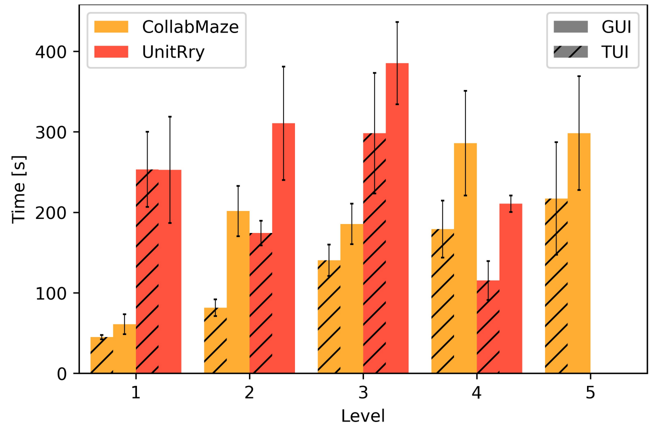

Figure 3: Each level's playing time with *UnitRry* and *CollabMaze*.

6.3 Performance

In the *UnitRry* study, children in the tangible condition made more mistakes when solving the tasks than using the tablet, see Figure 4. The help-seeking button was very rarely used, see Figure 4.

The character walking time in the *CollabMaze* was used to compare the engagement in the tablet or tangible condition. Character walking time and total playing time come from system data. Interactivity is equal to character walking time divided by total playing

Table 5: Mean frequency of each non-verbal and verbal behaviors per child in the *CollabMaze* study.

		GUI	TUI
Non-verbal behaviors		**14.8**	**12.2**
1	*Pointing at the iPad or computer screen **(Helping)***	7.3	6.3
2	*Gesturing in the air with hand gestures **(Helping)***	3.4	2.3
3	*Taking his/her partner's hand to help with the operating **(Helping)***	3.2	2.6
4	*Directly pushing away his/her partner's hand or body to gain control of from him/her **(Helping)***	0.9	1
5	*Unhappy facial expressions such as frowning or pouting **(Displeasure)***	-	-
Verbal behaviors		**20.9**	**27.3**
1	*Talking to each other such as "upwards" **(Helping)***	12.8	10.1
2	*Talking to each other such as "Let's take this way to get the coin" **(Sharing Ideas)***	7.9	16.2
3	*Talking to each other such as "You are stupid!" **(Displeasure)***	0.2	1

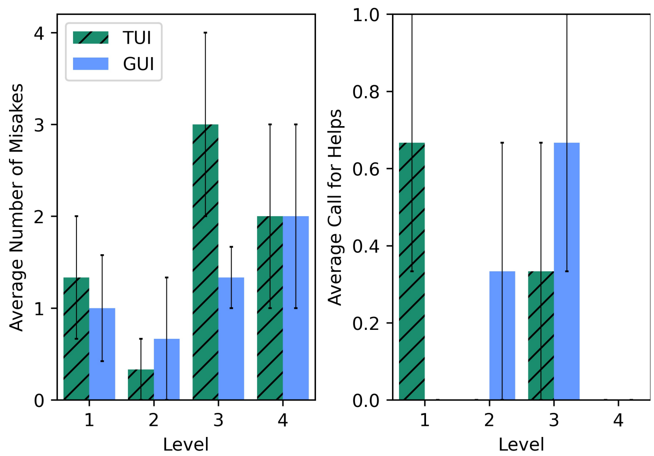

Figure 4: The average number of errors and average calls for help-seeking per level using *UnitRry*.

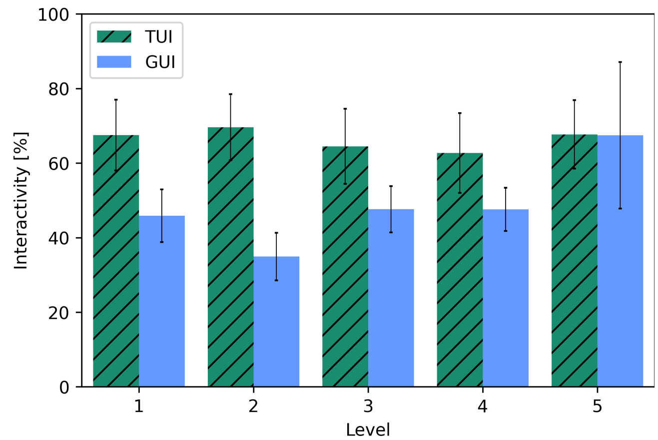

Figure 5: The interactivity with TUI and GUI in the *CollabMaze* study.

time: **Interactivity** = Walking time \ Playing time. Figure 5 shows that children in the tangible condition had a better engagement than with the tablet. We performed a t-test which showed that the two conditions are statistically significant different ($t(49) = 3.129$, $p < 003$).

6.4 Children Feedback

Given the age of the children, we designed most of the questions as yes/no questions or choice questions. After they had answered "yes" or "no", we asked additional "why" and "how" questions to elicit an explanation from them. Nevertheless, we found that most children were too shy to talk to strangers. The children who are shy tried to communicate with us only when his or her peer expressed ideas.

In the *UnitRry* study, seven of the twelve children answered that they were (best) friends. One child said *because we love each other.* Moreover, five children said that it was more fun playing together. Seven children (2 from the TUI group and 5 from the GUI group) said they liked the game, but three would like to see more cards or diverse difficulty levels. Two children using *UnitRry* prototype mentioned that they did not like to start the game by having to use the card box to connect the board simultaneously. One child wished for better sound quality. Children from tablet conditions said, "I played a card game." "When everything was correct, he laughed. Otherwise, he looked sad." (points at the smiley) "You have to press it if you do not know it." (pointing at the help button) After using *UnitRry*, children said "The smiley looked sad." "We played a game that was great." "We played with the computer. You have to put cards on it to practice." "We have to see if it is right or wrong."

In the *CollabMaze* study, when answering *Which part do you like most?*, fighting the monsters was the most common answer, then it was finding the way through the maze. All of the children indicated that they had helped each other during the game, and when I asked them how they had helped, some of the children gave examples such as "saying go down or down" or "it is shorter to go here." In terms of providing advice for improvement, seven children in both cases said that more levels, coins, monsters, and even backgrounds could be added to make it more challenging. Surprisingly, the children with ID 11 and ID 14 independently mentioned the possibility of designing a feature that would allow monsters to move and even attack the character.

6.5 Teacher Feedback

We conducted the *UnitRry* study in a German kindergarten. After the user study, the participants' kindergarten teacher, who has been working there for over 15 years, gave us some valuable feedback. Overall, he was enthusiastic about the idea that the children can learn and practice the relationship knowledge independently. However, from the teacher's perspective, he would like to see some improvements: First, it would also be necessary to adapt the menu for different ages children. For example, we could replace the text in the menu selection with easy-understanding symbols and add audio to explain the task content.

He was glad to see children working together well and considered two reasons: (1) each child had his or her cards. The sense of possession made the children more responsible; In the tablet condition, the cards were color-coded for each child, but there was no physical indicator that uniquely assigned the cards to the children. Therefore, the children often ignored the rules and dragged each other's cards. (2) Each child had to rely on the other child's cards to complete the task. Especially with the TUI, he said, the instruction that everyone has their cards was made very clear by the boxes containing the cards.

Second, he gave his opinions on what factors influenced the children's enjoyment. He said it was a new "toy" for the children, and they would always be excited initially, especially when they knew they were the first ones to use it. In the tangible condition, he noticed that the children were always delighted when they could observe that the card they placed on the TUI moved to the corresponding field on the screen. From the children's point of view, this function could be like magic, which impressed and fascinated them. In addition, the smiley face, which gives immediate automatic feedback on correctness, is also a factor. Because it gives the children a sense of achievement. Overall, he said he observed children had more collaboration, fun, and enjoyment with *UnitRry*.

7 DISCUSSION

Regarding the research questions, we would like to discuss (1) the effects of weak and strong goal interdependent designs; (2) key findings from comparing the tangible and tablet conditions; (3) the advantages of tangible interfaces to support the goal interdependence; (4) two limitations of our studies.

7.1 High Enjoyment and Interdependence with Both Weak and Strong Goal Interdependent Interfaces

As we can see in Table 4, weak and strong goal interdependent interfaces both made children have high interdependence and enjoyment. This finding might be valuable for designing tangible interfaces for children because the teachers or designers can be more concentrated on the tasks' actual requirements and do not worry about the influences of different interdependent tangible designs. In addition, we could see there were no significant differences in interdependence with tangible or tablet interfaces in both studies. However, we obtained some interesting findings about children's enjoyment. Children with *UnitRry* showed significantly higher enjoyment than using the tablet, but *CollabMaze* study did not have such finding. We would guess two probabilities: (1) *UnitRry* had younger participants (mean age = 5.4 years) than *CollabMaze* (mean age = 7.5 years). Young children are easier to be influenced by new things. Like the kindergarten teacher said, "*a new "toy" for the children and they would always be excited at the beginning, especially when they knew they were the first ones to use it.*; (2) Smiley face in the *UnitRry* gave children easy positive feedback. Furthermore, the synchronous movement of the virtual cards made children feel interesting. In *CollabMaze* study, children enjoyed collecting the coins and fighting the monster, but this was an ordinary game design.

We had some special considerations for children of different ages for weak and strong goal interdependent designs. Younger children have a shorter concentration span, and it is easier to lose interest. We thought it was better to have a weak goal interdependent design for them. Because they would concentrate more on solving the tasks without strictly following the interdependent rules. However, older children who go to primary school need to learn to follow the rules. Thus, they should have a strong goal interdependence, which helps them practice how to communicate and interact with others appropriately. Our studies provide two examples for showing the concepts supporting goal interdependence with different design degrees. Meanwhile, it opens a valuable research topic for future work: *How to understand and decide which goal interdependence design is better for which age children?*

7.2 Communication, Interactivity, and Task Solving with Tangible Interfaces

We found different collaborative styles used by children. The observation data indicated that children in the tablet condition had more non-verbal behaviors while showing more verbal behavior using tangible interfaces. It might be because children who used the joysticks as the input device to complete the *CollabMaze* were more possessive. In other words, they did not want their joysticks to be grabbed by their partner. Thus, verbal communication was more common in the tangible condition. Table 5 shows that the reason for the different frequency of verbal behaviors between the two interfaces is due to the different frequency of sharing ideas. This finding supports the assumption that tangible interfaces facilitate children to communicate their ideas in the situation of positive interdependence actively. *UnitRry* study had a similar finding, where children in the tangible condition talked all the time, however, only sometimes with the tablet.

In the TUI condition, we found that children took less time to reach the exit or finish the tasks than the tablet. We summarized three reasons for this result: First, children had different interactive spaces. In the tablet condition, the children had less interactive space. For example, it is difficult for two children to drag and drop the virtual cards on the tablet at the same time (*UnitRry* study). The same in the *CollabMaze* study, we designed three virtual buttons. Children need to manipulate them in a limited space. However, children are more flexible with tangible objects to manipulate in the tangible condition. Second, children had different interactive feedback. For example, *CollabMaze* tablet application has no tactile feedback by pressing virtual buttons, but joysticks are more intuitive to control without glancing while looking at the screen. Children can perceive the feedback by interacting with the physical object, saving manipulation time. Finally, tangible interfaces have a better affordance. In the tablet condition, up, down (or left and right), and shooting has three different buttons, whereas, in the tangible condition, a single joystick can do everything. Furthermore, most children can fully control the joystick with one hand, whereas the three buttons in the tablet application need to use with two hands simultaneously.

In addition, children in the tangible conditions showed higher interactivity (*CollabMaze*) and made more errors but used less time to finish the tasks (*UnitRry*). This result implies that a tangible interface might be an efficient tool for helping children engage in the task. As we know, children are easy to be distracted. The distraction could come from the tool itself or learning environments. Traditional learning tools, e.g., tablets and smartphones, have a high possibility to distract children from working together. In the long term, it would influence their concentrations. Tangible technology can design interactive mechanisms and have children focus more on the tasks. In our studies, the children have a clear collaborative goal and role in solving the tasks, which might be one reason for high interactivity. Another reason is what we have mentioned: tangible interfaces can create more interactive space and have a better affordance.

7.3 Interaction Space and Affordance for Goal Interdependence

Collaboration on a touch screen is limited due to many technical restrictions, such as small screen size, the maximum number of fingers detected synchronously, sensor accuracy, and restricted view field. We could tackle these problems with TUI because tangible objects could endow users with more interaction space and affordance. As we could see in Figure 3, the GUI condition always used a longer time than TUI to finish the same tasks. One main reason was users in the TUI condition had specific physical objects to put or control. In addition, they worked on a "bigger" and "independent" space without mutual interference.

Having enough interaction space and good affordance are essential for a goal interdependence activity. Interactive space provides users more flexibility and chances to communicate, not only orally but also using more body movements. It is more expensive to create an environment with exciting technologies, e.g., interactive or touch table, virtual reality. However, tangible technology is a promising idea to build a spacious interactive environment. In addition, TUIs offer good affordance. In other words, we could design the quality or property of a tangible object that defines its interdependent uses. In the *UnitRry* study, two children had different tangible cards. Each task required the cards from both of them. In the *CollabMaze* study, one child controlled up and down movements, and the other child controlled left and right movements. Such interdependent design elements provide good affordance for creating a collaborative learning environment.

7.4 Limitations

We provided the concept design, prototype development, and data evaluation of two studies to show how we could use tangible interfaces for goal interdependence. However, our studies also have two limitations: First, *UnitRry* participants were younger than *CollabMaze*'s. In other words, we had different ages of children for weak and strong interdependence designs. It was a hard decision because young children's behaviors were different. Younger children (e.g., around 5 years old in the *UnitRry* study) are easier to be distracted and stop playing the game. Older children (e.g., 7 years old in the *CollabMaze* study) need gamified challenges to keep them interested. Thus, we gave *UnitRry* to younger children and *CollabMaze* to older ones. However, this might cause an unequal comparison. Second, our prototypes, especially *CollabMaze*, were easy to be considered not as "typical" tangible interfaces. Currently, there is no agreement on the definition of TUI [19]. From the perspective of embodied interaction, we focused on the differences in input modalities. In other words, we designed the comparison studies to examine the differences between embodied and touchable interactions.

8 CONCLUSION

In this paper, we designed two tangible games, *UnitRry* and *CollabMaze*, to vary different goal interdependences through the tablet and tangible interface designs. Using these two games, we conducted two user studies with 32 children. We found that weak and strong goal interdependent interfaces help young children have high enjoyment and collaboration. However, when using tangible interfaces, children had more idea communication and needed less time to solve the tasks. Our findings showed that we could facilitate children's collaboration using tangible technologies.

With our work, we contribute to improving the design of tangible interfaces for young children's collaboration and help them have a better collaborative experience. In the long run, our findings also can support young children's social skills and learning development.

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