Designing a Tangible Interface to "Force" Children Collaboration

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ABSTRACT

Tangible technology provides opportunities to design collaborative interactions which allow children to engage in highly collaborative activities. Unfortunately, there are few guidelines on structuring children's interdependent collaboration with tangible technologies. In this study, we designed and developed a tangible game named *MemorINO* to "force" children to collaborate. We conducted a classroom study with 23 children and 3 kindergarten teachers. Our investigation revealed two main findings: (1) We could design interactive constraints with tangible technologies to "force" children to attend collaborative activities naturally and interdependently; (2) Tangible environments could help children have good engagements, especially for similar-age group children. Our findings could provide practical guidance on designing tangible interfaces to help children learn to collaborate.

CCS CONCEPTS

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

KEYWORDS

tangible learning, collaborative learning, children, tangible interaction, engagement

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1 INTRODUCTION

Tangible user interface (TUI) refers to physical artifacts embedded with interactive computing technologies, allowing learners the chance to explore their everyday experience and interaction with the real world [29]. Tangible collaborative learning [24] has been studied for children's exploration [1], problem-solving [8], skill development [20], and communication [6]. Matthews et al. [26] pointed out it was a challenge or even an obstacle for novices to use the tangible system as a design material to implement their ideas. We should consider productive collaboration, which has interdependence and rich external resource considerations [11]. When designing a collaborative environment, we need to consider making an experience arising for children aware of communal purpose. We can design interactive outcomes to engage children in a collaborative environment in such situations. Therefore, children could have an interdependency with each other to improve their collaborative experience [28]. There are many suggestions for promoting positive interdependence, however, only a few guidelines on structuring children's interdependent collaboration with tangible technologies.

Therefore, we investigate rationales, principles, and processes in designing a tangible learning game, named *MemorINO*, for children's interdependent collaboration. Furthermore, we explore an iterative design method to achieve interdependent interaction and communication mechanisms, which involve the kids and their kindergarten teachers. The study has five iterative design phases: designing and refining the concept idea, envisaging natural and interdependent interactions with paper prototype, testing such interactions with initial technical prototype, examining the actual user experience with the final prototype, and improving the user experience. Our evaluation study explored a valuable and practical guideline for designing TUIs for children's interdependent collaboration. Overall, the aims of *MemorINO* were to: (1) explore an iterative design method to understand how to design a tangible educational game for children; (2) investigate interdependent interaction and communication mechanisms for children to collaborate naturally; (3) evaluate the effects of such design on children's engagement.

Our investigation revealed two main findings. First, we could design interactive constraints with tangible technologies to "force" children to attend collaborative activities naturally and interdependently. Second, a tangible environment could help children have good engagements, especially for children of similar-age groups. Altogether, *MemorINO* showed great potential for promoting teamwork and providing fun.

2 RELATED WORK

To design TUIs for improving children's interdependent collaboration, the necessary understandings are: (1) how tangibles have

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specifically benefited children's collaborative learning; (2) the importance of positive interdependence design for effective collaboration, and (3) the evaluation of effective collaboration from learning engagement perspectives.

2.1 Tangible Collaborative Learning

Tangible technology provides opportunities to design collaborative interactions which allow learners to engage in highly collaborative activities [29]. For children's education, the physical world has an essential effect on coordinating learning activities and creating a shared collaborative space. Prior studies did not sufficiently consider the influences or potentials of the physical world interaction for facilitating such shared goals and mutual understanding of collaboration [22, 35]. However, the physical world offers a rich experience to facilitate collaboration [37]. Piaget [27] found that children did not passively obtain ideas from the external world but had to construct concepts or knowledge through active experimentation and observation. TUIs can offer such a "real" learning experience, where children can play with the actual physical learning tool to explore their understanding [25]. Tangible learning refers to the use of gesture, motion, or full-body interaction to convey knowledge in educational practice [24]. When interacting with physical manipulatives and embodied metaphors, young children can explore abstract concepts [5].

As we know, children learn by playing and exploring [35]. By social interaction or imitating others' behavior, children obtain new skills and learn to collaborate. Antle [3] claimed tangible interaction could be designed to help children develop intelligence in the real world. Li et al. [24] found that TUI promotes children's self-exploration, self-correction, and self-regulated learning. It was designed for children to learn in different fields, e.g., music, mathematics, gravitational force, principles of physics, and the popularisation of archaeology. However, Matthews et al. [26] pointed out it was a challenge or even an obstacle for novices to use the tangible system as a design material to implement their ideas. There should be a consideration of productive collaboration, which is characterized by interdependence and rich external resources [11, 39]. In other words, when designing an environment for collaborative learning, we need to consider how to make an experience arising in situations where children are aware of communal purpose. In addition, for children, the complexity of the interactive system and tangible interactions should be simplified [24].

2.2 Positive Interdependence

Interdependent collaboration provides a context where promotive interaction occurs so that interpersonal interaction produces a high achievement [10]. Promotive interaction refers to "individuals encourage and facilitate each other's effects to accomplish the group's goals" [18]. 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. [38] found that social/technological interdependence helped children produce more in-depth explanations and have fewer but longer cases of resolving conflicts jointly. Collazos et al. [10] claimed interdependent collaboration could motivate students to work hard and also facilitate the explorations of new insights and understandings. Antle et al. [4] had co-dependent input designs to make children coordinate for achieving the goal.

Interdependence refers to "the outcomes of individuals are affected by their own and others' actions" [18]. It has three types: positive (cooperation), negative (competition), and none (individualistic efforts) [18]. Positive interdependence, a basic element for collaborative learning [18, 21], refers to the success of one learner is possible only by the success of the others [10]. There are some different kinds of positive interdependencies [10, 21], e.g., positive goal interdependence, positive celebration/reward interdependence, and positive task interdependence. Designing such positive interdependencies could encourage children to negotiate, solve, and discuss tasks collaboratively [38]. 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 [28].

Different characteristics of group learners (e.g., age) could influence their interdependent collaboration [23, 32]. Children with different age have differences on their cognitive development [32]. In a different-age group, older child is likely more experienced or "knowledgeable" than the younger one. Thus, the older child tends to be a tutor, who could provide supports for knowledge or skills when collaborating. Stokes et al. [36] found preschool children could help each other understand the picture by describing relationships. Peer tutoring increases primary school children's ability of reading [7, 19]. Smith [33] found having peer mentors for younger children was a successful method to teach children the responsibilities. However, San Antonio et al. [31] got converse results on different-age group collaboration, where some children were motivated and belonged, but others felt overwhelmed and did not collaborate well. When grouping children to collaborate, age difference of group members is a common issue.

Even though many suggestions exist on how to promote positive interdependence [18], there were few guidelines on structuring children's interdependent collaboration with tangible technologies [21, 38]. It still has many questions, for example, *How to design tangible to promote positive interdependence? What is the uniqueness of tangible for such design? Will group characteristics (e.g., age difference) influence such design?* 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 [34]. It has a technological benefit, which can be employed to facilitate face-to-face collaboration [12] and its social interdependence [34]. Therefore, practical examples may be that only joint effects can move some objects, or that one learner needs to borrow some object from another to proceed.

2.3 Learning Engagement

Findings in the Computer-Supported Collaborative Learning (CSCL) field are mainly obtained by "after collaboration" measurement and lack tools and measures for examining learning processes [16]. Collaboration involves "...mutual engagement of participants in a coordinated effort to solve the problem together" [30], and has some actual state of engagement [11]. In other words, engagement is a critical criterion to measure or evaluate collaboration effects. Premo et al. [28] found that interdependent design increased students’ collaborative engagement, but not their achievements. Engagement maintains an individual’s interpersonal relations and identity in communities, which involves effective interactions with environments. Moreover, learning performance is closely related to learning engagement [9].

From previous research [15, 17], we see learning engagement as a multidimensional construct, which contains behavioral, emotional, and cognitive learning experiences, as well as their interrelationships. Behavioral engagement is often described as 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. Finally, cognitive engagement indicates strategic and self-regulated behavior, e.g., using meta-cognitive strategies for planning, monitoring, and evaluating cognition while finishing 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 the understanding through physical interactions. 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 [2].

3 RESEARCH QUESTIONS

TUI enables new forms of engagement and access to tools for supporting learning. However, it was unclear how to design such a tool for children [35]; what are the actual effects on their engagement; and how to ensure better design quality in the future. Therefore, we proposed two research questions:

- **RQ1:** How can a tangible educational game “force” children to attend collaborative activities in a natural and interdependent way?
- **RQ2:** What are the effects of such “force” designs on children’s collaborative behaviors and (behavioral, emotional, and cognitive) engagement? Does it have similar effects on similar-age and different-age children?

4 METHOD

4.1 *MemorINO* Design

An iterative design method was used in the study, which lasted for more than 5 months. It had four phases: concept idea, paper prototype, initial technical prototype, and final functional prototype. Interview and in-field observation with note-taking were used to obtain data for evaluating and revising the designs. (1) Three kindergarten teachers and three mothers were interviewed during the concept idea phase to give feedback about the learning content and prototype design. The first teacher (female, 60 years old) has done child psychology for 14 years and worked in kindergartens for 43 years. The second teacher (female, 52 yo) had 15 years of experience and has worked for 5 years at the current kindergarten. The last teacher (female, 34 yo) has worked at the kindergarten for 7 years. (2) Two children (aged 4 and 5) participated for the paper prototype study. Third, for the initial technical prototype study, one 6 yo girl tested the functions. (3) The user study was conducted within two kindergartens in Germany.

From socio-cognitive theory, learning tasks should promote communication and think in solutions. Therefore, suitable task content, proper task difficulty, and internalized interactive mechanisms must be considered [13]. First, in order to determine suitable task contents, two rounds of interviews were conducted. From our first round interview with three kindergarten teachers and three mothers, the conclusion was that gamified elements were critical for children. The second round of interview was conducted with the same teachers, which made more concrete the tasks to counting, rainbow colors, numbers, geometric forms, and patterns. Second, to provide children with gamified engagements, we designed and finalized eighteen different difficulty level tasks.

We designed two wooden boards (for two children), which connect to a specific software application. This application showed the animations of connecting the boards, a description of tasks, and instant feedback of children’s interactions. Children had 28 tangible cards to put on the boards. These cards have patterns on both sides, which we designed on purpose. First, it was impossible to see all patterns immediately. In order to see the backside pattern, children had to turn over the cards and search for them. Second, it allowed us to design more diverse tasks. When children doing the tasks, teachers were not required to facilitate learning. The system would give feedback for the entire interaction process, e.g., showing an instruction animation at the beginning and giving feedback once the two children complete the task.

In addition, we designed the boards flexibly for higher-level tasks. As shown in Figure 1, the boards could be connected horizontally or vertically. If it was horizontal, the task could be “Find cards with the numbers 1-6 and put them on the boards in a correct order.” However, if it was vertical, the task could be “□ + □ = 6.” For this situation, children were required to find a blue card to place on one board and a red card on the other board. Meanwhile, the numbers on the other sides need to be added up to 6. Therefore, we have a flexibility to design diverse tasks.

4.2 Participants and Context

Overall, 23 children (12 pairs, 15 girls, 8 boys, M(age) = 4.96 [4, 6]) and 3 kindergarten teachers (3 females, M(age) = 48.67 [34, 60]) participated in the final user study. The children were recruited in two local kindergartens, we assigned them according to their age difference. Therefore, there are 6 pairs with similar ages (i.e., same or one age difference), and the other 6 pairs have different ages (i.e., more than two ages difference). We conducted the studies in kindergarten classrooms. The children’s parents provided written consent for their children. At the same time, children also verbally agreed to take part in the activities and could stop at any time if they felt uncomfortable. Finally, the kindergarten teachers were present during all activities. As shown in Figure 2, children played in different-age or similar-age groups, with their kindergarten teacher observing their behavior. During the user study, *MemorINO* was set up in a large classroom without disturbances. The two tangible

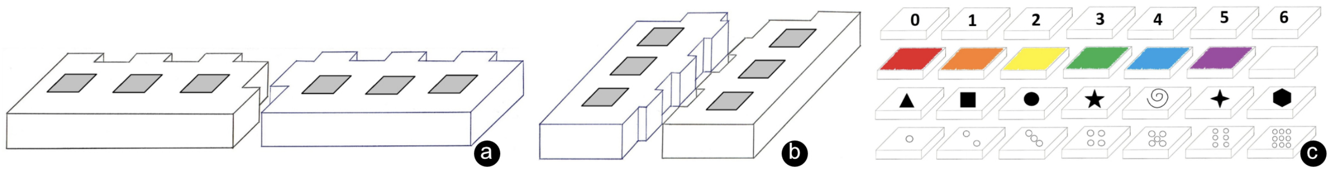

Figure 1: *MemorINO* boards and cards: a) Connect horizontally, b) Connect vertically, and c) Tangible cards with images on both sides.

boards and the *memory cards* were put on the table, and a laptop with a touch screen to show the learning contents.

4.3 Procedure

Children played *MemorINO* in pairs for 45-70 mins. The system has 18 tasks, e.g., putting cards with color in a correct order as rainbow. Two children complete the tasks without external help because the system will give them feedback. In addition, if they have difficulty solving the tasks, they could press the help button in the system. Then the system will give them some hint, e.g., by showing part of the missing colors in the above rainbow task.

In-field observations with a structural observation form were conducted for each group. The observation form consisted of five dimensions: understanding of the system setup and design (5 items), behavioral engagement (4 items), emotional engagement (4 items), cognitive engagement (5 items), and collaboration (5 items). For example, "*Do they get discouraged by initial failure to solve the tasks?*" (emotional engagement), "*Do they argue? When and over what?*" (cognitive engagement), "*Does one of them take charge without letting the other try things out?*" (collaboration). The after-study interview was conducted with each child for about 10 mins. Ten questions were prepared to ask their feelings of engagement and collaboration, e.g., "*Did you have fun?*" and "*Did you like to solve the task together with your partner?*" Second and third authors observed the children playing with *MemorINO* tangible prototype. Meanwhile, they calculated the times of each behavior in Table 1 for each child independently. After each experiment, they would look at each other's observation results to solve some inconsistent recordings.

Finally, we interviewed the kindergarten teachers, who talking about their observations on children's behavior changes. They know the participants well, therefore, they could see whether the child became more outgoing or shy than usual. All interview audios were transcribed and coded by two different authors. We obtained five analysis themes: system understanding, collaboration, behavioral, emotional, cognitive engagement. The results of these themes were translated from German into English by authors, who were native German speakers, but also fluent in English.

5 RESULTS

To answer the research questions, we analyzed participants' understanding of our interaction design, interdependent collaboration, learning engagement, and interview results of children and kindergarten teachers.

5.1 Understanding the Design

Regarding the design understanding, we got four findings: (1) 50% children need help to start the game, but only for the first time; (2) 75% understood how to put *MemorINO* boards together; (3) the designed learning tasks were understandable and clear for all participants; (4) no child has used tangible cards to do something unrelated to solving the tasks.

5.2 Interdependent Collaboration

As shown in Table 1, 66.7% of similar-age (SA) and different-age (DA) groups have talked with each other, and half of them asked the other for help. More DA (50%) than SA (16.7%) groups had the situation where one child took the lead. On the other hand, more SA (50%) than DA (16.7%) groups experimented with the exercise independently. In general, SA groups have better teamwork than DA. From in-field notes, only two DA groups showed evident collaborative behaviors. They were not siblings and matched with other children on their own. The older children seem inclined to be good mentors because they were patient and helpful.

5.3 Learning Engagement

In general, SA groups have a better behavioral, emotional, and cognitive engagement than DA, see Table 1. For behavioral engagement, most SA groups (83.3%) have continuously worked on the tasks. Few (16.7%) did some unrelated new things randomly. Even fewer (11.7%) needed motivation after 5 mins or 2 tasks. Regarding emotional engagement, all children showed good interests in the tasks, but still more SA groups (83.3%) than DA groups (66.7%). The same very few children (16.7%) got frustrated or angry while doing the exercises. Finally, it showed SA groups had a better cognitive engagement, where they argued with each other more (33.3%), and their attention wandered less (25.0%).

5.4 Interview Findings

Interviews were conducted after the children played *MemorINO*. We mainly asked four questions: (1) *Did you have fun? What made you have fun?* All the children said they had fun playing; (2) *Would you like to play MemorINO again? Why?* Only three DA children did not want to; (3) *What did you learn from this game?* 75% of children from both SA and DA said they learned something; (4) *Did you help your partner? Did your partner help you? How?* Only two children from DA groups said no. Younger children said "I followed his lead, but we took turns to place cards on the board." "I could not do it alone. We helped each other for the numbers." "He whispered

Figure 2: Children playing in pairs with *MemorINO*: a) Different-age group, and b) Similar-age group with their kindergarten teacher.

Table 1: Observational results of collaboration and engagement (SA = similar-age groups, DA = different-age groups).

		Observations	SA	DA	Better Group
Collaboration		Talk with each other	66.7%	66.7%	-
		Ask the other for help	50.0%	50.0%	-
		One child took the lead	16.7%	50.0%	SA
		Experiment the tasks on their own	50.0%	16.7%	DA
Engagement	Behavioral	Continuously work on the tasks	83.3%	66.7%	SA
		Need motivation after 5 mins or 2 tasks	11.7%	33.3%	SA
		Try unrelated new things causally	16.7%	33.3%	SA
	Emotional	Interested in the tasks	88.3%	66.7%	SA
		Get frustrated and angry	16.7%	16.7%	-
	Cognitive	Argue with each other	33.3%	16.7%	SA
		Understand the task	66.7%	66.7%	-
		Attention wanders after 20 mins	25.0%	33.3%	SA

answers, but I did not realize he was helping me." Older children said "Searching numbers, and he always found blue first." "I helped with counting. He was better at pattern exercises." "Siblings help each other, we also helped each other." "He helped me with the color blue and the six-sided shape."

Three kindergarten teachers, who observed the whole study process, accepted our after-study interviews to share their thoughts. They said *MemorINO* was an excellent learning tool: "*The shyest children were suddenly very open when playing with MemorINO. They usually have to be persuaded to participate in any game.*" "*The children worked together so well, and their concentration span was amazing. I have not seen them like this.*" "*They learned so much. I would not have thought the children would learn how to count to 18 or the correct colors of the rainbow so fast.*" "*They did not fight at all. This was unusual.*" One teacher liked the concept of *MemorINO* but was uncomfortable to have it in her class because she did not like any technology in the kindergarten classroom. However, she said this was only her personal preference.

6 DISCUSSION

Reflecting on the tangible design and study results, we think it is worth discussing how tangible interface represents collaborative practices, the importance of natural and interdependent tangible design for children collaboration, and why similar-age group children had better collaboration and engagement.

6.1 Tangible Interface as a Representation of Collaborative Practices

Traditional computer-support collaborative learning environments, e.g., web-based inquiry learning, online discussion, representational tools, and intelligent systems, focused more on resource, activity, and communicative design. For these situations, "computers" aims to create a communicative or feedback environment. However, only having such an environment could not make collaboration happen automatically. It is hard for children to engage in collaborative processes without guidance [14]. Therefore, we need to design a configuration of knowledge components and representations for collaborative practices.

In our study, we considered both knowledge and interactive representations. A physical collaborative environment could reduce children's cognitive loads and make interactive feedback easier to perceive. We used physical cards (*MemorINO*) to represent knowledge. Interactions with such tangible objects embodied a flexible error-and-trial process, which gave children instant feedback. In addition, we implemented a constrained interactions design. Thus, they could have an interdependent collaboration from two children. The benefits of using TUIs as a representation are: (1) It is easier to create a collaborative environment for children to communicate and interact. It is hands-on practice in the face-to-face space; (2) Error-and-trial is simple for children to perceive, which reduces their external cognitive loads and could let them concentrate more on task knowledge; (3) Some basic interactive modes could be designed on purpose to facilitate collaborative behaviors. In other words, we could design specific constraints to "force" children to coordinate actions, which foster group awareness and cooperation. Such constraints could mean reliance on interactions that must be coordinated or structured to encourage reciprocal helping.

6.2 Natural and Interdependent Tangible Design for Children Collaboration

For children's education, the physical world has an essential effect on coordinating learning activities and creating a shared collaborative space. TUIs provide opportunities to design collaborative interactions which allow children to engage in highly collaborative activities. However, it is essential to design intuitive and simple interactions for children to work together effectively. Tangibles (e.g., the combination of physical boards and constitution of physical cards) have an advantage to "force" interdependence and make the task solving process rely on each other. As a learning tool, TUI embeds an interaction mechanism, which can be specifically designed to orchestrate collaborative activities. In our study, two children could work together naturally to solve tasks. From an interactive perspective, we designed *MemorINO* with specific interdependent mechanisms. The interaction inputs have to come from both children. When solving tasks, each child has a responsibility to search and put cards on his or her board. Only when both interaction inputs are correct they could proceed to the next task. This process is a natural interdependent design to "force" children to help others.

In addition, children have an actual physical environment to physically engage in the activities. This environment provides children with more natural interaction and communication opportunities. Meanwhile, we also encountered some challenges in promoting such collaborative tangibles for children. First, sometimes children did not comply with the initial design concepts, e.g., the older child occupied the tasks and ignored the younger child. Thus, we should be open to diverse, flexible interaction options. Second, learning tasks were constrained with tangibles. For example, *MemorINO* is suitable for sequence or order tasks, e.g., spelling. However, it might be hard to adapt for non-linear or longer sequence tasks. Finally, a collaborative pattern was constrained by physical designs. *MemorINO* was designed for two children. It would be not difficult to extend the original design to include more children. However, we need to reconsider physical space configurations.

6.3 Better Collaboration and Engagement for Similar-age Group Children

Similar-age and different-age group children have similar frequencies of communication and help-seeking. Nevertheless, similar-age children are more behaviorally, emotionally, and cognitively engaged than different-age children. This result is an interesting finding. We think it results from two possible reasons. First, we considered and designed reliance and collaboration mainly from an interaction constraint perspective. If we put Human A, Human B, Computer in a scenario, we thought a specific dependent interaction could shape the communication. It had sound effects, at least from the results we got. However, our design was for an equal dependence interaction. When Human A and B have different previous knowledge and personalities, we did not adapt interactive mechanisms accordingly. Second, 2-7 years old children are in the preoperational stage, complex abstract thoughts are still tricky. When the younger partner does not know the answers, the kid might do not know how to express or behave like a mentor. Most of the time, they just took over the tasks. From the in-field observation, only two older girls behaved patiently to teach their partner to find valid cards. We felt it was a personality that is hard to be cultivated or influenced by a short experiment.

7 CONCLUSION

MemorINO showed great potential in promoting interdependent teamwork and providing fun for learning. From an HCI perspective, we designed interaction constraints to "force" two children both having to interact to reach the goal of success. It showed that all groups had good collaboration and engagement experience, and similar-age children groups better than different-age groups. Therefore, our design might be an effective scaffolding approach for helping children learn collaboration.

8 LIMITATIONS AND FUTURE WORK

Our designed tangible prototype *MemorINO* has shown good effects on children's collaboration and engagement, but it has two limitations. First, it might have a novelty effect on the results because participants only used *MemorINO* once. Second, the system lacked child-friendly designs, e.g., no audio feedback. We plan to improve *MemorINO* mainly from three aspects: (1) Add task audios. The task instruction was as texts. We read it for participants. However, to help children have an independent activity without involving teachers, it is vital to add audio explanations; (2) Improve the feedback design. We used a graphical schema for giving feedback for the interaction, but it is not child-friendly. We plan to add sound with special effects or animation; (3) Extend the number of boards. Currently, *MemorINO* only has two boards. which limited the task design and participant numbers. To have a variety of tasks and participants, we plan to add one or two more boards.

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