TANGIBLE USER INTERFACES TO SUPPORT COLLABORATIVE LEARNING

*Doctoral Thesis | LMU Munich | **Yanhong Li** | 03.2023*

Tangible User Interfaces to Support Collaborative Learning

Dissertation

an der Fakultät für Mathematik, Informatik und Statistik
der Ludwig-Maximilians-Universität München

vorgelegt von

Yanhong Li

M.Sc. Educational Technology

München, den 11. Juli 2022

Erstgutachter:	Prof. Dr. Sven Strickroth
Zweitgutachter:	Prof. Dr. Eva Eriksson
Drittgutachter:	Prof. Dr. James D. Slotta

Tag der mündlichen Prüfung: 29. 03. 2023

Abstract

Collaboration without scripting and orchestration is hard to succeed. Technologies, especially tangible user interfaces (UIs), show good advantages in supporting collaboration. Therefore, I explored how to design and develop tangible UIs for collaboration. Initially, I investigated tangible design space for collaboration. From theory, design principles, and method, I showed how to design and develop tangible UIs for positive interdependence and shared attention, which is essential for good collaboration.

Presenting three projects for positive interdependence and three for shared attention, I got **two key findings**: First, positive interdependence project participants had reasonable enjoyment, engagement, and collaboration. Tangible UIs with positive interdependence design implies **a**) an interactive and physical space for interdependence, **b**) physical representation with knowledge externalization for collaboration, and **c**) resource, interface, and interaction interdependence. Second, shared attention project participants liked the prototypes and showed good concentration. Tangible UIs with shared attention design implies **a**) a connected interactive space, **b**) information and interaction visualization to attract users' attention and **c**) an interactive loop from attention to action.

I dug into rationales and actual developments of tangible technologies to benefit collaboration. My research results show how tangible design can improve the collaborative experience. Overall, my doctoral thesis has three contributions. First, I provided a design space framework for tangible UI designs and elaborated practical design guidelines from theory, principle, and approach to the actual prototype development. Second, I designed and developed sixteen tangible prototypes to exemplify the approach. Finally, I discussed the insights of tangible mechanisms for positive interdependence and shared attention in collaboration.

Zusammenfassung

Zusammenarbeit ohne Skripting und Orchestrierung ist schwer zu erreichen. Technologien, insbesondere Tangible User Interfaces (UIs), zeigen gute Vorteile bei der Unterstützung der Zusammenarbeit. Daher habe ich untersucht, wie wir konkrete Benutzeroberflächen für die Zusammenarbeit entwerfen und entwickeln können. Zunächst untersuchte ich konkrete Gestaltungsräume für die Zusammenarbeit. Anhand von Theorie, Designprinzipien und Methoden habe ich gezeigt, wie wir konkrete UIs für positive Interdependenz und gemeinsame Aufmerksamkeit entwerfen und entwickeln können, was für eine gute Zusammenarbeit unerlässlich ist.

Indem ich drei Projekte für positive Interdependenz und drei für geteilte Aufmerksamkeit vorstellte, erhielt ich **zwei wichtige Ergebnisse**: Erstens hatten die Teilnehmer an positiven Interdependenzprojekten eine angemessene Freude, Engagement und Zusammenarbeit. Greifbare UIs mit positivem Interdependenzdesign implizieren: a) einen interaktiven und physischen Raum für Interdependenz, b) physische Repräsentation mit Wissensexternalisierung für die Zusammenarbeit und c) Ressourcen-, Schnittstellen- und Interaktionsinterdependenz. Zweitens mochten die Projektteilnehmer mit gemeinsamer Aufmerksamkeit die Prototypen und zeigten eine gute Konzentration. Greifbare Benutzeroberflächen mit geteilter Aufmerksamkeitsgestaltung implizieren: a) einen verbundenen interaktiven Raum, b) Informations- und Interaktionsvisualisierung, um die Aufmerksamkeit der Benutzer zu erregen, und c) eine interaktive Schleife von der Aufmerksamkeit zur Aktion.

Ich habe mich mit den Gründen und tatsächlichen Entwicklungen konkreter Technologien beschäftigt, um die Zusammenarbeit zu fördern. Meine Forschungsergebnisse zeigen, wie greifbares Design die Zusammenarbeit verbessern kann. Insgesamt hat meine Doktorarbeit drei Beiträge. Zunächst habe ich ein Design-Space-Framework für konkrete UI-Designs bereitgestellt und praktische Design-Richtlinien von Theorie, Prinzip und Ansatz bis zur eigentlichen Prototypenentwicklung ausgearbeitet. Zweitens entwarf und entwickelte ich sechzehn greifbare Prototypen, um den Ansatz zu veranschaulichen. Abschließend diskutierte ich die Erkenntnisse über konkrete Mechanismen für positive Interdependenz und gemeinsame Aufmerksamkeit in der Zusammenarbeit.

Acknowledgements

So long, I have been preparing and waiting for this day to become Dr. Li. I recall all my way from China, Canada, Germany, and Switzerland, and I feel appreciated to meet so many friends to support me. If let me close my eyes and count, then Nathan Zhao, Jim Slotta, Gaoxia Zhu, Paul Alexander, Joel Wieber, Kathy Zhou, Frank Fischer, **Heinrich Hussmann**, Beat Rossmy, Thomas Weber, Linda Hirsch, **Sven Mayer**, Pierre Dillenbourg, Barbara Bruno, Changkun Ou, Andreas Butz, Jingyi Li, Sven Strickroth, and Eva Eriksson like a star appear in my eyes. It is like magic; once a child has a dream in her heart to chase, she becomes so powerful, and the whole world comes to help her.

Special thanks to Heinrich; I am still sad about your passing away. I miss you; this feeling is like losing a father and a good friend. Occasionally, I remember that sunny day we walked around the island in Chiemsee. The sun was so shiny, and the clouds were so beautiful. I planned to talk with you about something but did not because I wanted to let us enjoy the moment. How I wish we could walk like that one more time! Maybe in a park with birds singing or along a lake with water running. You always smiled and listened carefully to people.

Maybe the best way to remember you is to become a supervisor, a professor, and a friend like you; be kind, friendly, and helpful to people around you. I will try my best, all my best. I hope you are still happy beyond this world, maybe in heaven. Let me read aloud one of my favorite poets and spiritual teachers Rumi's poem, which is called "*A Great Wagon*" and was written around the 8th century.

> *"Out beyond ideas of wrongdoing and rightdoing,*
>
> *there is a field. I'll meet you there.*
>
> *When the soul lies down in that grass,*
>
> *the world is too full to talk about.*
>
> *Ideas, language, even the phrase 'each other'*
>
> *doesn't make any sense.*
>
> *The breeze at dawn has secrets to tell you.*
>
> *Don't go back to sleep.*
>
> *You must ask for what you really want.*
>
> *Don't go back to sleep.*
>
> *People are going back and forth across the doorsill*
>
> *where the two worlds touch.*

The door is round and open.

Don't go back to sleep."

TABLE OF CONTENTS

1
INTRODUCTION

Cognition emerges from dynamical interactions among brain, body, and world.

– Shapiro [129] (p. 156)

Collaboration facilitates group work and problem-solving. It has shown many benefits, such as improved communication, innovation, and increased success. However, to have an effective collaboration, we must consider many factors, such as monitoring group processes and coordinating group communication. Tangible user interfaces (UI) are a promising technology to improve collaboration. Thus, my thesis study investigates how to design and develop tangible UIs to facilitate collaboration. This chapter introduces my research background, identifies previous research gaps, proposes my research questions, and shows my thesis overview.

1.1 Background

Collaboration has three core meanings [30, 50, 117, 146]: **a**) Participants mutually engage in a coordinated effort to solve the problem together, **b**) Tasks in collaboration intertwine with cognitive processes; **c**) Collaboration is an orchestrated activity where participants attempt to construct and maintain a shared problem conception. Collaboration has many advantages [30, 71], such as involving participants actively in a social-constructive, social-cultural, or shared cognition environment. However, a successful collaboration requires specific interaction patterns to occur [30], and this often needs instructional intervention [61]. Previous work suggests three [8, 146] to five [41, 115] interactive patterns, such as positive interdependence and promotive interaction, for collaboration to be productive. To facilitate promotive interaction [115] and knowledge construction [118], teachers or instructional designers need to script collaborative activities and orchestrate them [30, 57] to have desirable outcomes.

Technology can facilitate this orchestration by providing tools for monitoring group activity and intervening when necessary [30]. However, existing technologies (e.g., tablets and interactive whiteboards) have limited or preset interaction and communication patterns, which restrict the effectiveness of collaborative activities. In addition, available technology devices do not have specific considerations for the requirements of collaborative work from a human-computer interaction (HCI) perspective. Physical affordance can change the meaning of an artifact and actions put on it, which enhance ownership, enable engagement, and facilitate awareness [136]. Studies from the fields of psychology [97], HCI [123], and technology-enhanced learning [75] suggest that collaboration using tangible UIs is an essential research area [47, P9].

A tangible UI can be a system [56], representation [55], embedded technology [106], or computing paradigm [8]. Markova et al. [83] provided four criteria that a tangible UI must fulfill: **a**) *Tangible Objects*: Contain one or more physical objects as interactive devices; **c**) *Embodiment*: Input and output are closely related, temporally or spatially; **c**) *Metaphor*: Digital and physical spaces are closely integrated, and 4) *Continuity*: Support continuous interactions. Tangible UIs have been used in many collaborative scenarios, such as exploration [86, 99, 107], problem solving [79, 81, 156], skill development [62, 90], and communication [22, 45]. **Tangible UIs have four main advantages.** First, tangible interaction promotes or enhances collaborative processes. Because tangible UIs provide access to shared representations of the problem, thus increasing the group working memory and reducing cognitive load [29, 108]. Second, tangible UIs support collaborative activities by allowing multiple users to interact simultaneously with the system [104], which could implicitly facilitate group communication and collaboration [64]. Third, tangible UIs have the advantage of creating flexible, collaborative learning environments [72, 123], which can include whole-class activities and discussion [52]. Finally, tangible UIs can create interdependence, provide multiple perspectives, and make learners aware of their peers' actions and eye gaze, all promoting productive collaborative learning processes [29].

1.2 Problems

Even though many existing tangible studies support collaboration [7, 34, 45], **it remains unclear how to design tangible UIs as an orchestration tool for collaboration** [P8, 138]. Orchestration means to "manage (or subtly guide) the different activities occurring at different educational contexts and social levels, using different resources and tools in a synergic way" [109, p. 586]. Technologies benefit all orchestration parts, including planning, regulating, awareness, and intervening during collaborative learning [57, 109]. Compared to other technologies, there are **three main reasons** that tangible UIs can help orchestrate collaborative learning activities.

First, tangible UIs act as physical objects to embody learning knowledge. Thus, object manipulation becomes a process of knowledge internalization. For example, Rygh [119] found that metaphors and affordances in physical objects were why tangible tools support collaboration. *StoryBlocks* [69] was a tangible programming game where blind and visually impaired or sighted high school students create audio stories by combining code blocks, which helped novices learn computer science concepts. Sabuncuoglu [120] developed a tangible music platform where children could create a melody by placing the designed tangible blocks in an algorithmic structure. Baurley et al. [12] explored how tangible interfaces could capture and communicate embodied knowledge as a recipe-authoring tool for innovative food, where users could use their bodies to learn ingredients. In addition, many studies used cubic shapes to include learners' behaviors [73]. Students understand abstract concepts easier and better by manipulating, placing, and arranging physical objects in space as input.

Second, tangible UIs can be interactive objects to embed or visualize individual and group activity-related information to support teacher awareness. Depending on the group's progress, the teacher may need to frequently shift the students' attention to the learning requirements. A tangible device can provide the necessary information to orchestrate these changes. For example, *Lantern* [3], and *Shelve* [4] were designed to display teamwork information, such as which team is working on which exercise, how long they have been working on that exercise, whether they need help, and for how long. *FireFlies2* [144] was designed to convert the teacher's cognitive workload into distributed cognitive tasks, which helped the teacher focus more on adapting their instructions to students' abilities and needs. Do [33] designed tangible tabletops to help teachers manage the classroom and present visual information about students' progress. Finally, Baudisch et al. [11] developed *Lumino*, tangible blocks for tabletop computers, to demonstrate how to use tangible blocks to control a regular touch screen. The *Lumino* construction kit allows users to put together simple block constructions in which the system automatically checks the designs and problems of the hypothetical building.

Finally, tangible UIs can serve as a tool to facilitate communication and interaction, which aims at triggering specific types of collaborative learning processes known to generate learning gains, such as providing explanations or elaborations, resolving conflicts, or mutually regulating each other [31]. Compared to a tablet, the tangible device *Quizbot* [43] made the children reach a consensus easier and treat each other more respectfully. *PaperTUI* [113] used the social regulation approach to help users to create a web with digitally augmented physical papers, which helps identify and model interactions that support students' collaborative learning activity. *Sync Blocks* [28] coordinated children's collaboration by devising clear roles and reducing conflicts. In addition, Gelsomini et al. [44] explored a new Bring Your Own Device (BYOD)-based tangible technology-enhanced learning setup that supported the creation and management of storytelling activities and fostered the development of communication skills through mobile computer-supported collaborative learning. Meanwhile, this approach could be extended to designed environments for special-needs individuals.

1.3 My Work

To have productive group work, we need to know how to create a better interaction space and interaction affordance for collaboration. Collaboration does not always happen automatically [32]. Orchestration tools with tangible technologies targeting the elements of successful collaborations, e.g., positive interdependence (see its definition at Page 13) and shared attention (see its description at Page 15), are promising solutions. Existing studies have shown that tangible UIs could promote collaboration. However, we need systematic guidelines for structuring collaboration with tangible UIs. Therefore, I conducted eight studies to design tangible prototypes to facilitate collaboration. More specifically, I explored three research questions in my doctoral thesis:

RQ1 What are the design spaces for tangible user interfaces embedded with positive interdependence or shared attention for collaboration?

RQ2 What are the effects of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?

RQ3 What are the implications of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?

One thing that should clarify is the positioning of my studies and results in terms of the research field and the target audience of my thesis. People might feel an inconsistency between the thesis title ("collaborative learning") and the thesis aim (e.g., research questions, experiments, and contribution), referred to as "collaboration" and "collaborative experience". All my studies were in some learning contexts, but my purpose was to improve users' collaborative experience, then indirectly improve their learning performances. Strong bonds exist between the related work and the research approach to the learning sciences, but my design takeaways will target the HCI community.

1.4 Thesis Overview

My thesis includes five chapters:

chapter 1 I explained my research background, previous research gap, and my work contribution.

chapter 2 This chapter aims to answer **RQ1** (i.e., *What are the design spaces for tangible user interfaces embedded with positive interdependence or shared attention for collaboration?*). First, I elaborated on my initial research explorations of designing five tangible UIs. Then, I concreted on two research focuses tangible design for goal interdependence and tangible design for shared attention. Finally, I analyzed and summarized the theoretical foundation and design principle for designing tangible UIs for positive interdependence and shared attention.

chapter 3 This chapter aims to answer **RQ2** (i.e., *What are the effects of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?*). I designed eleven tangible prototypes but mainly introduced six of them: *SpellBoard* (in subsection 3.1.1), *MemorINO* (in subsection 3.1.2), *CollabMaze* (in subsection 3.1.3), *FlipCards* (in subsection 3.2.1), *Chilego* (in subsection 3.2.2), and *Study Marbles* (in subsection 3.2.3). The first three projects are for positive interdependence, and the latter for shared attention. In the end, I also summarised the designed-based research method for designing and developing these eleven tangible prototypes.

chapter 4 This chapter aims to answer **RQ3** (i.e., *What are the implications of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?*). Then, based on chapter 3, I discussed how to design embodied facilitation for scripting and orchestrating collaboration and create expressive representation for guiding and facilitating joint action. I also reflected on how to consider physical space, embodied interaction, and collaboration as a design system. In the end, I reflect on my study limitations.

chapter 5 I summarized my thesis study and proposed valuable future work directions.

2
DESIGN SPACE

... as if research always involves going over old territory, while art, craft and design are of course concerned with the new.

– Christopher Frayling [39] (p. 131)

This chapter will provide an overview of the design space that forms the main body of my thesis before annotating the projects concerning questions **RQ2** and **RQ3**. I briefly explain the design exploration and describe the theory foundation, design principle, and design-based research approach. An overview of design exploration is compiled in Table 2.1, which contains a short project description and references to the publications. The individual contribution types are indicated in three categories [152]: Artifact, Theoretical, and Empirical. This is only a contribution classification of the projects in my thesis and is not intended as a general classification. **This chapter is based on my publications in [P8, P9].**

2.1 Design Exploration

I developed five tangible prototypes to explore the design space with seventeen of my master's students. As shown in Table 2.1, these tangible prototypes explored different concepts, such as interdependence and shared attention.

Table 2.1: Overview of the five explorative projects and their contributions presented in my thesis.

	Project	A	T	E	Design Concepts	Ref.
Concept Exploration	***stayFOCUSed***	•	●	•	An exploration of common space to create **shared attention** (see Figure 2.1).	[P8]
	Group Hexagon	•	●	•	An interface concept for considering component composition as a method to make users **positively dependent** on each other (see Figure 2.2).	[P8]
	Tower	•	●	•	An interface concept for combining benefits of tangible interfaces with advantages of the ubiquitous interface to create **shared attention** (see Figure 2.3).	[P8]
	Glowing Wand	•	●	•	An interface concept for using embodied movement to create an **shared attention** (see Figure 2.4).	[P8]
	Remolight	•	●	•	An exploration of **shared attention** for physically distributed users (see Figure 2.5).	[P8]

Contribution types based on Wobbrock and Kientz [152]: **A**rtifact, **T**heoretical, **E**mpirical Research.

● = primary contribution; • = secondary contribution.

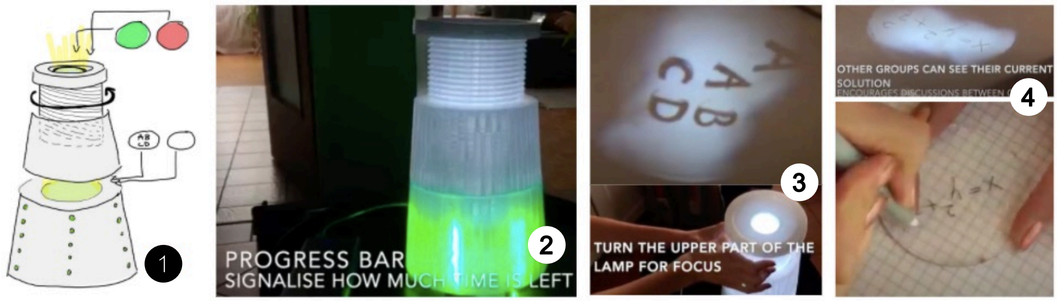

Figure 2.1: *stayFOCUSed* technical prototype (**1**. concept idea and structure; **2**. show timer with light progress bar; **3**. rotate the lamp to show answers; **4**. pen-writing on the disk).

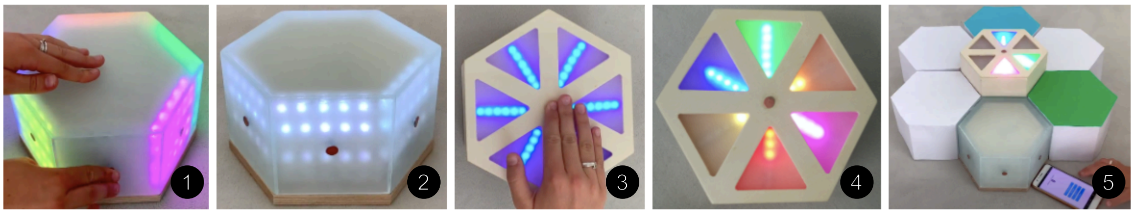

Figure 2.2: *Group Hexagon* technical prototype (**1**. touch side button to choose an answer with individual-hexagon (**IH**); **2**. show timer with light progress bar in the **IH**; **3**. touch the top button to seek help with the group-hexagon (**GH**); **4**. show answer distribution in the **GH**; **5**. app mode to interact and control **IH**).

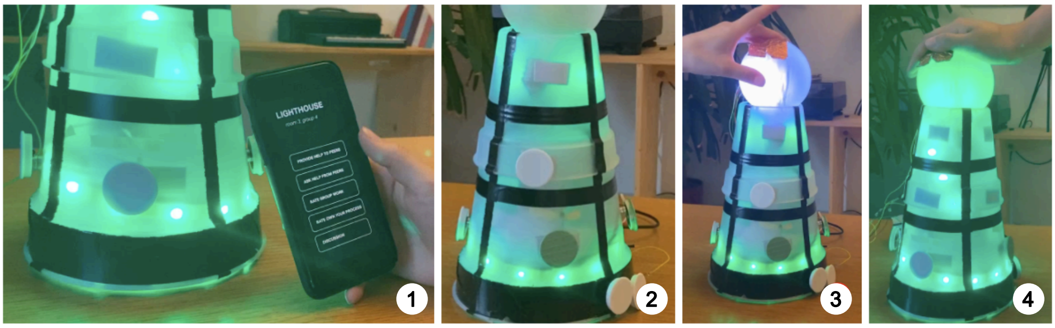

Figure 2.3: *Tower* technical prototype (**1**. use app to communicate with other groups; **2**. place magnets on the *Tower* to choose an answer, green means *I am confident*, white means *I am not sure*; **3**. rotate top bulb to seek help; **4**. touch the top bulb to finish the activity).

Figure 2.4: *Glowing Wand* technical prototype (**1**. different hand gesture designs; **2**. switch for a rainbow feedback; **3**. negative tick gesture to red light; **4**. circle gesture to yellow light; **5**. tick gesture to green light).

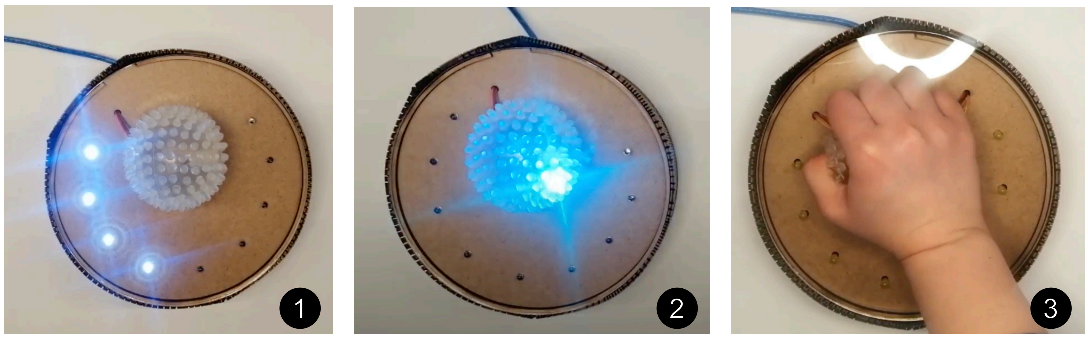

Figure 2.5: *Remolight* technical prototype (**1**. indicated timer with LED bar; **2**. show notifications with light shining in the ball; **3**. squeeze the ball to seek help or knock it to send an agreement message to other learners).

Our underlying assumption was that collaborative space and interactive methods made a difference between tangible and traditional interfaces. However, such interfaces must fit into a pedagogical concept. Cross-plane integration, sequentiality, time management, and physicality are essential considerations for an effective collaborative experience [31]. Putting these requirements together, we can design a tangible tool that creates a shared space for communication and interaction. More specifically, we need to consider three perspectives: **a**) create shared spaces for communication, **b**) support diverse interactive dynamics, **c**) visualize interaction and activity status.

2.1.1 Creating Shared Spaces for Communication

As an orchestration tool, tangible UIs need to enable shared spaces for communication where collaboration can happen. Tangibility involves gesture, motion, or full-body interaction and "emphasizes the use of the body in educational practice" [63, p. 2]. By embedding technology in physical objects with natural actions like grabbing, tangible UIs become ubiquitous, mixing the physical and digital world [149]. As shown in Figure 2.6, my students and I developed five tangible prototypes with different communicative mechanisms.

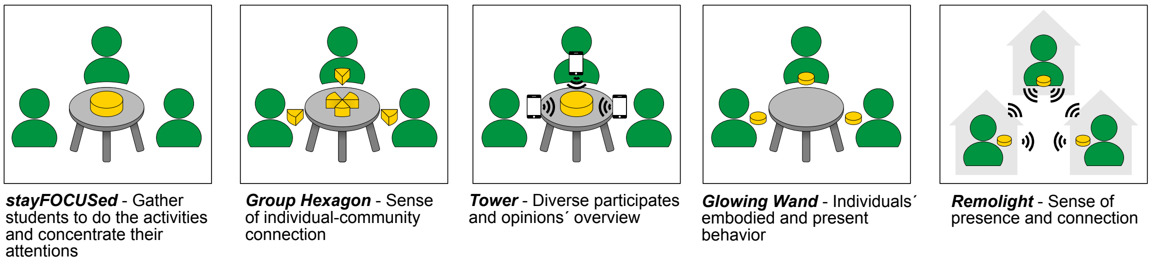

Figure 2.6: Communicative mechanisms for developing tangible UIs in my publication [P8].

stayFOCUSed (see Figure 2.1) acts as a tool to create a collaborative atmosphere where students have to get close and finish the activity together. Casting light on the ceiling is an excellent way to gather students and attract their attention. *Group Hexagon* (see Figure 2.2) gives each student an individual device to interact with; then, it connects these with a central group device. This process helps to build among students a sense of individual-community connection. *Tower* (see Figure 2.3) has both a group device and an App to make students share their opinions. *Glowing Wand* (see Figure 2.4) designs a playful and fun device for each student. It has no direct affordance for group work. However, this embodied and present behavior naturally attracts students to work together. *Remolight* (see Figure 2.5) connects individuals at different locations, where they have the same device as an ambient environment to convey important information. As we can see, **we can design tangible UIs with different forms to orchestrate group activities**, which make users positively dependent on each other and have shared attention on the tasks.

2.1.2 Supporting Diverse Interactive Dynamics

An orchestration tool needs to support different types of communications (e.g., within-group and inter-group) [4, 67] and help-seeking [148], a primary function for group discussion with supervision from teaching assistants or teachers. We designed different communicative approaches as shown in Table 2.2. All the prototypes can realize the communication and interaction within the group in different ways. For example, users write down their answers or questions, and *stayFOCUSed* will project them to the ceiling. *Group Hexagon* has an individual hexagon for each user in the group. Users can pick up a white or green magnet to stick on the different levels of the *Tower* to communicate. *Glowing Wand* can change color in different gestures. If the users in the group understand the meaning of different colors, they can effectively communicate. Users can squeeze the ball of *Remolight* to show an agreement with others' opinions in the group.

Table 2.2: Communication and interaction (**C & I**) designs in my publication [P8] (**G**: Group; **TA**: Teaching Assistant; **T**: Teacher; **CR**: Classroom).

C & I...	*stayFOCUSed*	*Group Hexagon*	*Tower*	*Glowing Wand*	*Remolight*
within **G**	Overhead Projection (OP)	Individual-Hexagon	Magnet Object	LEDs	Ball
inter-**G**	OP	Group-Hexagon	Top Bulb, App	LEDs	-
with **TA**s	OP	Group-Hexagon	Top Bulb	LEDs	Ball
with **T**	-	App	App	-	Ball
within **CR**	OP	Group-Hexagon	Top Bulb, App	LEDs	Ball
between **CR**s	-	App	App	-	-

Inter-group interactions are helpful for users to communicate and interact beyond the group. Users in different groups often do not sit together. Thus, inter-group interactions require a simple, straightforward, tangible design. As shown in Table 2.2, *stayFOCUSed* and *Glowing Wand* keep the within-group design for inter-group interaction. However, *Group Hexagon* designs an additional tangible object to show group work: a "group hexagon". The group hexagon changes to green or red to show the group work status. *Tower* provides an App to enable communication via the online platform. **We can see the possibilities of designing tangible UIs to support communication and interactions within and inter-group.**

2.1.3 Visualizing Interaction and Activity Status

Orchestration is like a regulation loop, with two concrete points of control: state awareness and workflow manipulation [32]. The notion of "awareness tools" [48] is to inform users about the activity of their co-workers, where awareness shares behavioral information among users without a cognitive diagnosis. To provide dynamics for consistent group communication, we stress the need for interactive information visualization in the design of orchestration technologies. In my publication [P8], my students and I designed light (brightness and color) to show the interaction and activity state information. *Minimalism* in the design of orchestration technologies with light was emphasized by Dillenbourg et al. [32]. For example, they used such minimalist design in *Lantern* [3].

Based on this, my students and I explored more possibilities to design information visualization with light, e.g., overhead projecting to the ceiling (*stayFOCUSed* [P8]) and hexagons with different colors (*Group Hexagon* [P8]). Providing and visualizing basic interactive information, e.g., activity time and help requests, is essential to maintain the collaborative activity. Therefore, as seen in Table 2.3, we designed tangible UIs to ensure they support the visualizations of different interactive information. For example, we used a light progress bar to show the timer. We can see that tangible UIs can visualize group interaction and process. **It has unique**

advantages due to visualization and physicality.

Table 2.3: Collaborative learning activities supported in my publication [P8] (**MCQA**: Multiple Choice Question Answer; **OQA**: Open Question Answer; **HR**: Help Request; **TA**: Teaching Assistant).

Activities	***stayFOCUSed***	***Group Hexagon***	***Tower***	***Glowing Wand***	***Remolight***
Submit **MCQA**	Write on disks	Turn on individual hexagon	Attach magnet object	Move wand	Change the ball color
Submit **OQA**	Write on disks	App	App	-	-
Set activity time	Light Progress Bar (**LPB**)	**LPB**	**LPB**	-	**LPB**
Share **MCQA**	Overhead projection (**OP**)	Connect group hexagon	Read magnet	-	-
Share **OQA**	**OP**	App	App	-	-
Finish activity	**OP**	Green light (**GL**)	**GL**	**GL**	-
HR for TAs	**OP**	Light flashing	Top bulb flashing	Rainbow light	Light flashing
HR for remote teacher	-	App	App	-	-
HR for near groups	**OP**	App	App	-	-
HR for remote groups	-	App	App	-	-

2.2 Tangibles to Support Positive Interdependence

Tangible UI is well-suited for collaboration [84, 123] because **a**) it provides particular affordances for fostering positive interdependence; **b**) The distributed work with particular duties brings object ownership; **c**) Users prefer to manipulate physical objects [137]. “Affordance” describes the specific physical characteristics of objects “naturally” reveal what they might be used for [97]. To better design tangible UI for supporting collaboration, Antle and Wise [6] 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 [36, 150].

To investigate “how” to design tangible restrictions to “focus” users’ positive interdependence for collaboration, I started by understanding theory foundations and design principles. Later, I followed a design-based research method [5] to design and develop tangible prototypes.

2.2.1 Theory Foundation

Interdependent collaboration provides a context where promotive interaction occurs so that interpersonal interaction produces a high achievement [25]. Promotive interaction refers to "individuals encouraging and facilitating each other's effects to accomplish the group's goals" [59, p. 366]. To achieve good collaboration, it is essential to structure collaborative activities with, e.g., collaborative tasks, interdependent roles, and interdependent interactions. **From the HCI perspective, we must consider designing interdependent interaction mechanisms to make learners influence and rely on each other to achieve the same goal.** Wise et al. [150] found social/technological interdependence helped users produce more in-depth explanations and have fewer but longer cases of resolving conflicts jointly. Collazos et al. [25] claimed that interdependent collaboration could motivate students to work hard and facilitate exploring new insights and understandings.

Interdependence refers to "the outcomes of individuals are affected by their own and others' actions" [59, p. 366]. It has three types: positive (cooperation), negative (competition), and none (individualistic efforts) [59]. Positive interdependence, an essential element for collaborative learning [59, 70], refers to the success of one learner is possible only by the success of the others [25]. There are different kinds of positive interdependencies [25, 70], e.g., positive goal interdependence, positive celebration/reward interdependence, and positive task interdependence. Designing positive interdependencies could encourage users to negotiate, solve, and discuss tasks collaboratively [150]. In other words, we should purposely design interaction to engage users in a collaborative environment. Therefore, they can have an interdependency, which improves their collaborative experience [105].

Even though many suggestions exist on promoting positive interdependence [59], there are few guidelines for structuring interdependent collaboration with tangible technologies. However, tangible UIs can afford to create an interdependent environment where users have a physical embodiment of distributed control and social engagement around the interactive object [137]. It has a technological benefit, which can be employed to facilitate face-to-face collaboration [29] and its social interdependence [137]. For example, we can design objects that can only be moved by joint effort or that one learner needs to borrow some object from another to proceed.

2.2.2 Design Principle

Tangible UIs, as a learning tool, embed an interaction mechanism that can be specifically designed to orchestrate collaborative activities. To have a productive collaboration, **we aimed to design an interdependent collaboration where two users could work together naturally to solve tasks**. From an interactive perspective, all my positive interdependence prototypes were designed with three specific interdependent mechanisms. **a**) The interaction inputs must come from both users; **b**) When solving tasks, each user must contribute to group work; **c**) Only when both interaction inputs are correct, users can proceed to the next task. This is a naturally interdependent design to "force" users to help each other. In addition, users have an actual physical environment to engage in the activities physically. This provides users with more natural interaction and communication opportunities. For some specific users, e.g., children, designing intuitive and simple interactions is critical for working effectively together. Tangible UIs have the advantage of "forcing" interdependence because it makes the task-solving processes easy and intuitive to understand.

There are two conditions for creating positive goal interdependence: set a clear group goal and design constrained or codependent accesses [25, 150]. Such designs 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 [53, 128], which contains three concepts: **a**) *embodied constraints* means to favor some actions and restrict others, **b**) *multiple access points* means to ensure that users can interact equally and simultaneously, and **c**) *tailored representations* refer to the interaction depending on the users' knowledge. Table 2.4 shows the overall designs of *UnitRry* with weak interdependence and *CollabMaze* with strong interdependence.

Table 2.4: Goal interdependent design of *UnitRry* with weak interdependence and *CollabMaze* with strong interdependence in my publication [P6].

	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

2.3 Tangibles to Facilitate Shared Attention

There is a social ability in human social activities called shared attention. It means two or more people can focus on one thing simultaneously without being distracted [14, 94]. Shared attention makes synchronous communication, interaction, and collaboration more efficient and smooth [134]. It is a process in which new knowledge expands to face further information, and perceived stimulus becomes common knowledge, which allows group coordination [131]. In other words, shared attention can be achieved by, e.g., seeing [131], hearing, and smelling [14, 134]. The most common attention in everyday life is the shared gaze [114]. It happens almost always when we are with others, e.g., "looking where someone else is looking" [19]. It also can be more psychological as individuals must know jointly that they are attending the same activity [9] and have common knowledge [131].

Shared attention is essential for synchronous collaboration in co-located [58, 122, 157] and remote [2, 26, 124] settings. Users had better experiences [51], higher motivation [131], and better social presence [88] when perceiving shared attention with others. Previous studies have explored mutual real-time gaze representations [23, 26, 122], shared gaze visualization [27], and augmented reality gaze [58] to improve collaboration. However, few studies explored how to "design" or "create" an environment that considers making interaction and shared attention design positively affect each other. To investigate "how" to design tangible representations to facilitate users' shared attention for collaboration, we started by understanding theory foundations and design principles. Later, we followed an iterative design process to design and develop tangible prototypes.

2.3.1 Theory Foundation

Shared attention theory assumes that human beings have the psychological ability to experience the world from a shared attention perspective [133]. Shared attention [131] involves the activation of a psychological perspective where users reckon the world is experienced from their *attention*. When we perceive shared attention, we process deeper cognition of information [130]. When updating mutual knowledge, shared attention facilitates users' communication and gives them shared attitudes and beliefs. Garriy [132, p.1249] claimed that "because shared attention is a psychological mode of attention, whether others are attending to the same information is inconsequential to the effects of experienced shared attention on thought and behavior. **It is the experience that *we are* attending to the information that matters**."

We can design input and output from an HCI perspective to create a collaborative shared attention environment. Ambient systems benefit collaborative activities [16, 91, 92, 98]. Ambient display [93] is a common approach to display shared attention information on dynamic off-screen points of interest, which can attract users' attention by showing information within their peripheral views [87, 92, 103]. As a peripheral perception, the user can be aware of visual information without being distracted from the main task. For example, *ShadowSparrow* [111] used light and shadow to display multiple relevant images of surroundings for informative notification and visualization. *Sparkle* [93], which increased usability and reduced workload, was a display for dynamic off-screen points of interest, where users needed to maintain an overview of changing status. Morrison-Smith et al. [91] developed *AmbiTeam* to support team awareness, and it displays up-to-date group information. The results show that participants perceived better collaboration and were more productive and motivated. **In summary, ambient systems make users less disturbed or distracted from main tasks and be more productive.** From an HCI perspective, we can intentionally design an ambient environment to improve collaboration.

2.3.2 Design Principle

Shared attention makes better collaboration in many settings [127]. Tangible interaction changes educational practice and uses embodiment to benefit co-located collaboration [36, 74, 142] and remote collaboration [68, 145]. For example, Kosmas and Zaphiris [68] investigated students' performance in a collaborative embodied learning environment and found that embodiment made students work more collaboratively. Schneider et al. [125] showed that joint visual attention is significantly related to co-located students' interaction quality with tangible objects. Marshall et al. [85] found that children fought for controlling physical objects, not digital objects, and discussed the benefits of embodied interaction when designing collaborative applications. Thus, we can create tangible interactions to increase shared attention for an effective collaborative activity [77] because physical objects take users from the digital world back to the real world [89].

Tangible materials positively influence users' comprehension and learning [127]. Physical objects [80] are visible and contain rich visual information, including the dimensions, forms, outlines, hues, or physical object labels. Controlling object orders in physical space can cognitively visualize solutions to problems [66, 100]. Tangible interfaces increased eye-contacts [96] and joint action [46, 158]. Schneider et al. [126] found that students in a tangible condition had significant better-shared attention than students in a paper condition. The measures of shared attention include eye contact [153], eye movement [15], gaze patterns [101], and experience questionnaire [49].

Wild theory [116] encourages new and innovative ideas, which implies our research purposes. We believe designing and developing functional prototypes to enable an *in situ* experience with novel interaction concepts is essential. **To lead to an effective design, we followed three design principles**: First, Siposova and Carpenter [134] summarized different attention levels' characteristics: individual, monitoring, common, mutual, and shared attention. As shown in Table 2.5, we designed tangible prototypes *FlipCards* [P10] and *Chilego* [P10] according to Siposova and Carpenter [134]'s shared attention principles.

Second, we followed Antle and Wise [8, p.13]'s tenth guideline to design tangible UIs for collaboration: "creating configurations in which participants can monitor each other's activity and gaze can support the development of the shared understanding design of physical and digital objects." As shown in Table 2.6, we considered using positive interdependence [P6] and tangible ambient system [P11] to help users monitor and be aware of the collaborative progress.

Finally, we leveraged physical object properties with light to allow users to share their attention and concentrate on the collaborative task. We used many light designs to increase users' shared attention in our shared attention projects (see section 3.2). There are three reasons to implement light into our tangible prototypes: **a**) Light is an essential output modality [P11], which facilitates the interaction [24]. We can embed light into all the interactive processes easily, which is impossible for other materials [154]; **b**) Light in the tangible UIs could visualize

Table 2.5: Tangible designs according to Siposova and Carpenter [134]'s shared attention principles.

	Shared Attention Criterion [134]	***Study Marbles***	***FlipCards***	***Chilego***
Type of perspective	Second person	Two or more users work together	Two users work together	
Description of the experience	You and I (we) attend to X and are actively communicating about this	Check others' marble light status	Check the English vocabulary correctness for the other, help-seeking	Remember the false writing of the other, know the turn to write
Type of interaction	Triadic	Interact with the prototype		
Knowledge gained	Shared knowledge	Work on the group project together	Learn the English vocabulary together	Learn the Chinese character writing together
Does the second individual know that the first is in that level of attention?	Yes	One needs to check the status of others	One person needs to check the answer correctness of the other	One person needs to know and remember the writing order of the other
"Intimate I+you we feeling"	Yes, stronger	Direct connection with the other		
Commitments and obligations	Yes	Check each other		

feedback, create a collaborative environment, and improve tangible experience [P11]. **c**) Light can create a feeling and meaning of interaction with visual aesthetics [76, 155] and stimulate users' deep emotions [95]. Many experiments show that ambient light to display information can grab users' attention and enhance their motivations without distracting them from the primary task [91]. Therefore, light allows users to focus on collaboration while noticing the interaction with their partners, which is an excellent way to increase their shared attention.

2.4 Takeaways

RQ1: What are the design spaces for tangible user interfaces embedded with positive interdependence or shared attention for collaboration?

To answer this research question, I first did some open explorations and later focused on designing and developing positive interdependence and shared attention for tangible UIs. When exploring the benefits of tangible UIs for collaboration, my students and I found three critical rationales: **a**) create shared spaces for communication, **b**) support diverse interactive dynamics, and **c**) visualize interaction and activity status.

Table 2.6: Designs according to Antle and Wise [8]'s tangible collaboration guidelines.

Tangible Collaboration Guidelines [8]	***Study Marbles***	***FlipCards***	***Chilego***
Users monitor each other	One has to check the other's marble light statue	One has to check the other's English vocabulary correctness	One has to check the other's Chinese writing correctness
Gazes support shared understanding	Different marble colors or statues show different meanings	A lightbox near the users has two LED bars to show the timer and work progress	The LEDs in the groove of the Chinese character show different colors to indicate to users the results

Later, when **designing and developing** a specific tangible UI, we found three critical rationales: **a**) start from theory foundations, e.g., we referred to interdependence and shared attention theory; and **b**) follow existing research design principles. For example, we comply with the following design processes: concept idea → feedback (with interview) → paper prototype development → feedback (with an interview or paper prototype user study) → technical prototype development → feedback (with pilot user study) → technical prototype improvement → final user study.

We explored the design space for designing and developing tangible UIs for various collaborations. I did not elaborate on it in section 2.1, but we summarized the design space of tangible collaboration as shown in Table 2.7. We explored the highlighted dimensions, such as designing object manipulations to help users to solve problems. It is far too less to provide specific design guidelines. However, it is impossible to investigate the combinations of all the elements and dimensions in Table 2.7. Therefore, we can use it as an excellent reference to help us think about how to find suitable applications of tangible UIs.

Table 2.7: Design space for tangible collaboration in my publication [P8] (Note: Highlighted dimensions are what we used for exploring design space in section 2.1).

Elements	Dimensions			
User	**Type**	Child	Teenager	Adult
	Group size	Pair (2)	Small group (3-5)	Large group (6+)
	Characteristic	Visually impaired (e.g., blind)	Action or perception impaired (e.g., stroke, autism, dyslexia)	Other general users
Context	**Mode**	Face-to-face	Remote	Blended
	Location	In-door (e.g., classroom, museum)	Out-door (e.g., outing)	
Collaboration	**Purpose**	Problem-solving [65]	Brainstorming [147]	Knowledge building [121]
	Mechanism [115, 148]	Interdependence	Coordination	Monitor the learning process
	Scenario	Within the group	Between groups	
Interaction	**Input**	Body-based gesture	Object manipulation	Move objects on interactive screens (e.g., tablet)
	Physical representation [106]	Symbolic	Literal	
	Output [106]	Visuospatial	Audial	Haptic
	Interactive metaphor [140]	Cartesian space	State space	Relational metaphors (human relations)

3
PROJECTS

Cognitive processes are computational. If the computational processes that comprise some cognitive systems have constituents outside the head, then these cognitive systems extend outside the head. The computational processes that comprise some cognitive systems do have constituents outside the head.

– Shapiro [129] (p. 236)

This chapter aims to investigate the **RQ2**. I use two main categories to summarize the projects: positive interdependence and shared attention. As shown in Table 3.1, I developed six projects for exploring positive interdependence and the other five for exploring shared attention. The reasons to develop different tangible prototypes for the same concept are **a**) To have effective results, a prototype design must target specific users and contexts. In other words, the individual study can only consider one specific scenario, and its findings are limited. Therefore, to generalize design principles, we need various examples to confirm or adjust the initial design guess; **b**) Different studies emphasize different perspectives, such as theory, artifact, and experiment. We need to use different studies to show design rationales and effects.

The subsequent project descriptions give a short introduction to the artifact and concepts for the context. Regarding how the evaluation criteria have been defined concerning the aim of the tangible technology for collaborative learning, I did not directly measure learning effects. I used measures, e.g., "concentration", "enjoyment", and "immersion", instead. The main reason is these measures are important for learning. Furthermore, actual learning effects need a longer time to determine, but all our studies were lab studies and were only done once.

I indicate the contribution of individual publications to a project when it consists of multiple publications. All original contributing publications with detailed information on the contributions, technical implementations, and used methodologies are added in the appendix of the thesis (see page 79).

3.1 Tangibles for Positive Interdependence

This section is based on my published papers [P2, P6, P7]. I will abstract the main contents to explain how I designed tangible UIs, from interactive constraints, embodied facilitation, and strict conditions, to building positive interdependence. I introduced these three projects, not the other four because they were more representative examples of positive interdependence. In addition, their user study results were also more comprehensive.

3.1.1 *SpellBoard*

I designed and conducted *SpellBoard* study [P7] with one of my master's and one of my bachelor's students. *SpellBoard* is a tangible device to help children learn German spelling.

Setup As shown in Figure 3.1, it mainly has four parts: one board, ten blue blocks, ten orange blocks, and a tablet application.

We created twenty letter blocks. To help children naturally collaborate, we made an interdependent design: **a**) There were blue and orange colored letters with similar usage percentages and **b**) 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 [13]. Then, as shown in Table 3.2, we balanced the blue and orange letters with similar frequency.

Table 3.1: Overview of the eleven projects and their contributions presented in this thesis (I will explain the highlight projects).

	Project	A	T	E	Design Concepts	Ref.
Positive Interdependence	***SpellBoard***	•	●	●	An investigation of **interactive constrictions** of positive interdependence.	[P7]
	MemorINO	●	•	●	An investigation of **embodied facilitation** of positive interdependence.	[P2]
	Paint-Matics	•	●	●	An investigation of **interactive metaphor** of positive interdependence.	[P4]
	Slimo	●	•	●	An investigation of **interactive metaphor** of positive interdependence.	[P4]
	UnitRry	●	•	●	An investigation of **weak positive interdependence**.	[P6]
	CollabMaze	●	•	●	An investigation of **strong positive interdependence**.	[P6]
Shared Attention	***FlipCards***	●	•	●	An investigation of tangible manipulation for shared attention with **visual feedback** in the **F2F pair**.	[P10]
	TalkinGlass	•	●	●	An investigation of tangible manipulation for shared attention with **visual feedback** in the **F2F group**.	[P1]
	Chilego	●	•	●	An investigation of tangible manipulation for shared attention with **visual feedback** in the **remote pair**.	[P10]
	GrouPen	•	●	●	An investigation of tangible manipulation for shared attention with **haptic feedback** in the **remote pair**.	[P13]
	Study Marbles	●	•	●	An investigation of tangible manipulation for shared attention with **visual feedback** in the **remote group**.	[P3]

Contribution types based on Wobbrock and Kientz [152]: **A**rtifact, **T**heoretical, **E**mpirical Research.

● = primary contribution; • = secondary contribution.

Figure 3.1: *SpellBoard* study setup.

Table 3.2: Twenty German words for spelling in the first user study in my publication [P7] (Orange letters are for one child. Blue letters are for the other child. Black letters have been already provided in the system).

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

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 blue and orange colors. Thus, children will naturally work together to finish the tasks because each child only has either blue or orange letter blocks.

User Study The user study was conducted with four children (3 girls, one boy, M(age) = 8.25). It consisted of two pairs, one with 7-7 yo and the other with 9-10 yo children. **Each pair attended our user study four times within two weeks with the same experimental interval.** We got written consent from the participants' parents. Participants could stop whenever they wanted.

Participants played *SpellBoard* in pairs for around 25 minutes with video recording. We conducted in-field observations with a structural observation form for each pair. The observation form consisted of six dimensions: understanding of the system setup and design (5 items), behavioral engagement (3 items), emotional engagement (5 items), cognitive engagement (5 items), collaboration (4 items), and motivation (3 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 an audio recording.

Main Findings Children have 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 also switched 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 Figure 3.2, their collaborations increased until Session 2, then started to decrease.

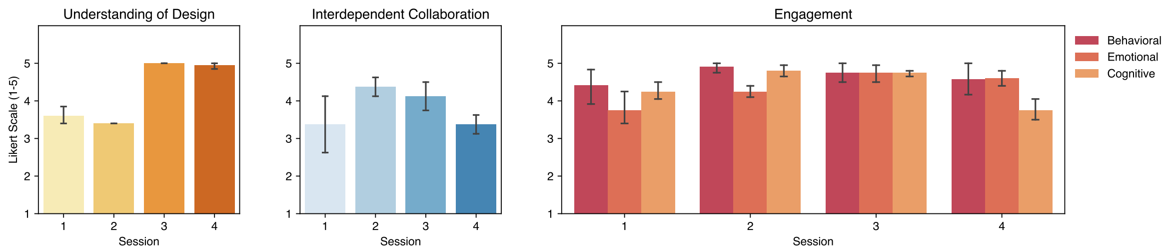

Figure 3.2: Children's understanding of design, interdependent collaboration, and (behavioral, emotional, and cognitive) engagement from Session 1 to Session 4.

Children showed good behavioral engagement in all four sessions, even though it was not stable (see Figure 3.2). The video analysis showed that 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 Sessions 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 were 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 often motivated each other 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 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 Figure 3.2-cognitive engagement). High cognitive engagement indicated learners could realize a knowledge link between school learning and everyday life [40]. 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."*

Summary We dug out three key findings: **a**) Interactive constraints can be specially designed to allow children to coordinate their collaborative actions; **b**) From an actual usage effect, we need to redesign *SpellBoard* to consider children's cognitive engagement and interdependency in collaborative activities; **c**) 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 positively impact children's collaborative learning.

3.1.2 *MemorINO*

I designed and conducted *MemorINO* study [P2] with two of my bachelor's students. *MemorINO* is a tangible device to help children learn mathematics and sequence.

Setup *MemorINO* has three parts: two boards, 28 cards, and a laptop application. As shown in Figure 3.3a and b, we can connect the boards horizontally and vertically to create different tasks. For example, if the boards are connected as Figure 3.3a, we can create a task as "Put the rainbow colors in order" (see Figure 3.4). If the boards are connected as Figure 3.3b, the task could be "$\square + \square = 6$.".

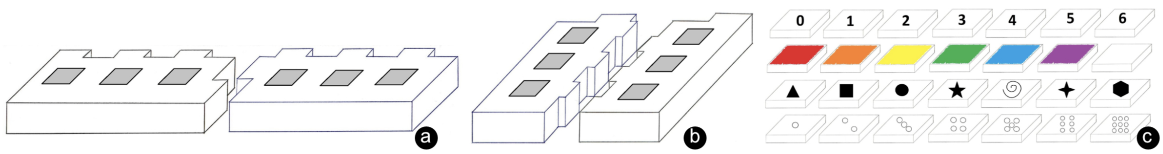

Figure 3.3: *MemorINO* boards and cards: **a**) Connect horizontally, **b**) Connect vertically, and **c**) Tangible cards with images on both sides.

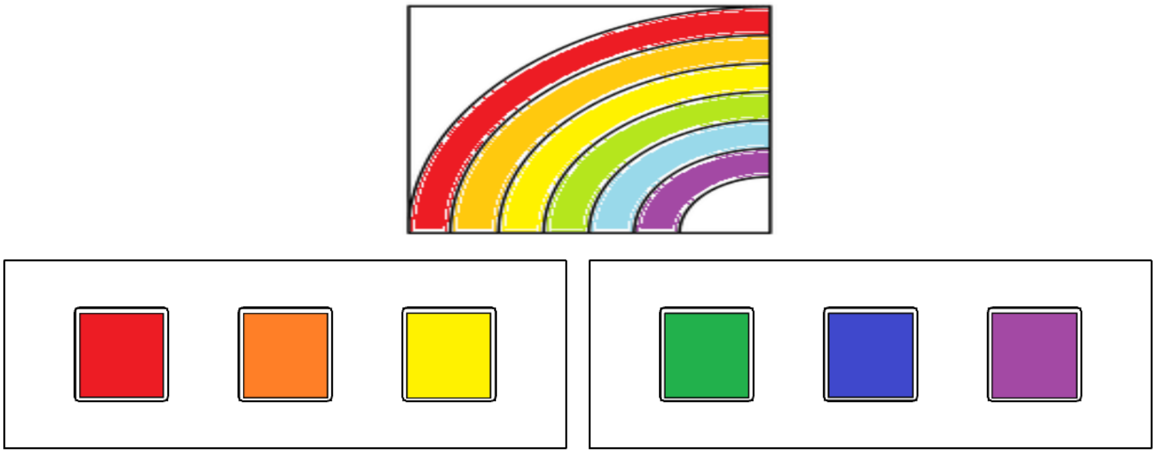

Figure 3.4: An example of *MemorINO* task.

User Study Twenty-three children (12 pairs, 15 girls, eight boys, M(age) = 4.96 [4, 6]) and three kindergarten teachers (3 females, M(age) = 48.67 [34, 60]) participated in the final user study. The children were recruited from two German kindergartens; we assigned them according to their age difference. Therefore, there are six pairs with similar ages (i.e., identical or one age difference), and the other six have different ages (i.e., more than two ages difference).

We conducted the studies in kindergarten classrooms. We got written consent from all participants' parents, and the kindergarten teacher was constantly observing the studies. As shown in Figure 3.5, children played in different-age or similar-age pairs for around 45-70 mins, with their kindergarten teacher observing their behaviors. The system has 18 tasks, e.g., putting cards with colors in the correct order as the 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 hints, 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 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 3.3 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 about their observations of 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 audio was transcribed and coded by two different 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 but also fluent in English.

Figure 3.5: Children playing in pairs with *MemorINO*: **a**) Different-age group, and **b**) Similar-age group with their kindergarten teacher.

Main Findings As shown in Table 3.3, 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 a situation where one child took the lead. In addition, 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 were matched with other children on their own. The older children seemed inclined to be good mentors because they were patient and helpful.

SA groups generally have better behavioral, emotional, and cognitive engagement than DA, see Table 3.3. Most SA groups (83.3%) for behavioral engagement 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 two tasks. Regarding emotional engagement, all children showed good interest in the tasks, but still more SA groups (83.3%) than DA groups (66.7%). Very few children (16.7%) got frustrated or angry while doing the exercises. Finally, it showed SA groups had better cognitive engagement, where they argued with each other more (33.3%), and their attention wandered less (25.0%).

Summary Our investigation revealed two main findings: a) We could design interactive constraints with tangible technologies to "force" children to attend collaborative activities

Table 3.3: 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

naturally and interdependently; **b**) 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.

3.1.3 *CollabMaze*

I designed and conducted *CollabMaze* study [P6] with one of my bachelor's students. *CollabMaze* is a tangible game to help children learn how to collaborate.

Setup *CollabMaze* contains two main components: two joysticks (the size is $4 \times 2.6 \times 3.2$ cm) and a base box (see Figure 3.6). To accomplish divided movement control, one joystick is designed for up-down movement (y-axis), while the other is for the left-right (x-axis). To prevent other directions' movement, we created wooden rails. The children can control the game character left-right, up-down, or beat monsters by simply moving or pressing the joystick. We drilled a hole in the middle of the wood to make it easier to grip the joysticks as a joystick cap.

User Study Twenty children (9 girls, 11 boys) with a mean age of 7.7 (SD = 1.6) participated in the user study. In the *CollabMaze* condition, we had ten participants (three girls and seven

Figure 3.6: Children are playing in pairs with *CollabMaze*

boys) with a mean age of 7.8 (*SD* = 1.5). In the tablet condition, the other 10 participants (6 girls, four boys) with a mean age of 7.5 (*SD* = 1.8) used the tablet. We got written consent from the participants' parents. Participants could stop whenever they wanted.

Children work in pairs to play the maze game for around 30 mins. 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, verbal and non-verbal interaction, helpfulness, and approach are noted. In advance, possible child behaviors were considered for each item to facilitate observation and evaluate the results later. 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 [143] to measure participants' enjoyment, which has seven items. The Social Interdependence Scales [60] 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 [112] to answer.

Main Findings Participants show no such significant difference regarding their enjoyment and interdependence. However, as shown in Table 3.4, children in the tablet condition used more time to finish the tasks than with *CollabMaze*.

Table 3.4: *T*-test results of *CollabMaze* participants' enjoyment, interdependence, and play time.

	M	*SD*	*t*	*p*
Enjoyment [5-point Likert scale]				
Graphical UI	4.2	0.5	-0.152	.881
Tangible UI	4.2	0.6		
Cooperative interdependence [5-point Likert scale]				
Graphical UI	4.3	0.5	-0.830	.417
Tangible UI	4.1	0.5		
Competitive interdependence [5-point Likert scale]				
Graphical UI	3.6	1.0	-1.029	.317
Tangible UI	3.1	0.7		
Individualistic interdependence [5-point Likert scale]				
Graphical UI	2.6	0.5	-0.626	.539
Tangible UI	2.4	0.6		
Play Time [min]				
Graphical UI	17.2	5.8	-2.412	**<.020**
Tangible UI	11.1	3.4		

We summarized "non-verbal" and "verbal" behaviors. The average frequency of each non-verbal and verbal behavior for each child was recorded in Table 3.5. The results demonstrate that the average frequency of non-verbal behaviors per child is higher in tablet conditions than with *CollabMaze*. In contrast, verbal behaviors are higher with *CollabMaze* than in tablet conditions.

Summary Our investigation revealed three main findings. First, goal interdependent interfaces had high enjoyment and interdependence. Second, tangible interfaces help young children have more ideas for communication and need less time to solve 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.

Table 3.5: Mean frequency of each non-verbal and verbal behavior per child in the *CollabMaze* study.

		Graphical UI	Tangible UI
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

3.2 Tangibles for Shared Attention

This section is based on my published paper [P3] and submitted paper [P10]. I abstracted the main contents to explain how we can design tangible UIs to facilitate shared attention. I chose them for the same reason as positive interdependence projects due to their representativeness.

3.2.1 *FlipCards*

I designed and conducted *FlipCards* study [P10] with one of my bachelor's students. *FlipCards* aimed to create a gamified device for two users to learn English vocabulary together.

Setup *FlipCards* has three components: a smartphone with an Android *FlipCards* application, a flip box, and a lightbox with a moving and health LED bar (see Figure 3.7). The application had an actual flashcard use experience. We designed the flip box to contain the smartphone, whose close and open motions were flipping a "card." The lightbox has two LED strips (moving and health bar), each with 20 LEDs. The lightbox receives data from the smartphone. The LEDs in the moving bar light off individually until the user answers the task. If the answer is correct, one LED in the health bar lights on. From left to right, if the light progress is less than 20%, the LEDs are red; between 20% and 49% is yellow, and above 50% is green. This light coding helps the users better understand the current working progress.

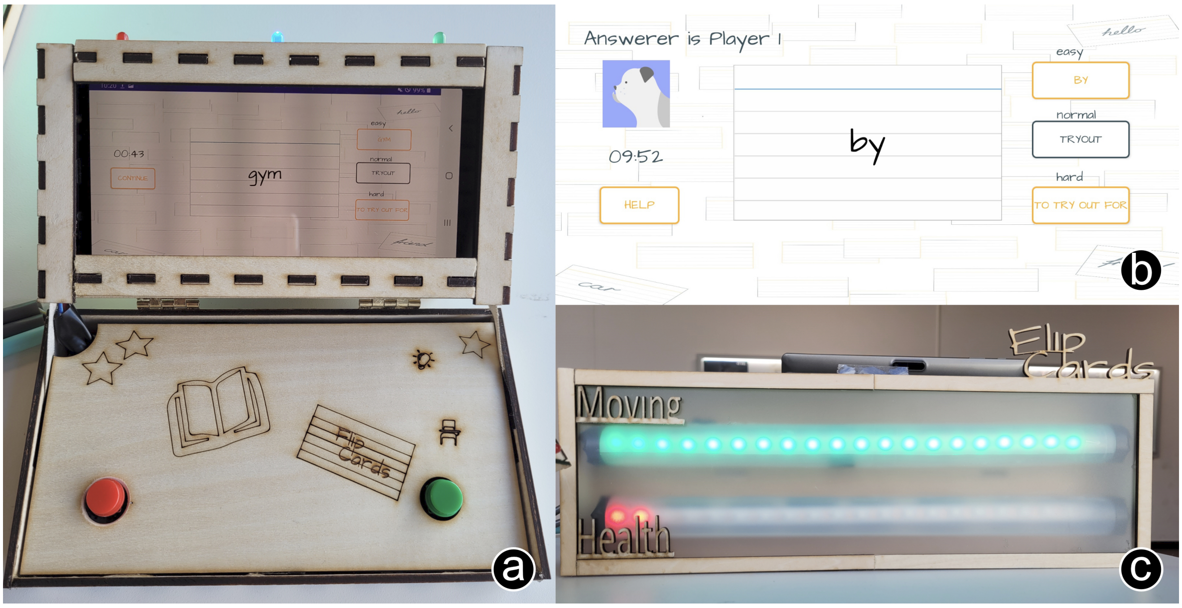

Figure 3.7: *FlipCards* tangible prototype. It contains three parts: **a**) A flip box with an embedded smartphone, two buttons (red and green), and three LEDs (red, blue, and green); **b**) An android application with *FlipCards* English vocabulary learning system. **c**) A lightbox with two LED bars: moving (light-on LEDs will decrease from 20 to 0) and health (light-on LEDs will increase from 0 to 20).

User Study Twenty participants (all female), whose age range was 12–15 ($M = 12.55, SD = 0.83$), attended our user study. All participants were German students and were learning English. They were from the same female secondary school. We intentionally matched participants not in the same class as a pair to avoid its influence on experimental results. We conducted user studies in a quiet study room in this school; each experiment only had two participants and one experimenter. We got written consent from all participants' parents.

The experiment has three processes: **a**) The experimenter introduced the experimental process and collected the consent forms, signed by the participant's parents; **b**) Two participants worked together face-to-face to learn 30 English vocabularies with our tangible prototype *FlipCards* or paper flashcard. The participants' English teacher recommended these vocabularies to us based on the participants' learning progress; **c**) Participants filled out our questionnaire and attended our semi-interviews with audio recordings. Each experiment lasted around 45 minutes.

Study data has three resources: system data, questionnaire, and semi-interview. *FlipCards* system recorded each participant's mistake number for learning English vocabulary. The questionnaire contains concentration (4 items) [42], immersion (4 items) [42], and collaboration (5 items) [135]. All items used 5-point Likert scale with 1 = "*strongly disagree*" and 5 =

"*strongly agree*." The interview has five questions about their user experience by using *FlipCards*. For instance, "*What was your overall experience using FlipCards?*" "*How did you feel FlipCards facilitate your shared attention in collaboration?*" and "*How did you feel FlipCards facilitate your concentration on the task?*" If the participants did not understand the concept, e.g., shared attention, the experimenter would show them an example and explain the meaning until they understood it clearly.

We did not measure shared attention directly, the same for the *Chilego* study (see subsection 3.2.2). Instead, we examined **concentration** [78], **immersion** [18, 102], and **collaboration** [21] to see the effects. We have three reasons: **a**) We aimed to see natural interactions and communications between users. However, users have to wear an eye tracking device to obtain their eye contact, movement, or gaze information [141]; **b**) The tangible devices we designed could track users' behaviors, e.g., interaction frequency and time. It was not the same as shared attention. However, it provided shared attention information because we analyzed it together with observation data [38]; and **c**) Concentration and immersion are important for shared attention [35, 102, 110]. In addition, my prototypes were for improving co-located and remote collaboration. Thus, we considered collaboration as another important factor.

Main Findings The survey results showed that participants' sense of concentration was 4.5 (*SD* = 0.293), immersion was 3.7 (*SD* = 0.568), and collaboration was 3.2 (*SD* = 0.116). Our interviews were semi-structural. Therefore, we coded the answers from the audio interview transcript regarding interview questions. We summarized some representative results from interviews, which came from the discussion and agreement of the experimenter and first author. As seen in Table 3.6, participants' overall experiences are positive for *FlipCards*. Participants felt *FlipCards* having good communication (75%). Lights in the *FlipCards* (95%) gave participants a sense of shared attention. *FlipCards* made the user focus on the partner (85%). Being curious to see the results of flipping motion (85%) made *FlipCards* users feel immersive. Answering answers or mistakes made users sense the collaboration (85%). Finally, the participants gave us some suggestions, such as making the flipping motion more interesting (35%).

Summary My primary findings were: **a**) Students who used *FlipCards* showed a better performance; **b**) *FlipCards* and paper flashcards have similarities in terms of concentration and immersion; **c**) *FlipCards* students had more verbal interaction (especially sharing ideas and providing help) than comparison groups.

3.2.2 *Chilego*

I designed and conducted *Chilego* study [P10] with one of my master's students. *Chilego* is a tangible device to help remote users to learn Chinese writing together.

Setup Each tangible block stands for an indexing component. As shown in Figure 3.8, users can assemble two *Chilego* blocks to make a new Chinese character. We implemented touch

Table 3.6: Representative interview results of *FlipCards*(* % = mentioned participants / all participants).

	Suggestions
Overall Experience	communication (75%), learn English (65%), fun (45%), teamwork (30%), game (30%)
Shared Attention	**timer in the lightbox (95%)**, learning progress in the lightbox (75%), light in the flip box (65%)
Tangible for Shared Attention	physical device in the view (90%), physical interaction changes the status of lightbox (70%), information shows in the physical device (65%)
Concentration	focus on the partner (85%), try to get more lights in the health bar (70%)
Immersion	curious to see the results of flipping motion (85%), look at the partner (75%), wait for the answer (75%)
Collaboration	check the answer (85%)
Suggestion	add English pronunciation (85%), make some light effects, e.g., shining (65%), make the flipping motion more interesting (35%)

sensors at the beginning and end of each stroke. This way, *Chilego* can recognize the writing order. We designed different LED color representations to let the user understand the writing mistakes as shown in Figure 3.9, users can use their finger as a pen to write the Chinese character directly, and the *Chilego* system will give feedback.

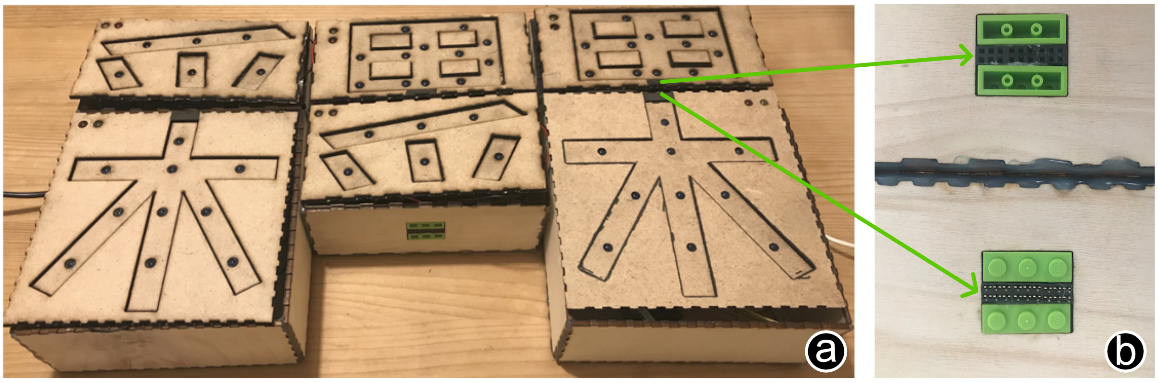

Figure 3.8: *Chilego* technical prototype. **a**) All the technical blocks we developed. It has two sets; each set has three blocks: "爪" (means hand), "田" (means field) and "木" (mean wood). **b**) We can constitute two blocks to create a new character with a male and female Lego connector. For example, we can connect "爪" and "木" to get "采" (means pick up), connect "田" and "木" to get "果" (means fruit).

User Study Twenty participants (ten males and ten females) attended our user study, whose age range was 20–29 ($M = 25.35, SD = 2.41$). All participants had some basic knowledge of Chinese but had never taken Chinese courses. Their mother tongue was German, Italian,

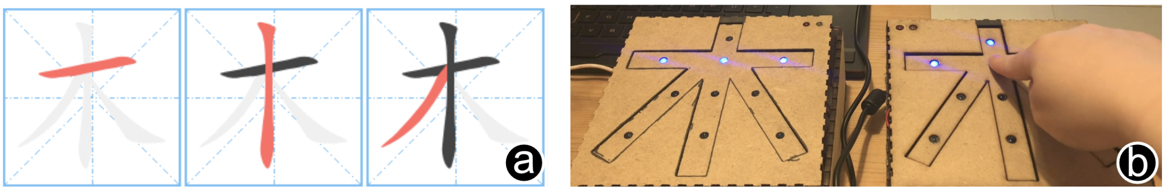

Figure 3.9: The user is using an index finger to write on the *Chilego* block, whose LED feedback will light on automatically. Meanwhile, the remote partner's *Chilego* will show the same light feedback.

Spanish, and French. We intentionally matched participants who did not know each other as a pair to avoid its influence on experimental results. All participants visited the experimenter's house and attended the user study in two rooms. Two participants were remote in each experiment but could talk via video. They practiced Chinese character writing using our tangible prototype *Chilego*, invisible from the video call. We got written consent from participants.

Main Findings The survey results showed that participants' sense of concentration was 4.0 ($SD = 0.194$), immersion was 3.2 ($SD = 0.499$), and collaboration was 3.8 ($SD = 0.211$).

Our interviews were semi-structural. Therefore, we coded the answers from the audio interview transcript regarding interview questions. We summarized some representative results from interviews, which came from the discussion and agreement of the experimenter and first author. As seen in Table 3.7, participants' overall experiences are positive for *Chilego*. Participants felt *Chilego* being interesting (90%). Lights (90%) gave participants a sense of shared attention. *Chilego* participants tried to write correctly (70%). Using the finger to write on the block (75%) made *Chilego* users feel immersive. Checking the answers or mistakes made users sense the collaboration (85%). Finally, the participants suggested making users sense of the common mistake place (40%) by adding haptic feelings.

Summary We got three key findings: **a**) *Chilego* has a positive effect on collaboration; **b**) Users become more immersive after being familiar with the system and their partners. **c**) *Chilego* enables users to have a good learning performance.

3.2.3 *Study Marbles*

I designed and conducted *Study Marbles* study [P3] with two of my master's students. *Study Marbles* is a tangible necklace for remote video group collaboration.

Setup *Study Marbles* contains a hexagonal box and three marbles (see Figure 3.10). The marbles have two functions: **a**) To visualize the users' current status, e.g., their feeling and answer to a task or the status of their work progress. **b**) Moderate group discussion by lighting up the marble of the current speaker. As shown in Figure 3.11, users wear *Study Marbles* in the remote conferencing meeting.

Table 3.7: Representative interview results of *Chilego* (*% = mentioned participants / all participants).

	Suggestions
Overall Experience	interesting (90%), creative (80%), writing practice (75%), learn with the partner (55%)
Shared Attention	**light indication on the block (90%)**, mistakes (75%)
Tangible for Shared Attention	connected physical devices (85%), light feedback on the physical device (75%)
Concentration	try to write correctly (70%), try to remember the partner's mistake (65%)
Immersion	use the finger to write on the block (75%), look at the *Chilego* (65%)
Collaboration	correct the partner's mistake (85%), wait for the partner's mistake (70%)
Suggestion	design some gamification to motivate us to learn (65%), make two users can write at the same time (55%), make users sense the common mistake place (40%), e.g., haptic feeling

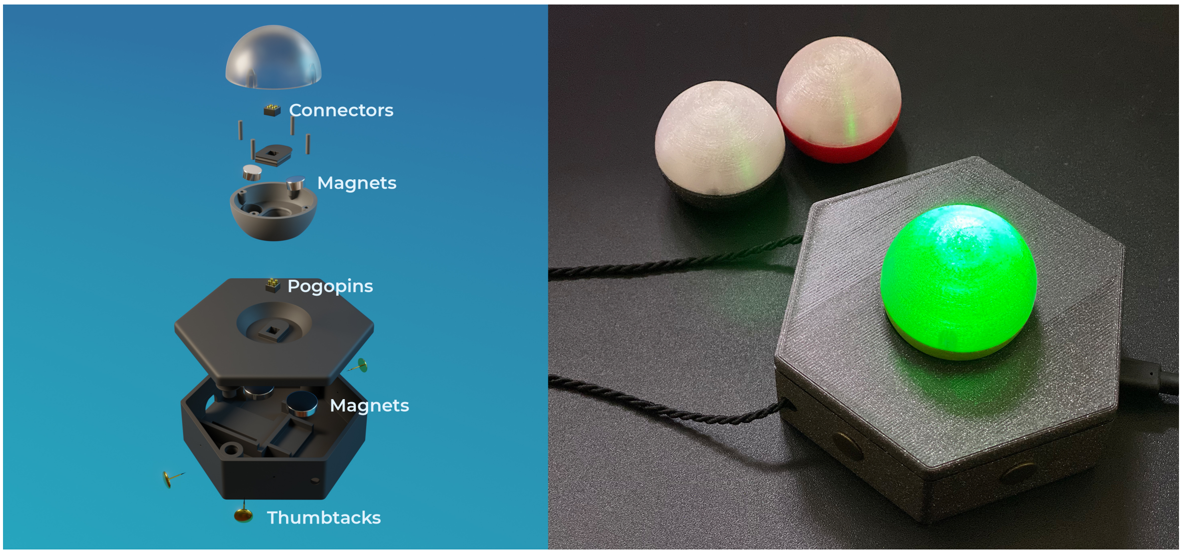

Figure 3.10: **Left**: 3D model render of components; **Right**: *Study Marbles* prototype with an inserted illuminated color marble.

User Study We conducted an online survey and got consent from all participants. Unfortunately, the online format of the survey (due to the pandemic situation) is a limitation of our user study. However, we included detailed videos to show all the functions and text descriptions. We got 41 participants (19 females and 22 males). Eighteen of the 41 participants were 18-24 years old, and ten were 26-34. The rest were 35-74 years old. More than half of them were students. Thirty-five participants had higher education, and 31 used video meetings multiple times a week or more often. The most common reasons for video conferencing were "attending university lectures, classes, and work meetings".

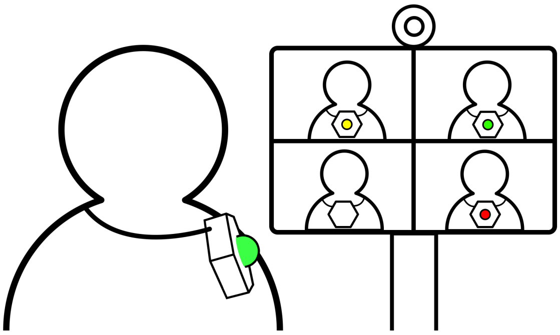

Figure 3.11: Illuminated marbles in the video call show the current status of each call member using traffic light color coding. The participant in the lower left corner has not selected a marble, and the necklace remains empty as the marbles are detachable.

The experiment has three processes: **a**) Participants watch *Study Marbles*'s function video and read its explanations. **b**) If participants have questions, they can ask experimenters to explain them. **c**) Participants fill out the *System Usability Scale* (SUS) [17] and ten questions about their experience. In addition, we have three open questions to get their opinions and suggestions.

Main Findings As seen in Figure 3.12, participants showed their feeling and opinions of *Study Marbles*.

Wearable: 63% of participants liked our wearable design, and 83% thought that the light of the marbles was an excellent way to convey information. On the other hand, participants' opinions were more divided when asked if it is desirable to have a wearable tool for online meetings.

Video meetings: 76% of participants thought they would pay more attention to the video when using *Study Marbles*. However, only 39% thought they would feel more comfortable turning on their video when using *Study Marbles*. The last two questions about video meetings asked if *Study Marbles* could be distracting during video calls. This was approved by almost half of the participants. This raises the question of *Study Marbles* is more likely to distract the users than help. Here, the participants were uncertain, as this is still a very new area, and lacked technology experience.

Collaboration: Regarding *Study Marbles'* effect on collaboration, most participants thought it could make them more willing to participate in group work and help them communicate with group members more effectively. Most agreed that it could make them feel more connected with group members. Overall, *Study Marbles* was rated to impact collaboration positively.

Participants commented: "*I think this is a good way to enforce participation in a lecture setting*", "*Study Marbles is especially advantageous in video conferences with many people to make the participants feel more included*", "*Good idea to make everyone more active in the meeting*".

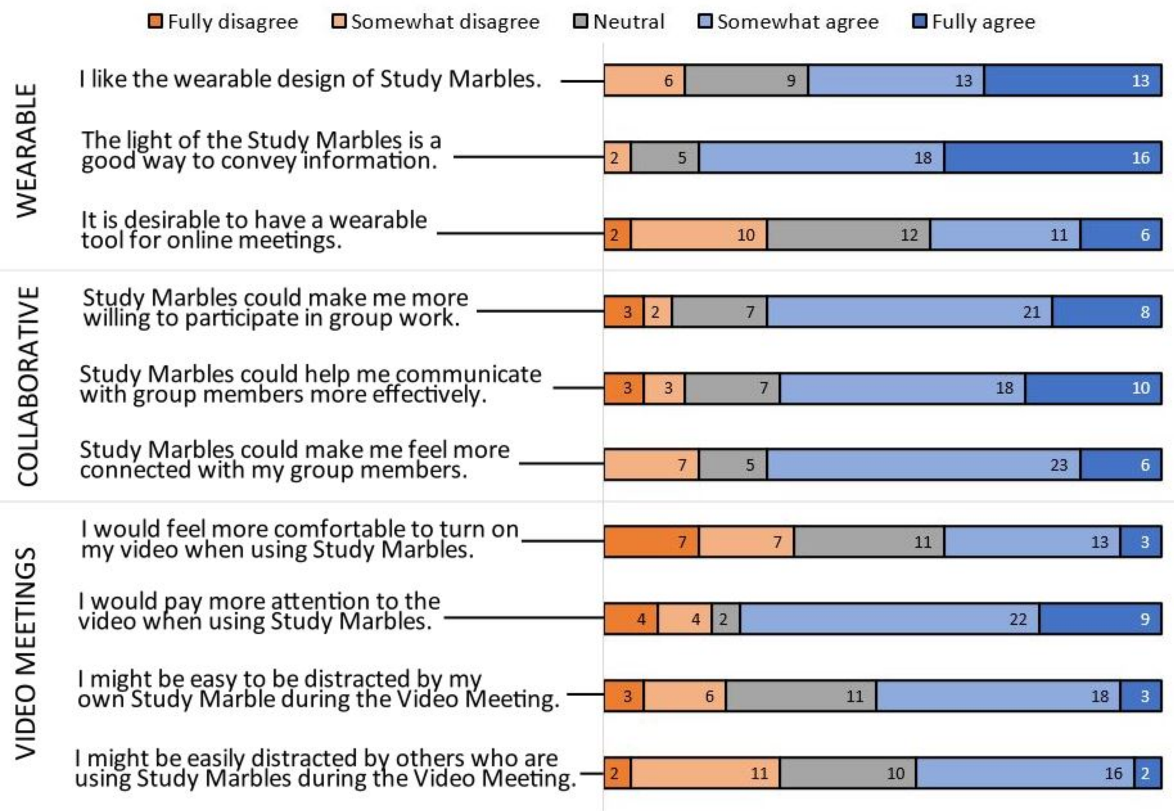

Figure 3.12: Users' experience about *Study Marbles*'s wearable, collaborative and video meeting characteristics.

Summary Making students feel engaged and connected during video meetings is a challenge. In this study, we addressed this problem with a prototype for a wearable user interface called *Study Marbles*. It aimed to create a more social and active sense of remote, collaborative learning in video conferences. *Study Marbles* is a tangible necklace with attachable, illuminated marbles that can be worn during video meetings. In addition, it could visualize students' learning status, moderate group discussions, and enable voting. The user study showed that participants perceived our prototype as an excellent way to create a more active and connected environment and improve group members' interaction in video conferences.

3.3 Designed-based Research Method

I used a design-based research method to develop tangible prototypes in my thesis. All our project developments follow the following steps:

Concept idea → Feedback (with interview) → **Paper prototype development** → Feedback (with interview or paper prototype user study) → **Technical prototype development** → Feedback (with pilot user study) → Technical prototype improvement → **Final user study**

In the concept idea phase, we usually brainstormed the possible users or scenarios which could benefit from positive interdependence and shared attention. For example, we interviewed a kindergarten teacher (61 years old, female) who had worked in the kindergarten for over 25 years. She told us about their exercises with the children and particularly mentioned a card game. This game has many pictures, and the children must find two cards that could match (e.g., hand and glove, garden, and house). We used a similar idea to design our positive interdependence prototype *UnitRry* in [P6], where two children must find cards with a relationship.

In the paper prototype development phase, we usually use paper to build the prototype, which helps us decide the actual prototype's shape, size, and interaction position. In the paper prototype user study, we use the Wizard of Oz experiment [139] to see the effects of interaction designs. To develop the final prototype, we mainly used Arduino or ESP to realize the functions. As shown in Table 3.8, we have a whole design process for each project.

3.4 Takeaways

RQ2: What are the effects of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?

I introduced three projects to show how tangible UIs can support positive interdependence: *SpellBoard*, *MemorINO*, and *CollabMaze*. They have three commons: **a**) Our target users are children; **b**) We designed them for two users to collaborate, and **c**) The study results showed that interactive constraints could be specifically designed to allow children to coordinate their collaborative actions. As you can see from our setups in Figure 3.1, Figure 3.3, and Figure 3.6, we designed **resource interdependence** (e.g., to spell a word in *SpellBoard* must with both blue and orange blocks), **interface interdependence** (e.g., to solve a problem in *MemorINO* must connect the boards owned by both kids), and **interaction interdependence** (e.g., to move the character in the maze game, both kids must control the character).

User studies showed that these interdependence strategies had sound effects. **Overall, participants had reasonable enjoyment, engagement, and collaboration.** In particular, there are three valuable findings: **a**) Participants' cognitive engagement decreased after three experiments; **b**) Similar age groups had better engagement and collaboration; **c**) Compared to tablet condition, a tangible UI made interaction more efficient and communication more.

I introduced three projects to show how tangible UIs support shared attention: *FlipCards*, *Chilego*, and *Study Marbles*. They also have three commons: **a**) Our target users are not children;

Table 3.8: Iterate design processes [8] of shared attention prototypes.

Design Process	***Study Marbles***	***FlipCards***	***Chilego***
Idea:			
Create a shared attention environment for two users to learn collaboratively...	... how to work together effectively	... English vocabulary from German.	... Chinese character writing.
Requirement Elicitation:			
Teacher Interview with...		... one English teacher with 23 years of teaching experience.	... three Chinese teachers with three, five, and seven years of teaching experience.
Design Concept:			
	- Create a "shared attention - tangible interaction - enhanced shared attention" loop.		
	- Two or more users collaborate **remotely**to discuss the project	- Two users collaborate **locally** to learn English vocabulary from German.	- Two users collaborate **remotely** to learn Chinese character writing.
	- The interactive device's light colors and patterns give interaction feedback.	- An ambient light system connects to the interactive device to give interaction feedback.	- The interactive device's light colors and patterns give interaction feedback.
	- **Touch, wave, or press** the device to change the marble color as an indicator	- **Flip** the device to know English from German.	- **Draw** on the device to practice Chinese character writing.
Paper Prototype:			
	Validation of each design with two users in a pilot study of one hour each.		
Technical Prototype:			
	41 participants, each used half an hour	45-minute user study with 20 participants in 10 pairs.	

b) We designed them for two users to collaborate, and **c**) The study results showed light as output could be designed to capture users' attention and guide their interactions. As we can see from our setups in Figure 3.7, Figure 3.8, and Figure 3.10, we designed status light, interactive light, and wearable light to capture user attention in the collaborative task.

The study results showed that these shared attention designs had sound effects. **Overall, participants liked the prototypes and felt good concentration.** In particular, there are three valuable findings: **a**) Compared to a non-tangible setting, a tangible UI created an environment with more communication. For example, *FlipCards* participants showed more idea-sharing and help-providing behaviors. **b**) The collaborative mechanism was not strong. Participants felt the collaboration only by checking the answers for the partner in *FlipCards* study and

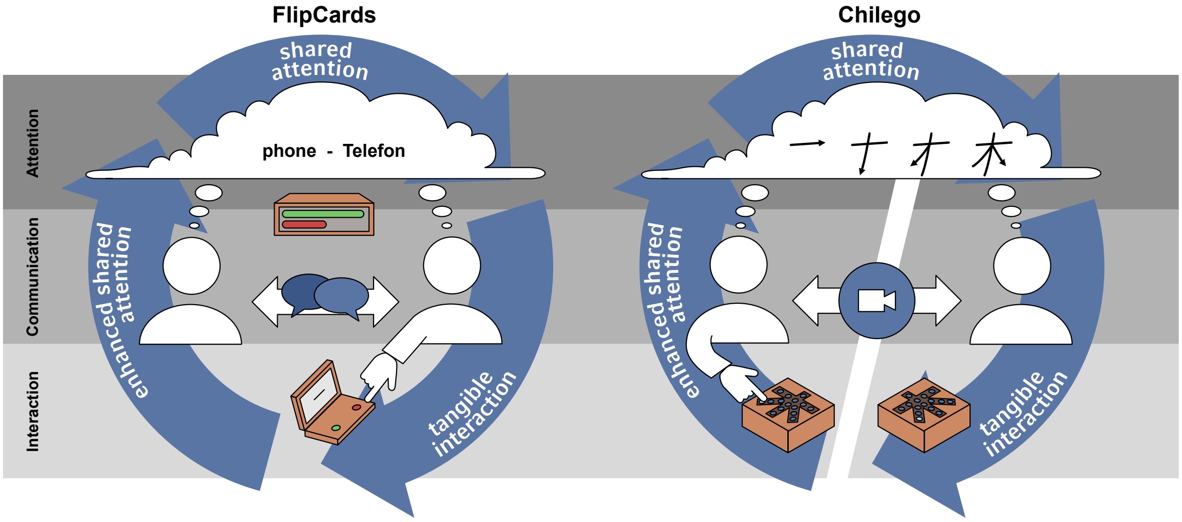

Figure 3.13: *FlipCards* and *Chilego* prototype use scenarios and concept ideas. We aim to create a “shared attention - tangible interaction - enhance shared attention” loop, where users can learn from German to English (e.g., Telefon - phone) using *FlipCards* and Chinese character writing practice with *Chilego*, e.g., write “木” (wood), you need to write in the correct order: “一”, “十”...“木”. In addition, each stroke should also be in the correct order. For instance, when you draw “ 一”, you should draw it from left to right. The system will show you it was wrong writing if it is from right to left.

correcting the partner’s mistakes in *Chilego* study. **c**) Tangible UIs gave participants a good learning performance. As shown in Figure 3.13, we aim to include users in a “shared attention - tangible interaction - enhanced shared attention” loop. The loop might be helpful for users to focus on their tasks and improve their learning performance.

My Published Paper List

[P1] Li, Y., Bachl, N., Dutoit, M., Weber, T., Mayer, S., and Hussmann, H. "Designing Tangible Tools to Engage Silent Students in Group Discussion." In: *2022 International Symposium on Educational Technology (ISET)*. 2022, pp. 286–291. DOI: `10.1109/ISET55194.2022.00067`.

[P2] Li, Y., Balogh, S., Luttringer, A., Weber, T., Mayer, S., and Hussmann, H. "Designing a Tangible Interface to "Force" Children Collaboration." In: *Interaction Design and Children*. IDC '22. Association for Computing Machinery, 2022, pp. 576–582. DOI: `10.1145/3501712.3535280`.

[P3] Li, Y., Bapisch, B., Phu, J., Weber, T., and Hußmann, H. "Study Marbles: A Wearable Light for Online Collaborative Learning in Video Meetings." In: *Human-Computer Interaction – INTERACT 2021*. Ed. by C. Ardito, R. Lanzilotti, A. Malizia, H. Petrie, A. Piccinno, G. Desolda, and K. Inkpen. Springer International Publishing, 2021, pp. 712–721.

[P4] Li, Y., Corz, N., and Marschall, T. "Interactive Metaphor Interfaces for Young Children to Learn Color Mixing and Music Composition." In: *Proceedings of the 16th International Conference on Computer-Supported Collaborative Learning-CSCL 2021*. International Society of the Learning Sciences. 2022, pp. 36–39.

[P5] Li, Y., Dai, J., Wang, X., and Slotta, J. "Active learning designs for Calculus II: a learning community approach for interconnected smart classrooms." In: *International Journal of Smart Technology and Learning* 2.1 (2020), pp. 66–87. DOI: `10.1504/IJSMARTTL.2020.109504`. eprint: `https://www.inderscienceonline.com/doi/pdf/10.1504/IJSMARTTL.2020.109504`.

[P6] Li, Y., Gao, Z., Egger, S., Mayer, S., and Hussmann, H. "Tangible Interfaces Support Young Children's Goal Interdependence." In: *Proceedings of Mensch Und Computer 2022*. MuC '22. Association for Computing Machinery, 2022, pp. 147–157. DOI: `10.1145/3543758.3543782`.

[P7] Li, Y., Harmat, E., Mayer, M., and Ou, C. "Examining Actual Effects of a Tangible Tool on Children's Collaboration." In: *2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. 2022, pp. 582–587. DOI: `10.1109/ISMAR-Adjunct57072.2022.00121`.

[P8] Li, Y., Kothiyal, A., Weber, T., Rossmy, B., Mayer, S., and Hussmann, H. "Designing Tangible as an Orchestration Tool for Collaborative Activities." In: *Multimodal Technologies and Interaction* 6.5 (2022). DOI: `10.3390/mti6050030`.

[P9] Li, Y., Liang, M., Preissing, J., Bachl, N., Dutoit, M. M., Weber, T., Mayer, S., and Hussmann, H. "A Meta-Analysis of Tangible Learning Studies from the TEI Conference." In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '22. Association for Computing Machinery, 2022. DOI: `10.1145/3490149.3501313`.

[P10] Li, Y., Ou, C., Weber, T., Mayer, S., and Strickroth, S. "Exploring Tangible Designs to Facilitate Shared Attention in Co-located and Remote Collaborations." In: *19th International Conference of Technical Committee 13 (Human- Computer Interaction) of IFIP*

(International Federation for Information Processing). INTERACT ’23. Springer International Publishing, Submitted.

[P11] Li, Y., Rossmy, B., and Hußmann, H. “Tangible Interaction with Light: A Review.” In: *Multimodal Technologies and Interaction* 4.4 (2020). DOI: 10.3390/mti4040072.

[P12] Li, Y., Sommerhoff, D., Ufer, S., and Slotta, J. D. “Scripting Small Group Processes within a Learning Community.” In: *Proceedings of the 14th International Conference on Computer-Supported Collaborative Learning-CSCL 2021*. International Society of the Learning Sciences. 2021, pp. 123–130.

[P13] Li, Y., Sun, Y., Lu, T., Weber, T., and Hußmann, H. “GrouPen: A Tangible User Interface to Support Remote Collaborative Learning.” In: *Human-Computer Interaction – INTERACT 2021*. Ed. by C. Ardito, R. Lanzilotti, A. Malizia, H. Petrie, A. Piccinno, G. Desolda, and K. Inkpen. Springer International Publishing, 2021, pp. 590–598.

[P14] Liang, M., Li, Y., Weber, T., and Hussmann, H. “Tangible Interaction for Children’s Creative Learning: A Review.” In: *Creativity and Cognition*. Camp;C ’21. Association for Computing Machinery, 2021. DOI: 10.1145/3450741.3465262.

4
DISCUSSION

> *As an experience occurs (e.g., easing into a chair), the brain captures states across the modalities and integrates them with a multimodal representation stored in memory (e.g., how a chair looks and feels, the action of sitting, introspections of comfort and relaxation). Later, when knowledge is needed to represent a category (e.g., chair), multimodal representations captured during experiences with its instances are reactivated to simulate how the brain represented perception, action, and introspection associated with it.*
>
> **– Barsalou [10] (pp. 618-619)**

This chapter aims to show the insights on **RQ3**. I reflected on the projects in chapter 3 and proposed three topics: **a**) Embodied facilitation for scripting and orchestrating collaboration; **b**) Expressive representation for guiding and facilitating joint action; and **c**) Manipulating and creating resources with appropriate task difficulties and intuitive actions.

4.1 Embodied Facilitation for Scripting and Orchestrating Collaboration

Reflecting on my studies about tangible UIs for positive interference (i.e., *SpellBoard* [P7], *MemorINO* [P2], and *CollabMaze* [P6]), I would like to discuss: **a**) Tangible UI as a representation of collaborative practices; **b**) Communication, interactivity, and task solving with tangible interfaces; and **c**) Manipulating and creating resources with appropriate task difficulties and intuitive actions.

4.1.1 Tangible as a Representation of Collaborative Practices

Traditional computer-supported 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 aim to create a communicative or feedback environment. However, only having such an environment could not make collaboration happen automatically. Users are hard to engage in collaborative processes without guidance, we need to design a configuration of knowledge components and representations for collaborative practices [37]. Therefore, I considered both knowledge and interactive representations in my studies [P2, P7].

A collaborative physical environment could reduce users' cognitive loads and make interactive feedback easier to perceive. I used letter blocks (see our study in *SpellBoard* [P7]) and physical cards (see our study in *MemorINO* [P2]) to represent knowledge. Interactions with such tangible objects embodied a flexible error-and-trial process, which gave users instant feedback. In addition, it had constrained interactions between two users. Thus, they could have an interdependent collaboration. The benefits of using tangible UIs as a representation are **a**) It was easier to create a collaborative environment for users to communicate and interact, which came from hands-on participants; **b**) Trial-and-Error was more evident for users to perceive, which reduced their external cognitive loads and could focus more on task knowledge; **c**) Some basic interactive modes could be designed on purpose to facilitate collaborative behaviors. In other words, we could create specific constraints to "force" users to coordinate actions, which foster group awareness and cooperation. Such constraints could mean reliance on interactions that must be coordinated or on structures encouraging reciprocal helping.

I also found some challenges to promoting such collaboration with tangible UIs. First, sometimes users did not comply with the initial design concepts, e.g., they mixed the blue and orange letter blocks in our *SpellBoard* study [P7]. Thus, we should be open to diverse, flexible interaction options. Second, learning tasks were constrained by tangible UIs. For example, *SpellBoard* [P7] and *MemorINO* [P2] was suitable for sequence or order tasks, e.g., spelling. However, adapting to non-linear or longer sequence tasks might be challenging. Third, the collaborative mode was constrained by physical designs. Our tangible UIs were designed for two users. Extending the original design to include more users would not be difficult. However, physical space configurations need to be reconsidered. Finally, most of our users understood the interaction designs, but it might take some time. For example, in our *SpellBoard* study [P7] (more detailed information in subsection 3.1.1), participants had a good and stable understanding of the interaction designs until they played on the third time.

4.1.2 Communication, Interactivity, and Task Solving with Tangible UIs

Tangible UIs users showed more oral communication and better efficiency but more mistakes in solving the task. That means tangible users have different collaborative styles. For example, *CollabMaze* [P6] study's observation data indicated that participants in the tablet condition had more non-verbal behaviors while showing more verbal behaviors using tangible interfaces. It might be because participants who used the physical object as the input device to complete the task were more possessive. In other words, they did not want their physical device to be grabbed by their partner. Thus, verbal communication was more common in the tangible condition. 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 participants to communicate their ideas in a positive interdependence context.

In the tangible condition, we also found that tangible users took less time to finish the tasks than tablet users. We summarized three reasons for this result: Participants had different interactive spaces. In the tablet condition, the participants had less interactive space. For example, it is difficult for two participants to drag and drop the virtual buttons on the tablet simultaneously (see our *CollabMaze* study [P6]). Participants need to manipulate them in a limited space. However, participants are more flexible with tangible objects to work in the tangible condition. Second, participants had different interactive feedback. For example, *CollabMaze* tablet application has no tactile feedback by pressing virtual buttons, but physical objects are more intuitive to control without glancing while looking at the screen. Participants can perceive the input by interacting with the physical object, saving manipulation time. Finally, tangible interfaces have 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 physical device can do everything. Most participants can fully control the physical device with one hand, whereas the tablet application's three buttons must be used simultaneously with two hands.

Finally, participants in the tangible conditions showed higher interactivity and made more errors but used less time to finish the tasks (see my study in [P6]). These results imply that tangible UIs might be an efficient tool for helping participants engage in the task. As we know, participants, particularly young children, are easily distracted. The distraction could come from the device itself or learning environments. Traditional learning tools, e.g., tablets and smartphones, can distract participants from working together. In the long term, it would influence their concentration. Tangible technology can design interactive mechanisms and have participants focus more on the tasks. In our studies, the participants 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 better affordance.

4.1.3 Tangible Interactive Space and Affordance for Goal Interdependence

Collaboration on a touch screen is limited due to 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 tangible UIs because tangible objects could give users more interaction space and affordance. The findings show that the graphical UIs condition always took longer than tangible UIs to finish the same tasks. One main reason was users in the tangible condition had specific physical objects to put or control. In addition, they worked on a "bigger" and "independent" space without mutual interference. Therefore, having enough interaction space and good affordance is essential for a goal interdependence activity. Interactive space gives users more flexibility and chances to communicate orally and use more body movements.

Creating an environment with exciting technologies, e.g., interactive or touch table, virtual reality, is more expensive. However, tangible technology is promising for building a spacious interactive environment. In addition, tangible UIs offer good affordance. In other words, we could design the quality or property of a tangible object that defines its interdependent uses. For example, two participants had different tangible blocks in our *SpellBoard* [P7] study. Each task required cards from both of them. In our *CollabMaze* study [P6], one user controls up and down movements, while the other controls left and right directions. Such interdependent design elements provide good affordance for creating a collaborative learning environment.

4.2 Expressive Representation for Guiding and Facilitating Joint Action

Reflecting on my studies (i.e., *FlipCards* [P10], *Chilego* [P10], and *Study Marbles* [P3]) about tangible UIs for shared attention, I would like to discuss: **a**) Using visualizations to motivate users to take action for collaboration; **b**) Shared attention design for co-located and remote collaboration, and **c**) Creating a "attention - action - enhanced attention" loop for collaboration.

4.2.1 Using Visualizations to Motivate Users to Take Action for Collaboration

Shared attention on an object or content can deepen the collaborative processing of that object or content, amplifying its impact on users' cognition and affect. Collaboration works best only under certain conditions [30] (e.g., appropriate feedback and support), and shared attention is strongly associated with co-located or remote settings. Collaboration without shared attention is inefficient and frustrating because users quickly fail to engage and build on one another's contributions [124]. However, creating shared attention environments for collaboration is challenging. Researchers developed mutual real-time gaze representations, shared gaze visualization, and augmented reality gaze to facilitate shared attention in collaboration. They attempted to visualize output information of share attention to help users be aware of the group process. It is helpful if users have a common understanding of the visualized outputs and make it a peripheral-vision awareness display; however, if such visualizations indicate users' different engagements or are challenging to understand, which might distract them from collaboration.

My students and I designed and developed two tangible interfaces, *FlipCards* [P10] for co-located collaboration and *Chilego* [P10] for remote collaboration, to facilitate embodied interaction as inputs to influence shared attention as an output in collaboration. We did four design iterations from theory foundations and design principles and conducted user studies with 40 participants. Unlike previous studies that mainly focused on visualizing gaze information, I also aimed to use visualizations to motivate users to take action. In other words, I sought to involve users in a "*attention - action - enhanced attention*" loop to improve the collaborative experience. The analysis results show three key findings: First, creating a "shared attention - tangible interaction - enhanced shared attention" loop is essential to improve users' collaborative experience. Second, all participants perceived high concentration; Finally, co-located participants sensed high concentration and immersion, and remote users showed good collaboration. From an HCI perspective, I provided practical solutions to improve users' shared attention in collaboration. Future researchers can refer to my design processes as guidance for designing other interfaces for new scenarios.

4.2.2 Shared Attention Design for Co-located and Remote Collaboration

Two main findings from my quantitative data analysis in [P10] exist. The first key finding is that co-located designs showed good concentration and immersion. I conjecture that three reasons could result in it. First, *FlipCards* is an integrated environment independent of computer-mediated communication. However, remote users must communicate by observing the *Chilego* and talking in the video call. Maybe such a context, where users interact in a physical environment but with computer-mediated communications, distracts and separates users. Second, co-located scenario uses one object to attract users' shared attention. Besides peeping on the lightbox, users also have eye contact, which might facilitate their concentration and immersion. However, remote design has two objects. Even though the light feedback in one device synchronizes with the other, participants might understand or perceive such synchronization as information visualization and not an immersive experience. Finally, face-to-face is inherently better than a synchronous video call to make users concentrate and immerse because face-to-face has the highest presence. As Witmer et al. [151] proposed, concentration and immersion were two essential components of presence.

The second key finding is that remote designs showed good collaboration. The interview results also approved it. During the interview, *FlipCards* participants mentioned that they perceived collaboration as checking vocabulary answers for the partner. However, *Chilego* participants also expected to know and remember their partner's mistakes to avoid their own mistakes. Therefore, this result might occur due to the differences in task collaborative requirements. In addition, we only measured participants' subjective perceptions of collaboration in general. It might be inaccurate because what we care about is the shared attention on collaboration. Measuring such a concept is complex, but we should consider the differences.

To improve the design, I can propose three valuable reflections: **a**) *What are the differences between a "joint" view from two co-located users looking at the same object and a "shared" view from two remote users looking at different objects but has the synchronous information?* The information shown through the objects is the same in the above two situations. Therefore, their information perceptions are similar. However, joint view facilitates eye contact, which might increase the shared attention; **b**) *What are the differences between receiving an output of tangible interactions from a different device and the same one? How do such differences affect users' concentration and immersion?* My findings show that participants who received tangible interaction output from a different device felt better concentration and immersion. It might imply that the separation between action and vision helps users to be more concentrated and immersive; **c**) *What are the collaboration differences between a co-located setting with a shared device and a remote location with synchronous devices, repressively?* Our results showed that a remote environment with synchronous devices was suitable for collaboration. In other words, object ownership and a sense of control might facilitate collaboration.

4.2.3 Creating a "Attention - Action - Enhanced Attention " Loop for Collaboration

We wanted to involve users in a "shared attention - tangible interaction - enhanced shared attention" loop to improve their collaborative experience. Our approach was to enrich the physical action and the inherent "feedback →" and "feedforward ←" [20] to allow richer couplings between action and shared attention. In our *FlipCards* study [P10], the flipping interaction is connected to a lightbox to show the timer and performance information. We used the timer to push the users to take action (←), which on the other way around, also made them have to inspect the lightbox (←). Therefore, 95% of participants mentioned that the timer showing in the lightbox helped them create shared attention. We received similar interview feedback in our *Chilego* study [P10]. We implemented LED lights in the Chinese character groove to indicate whether the writing was correct or wrong. Ninety percent of participants used such indications to remember the mistake (←) and confirm the action (→). In addition, the physical device in sight and tangible interaction were two highly mentioned tangible properties for shared attention. The above results are consistent with our design rationales: leveraging the ambient light into physical properties to convey essential information for tangible interaction.

Our studies in [P10] are like a probe of the representative output for the "shared attention - tangible interaction - enhanced shared attention" loop. The user study results confirm some of our design assumptions, e.g., physical and visual design. However, we still need more deliberate studies to narrow the design differences and their effects. My studies show that the following three questions deserve future work. **a**) Which main factor facilitates shared attention? Is it interaction output or information output? **b**) What else could be considered an appropriate output to enable the shared attention except for ambient lights? For example, can we design movement, haptic, heat, or coldness to improve users' shared attention experience? **c**) Do other tangibilities (e.g., deformation, conduction, and connection) also affect the shared attention experiences? If yes, what are the rationales? In our studies, we mainly explored process visualization and used it to create "*the experience of attending to the information that matters*." However, if tangibility involves, the design rationales might need to change because it is beyond visual feedback but also physical perception.

4.3 Physical Space, Embodied Interaction, and Collaboration

From a deeper conceptual level, I would like to discuss the values of tangible UIs for collaboration: **a**) Object-driven perception to improve collaboration; **b**) Embodied facilitation as design decisions to support collaboration; and **c**) Manipulate and create resources with appropriate task difficulties and intuitive actions.

4.3.1 Object-driven Perception to Improve Collaboration

Collaboration is an inherent object-driven process. Authentic tasks and physical materials in the real world enable users to concrete their imagination and creative ideas into a solid form and finally change reality. In other words, tangible UIs make users better understand abstract concepts in an authentic context and implement the knowledge they have learned into practice. In a collaborative context, such object-driven perceptions become even more beneficial because they reduce the requirements for common understanding. As designers, we can design the object forms, e.g., shape, color, texture, indicator, and meaning, to scaffold users to take actions and inherent the interactive implications. For example, in our *SpellBoard* study [P7], we had the LED feedback indicator at each block's left top. It can reduce the misunderstandings of some letters, such as "M" and "W". We can also design different block shapes to decrease the irrelevant intervenes and focus on internalizing knowledge. Finally, it is worth mentioning that design might also restrict the interaction. Therefore, **we should be aware to see and understand the pros and cons of tangible interaction**.

In addition, different materials, especially familiar ones, trigger the potential of users' actions in an unexpected situation. For example, as a playful material, slime can visualize traces of use in users' interactive behavior. I did not introduce it in chapter 3 but did a metaphor interface with the slime in [P4]. It showed good potential to explore how materials can scaffold our knowledge and understanding. It is an actual interactive experience with tangible technologies. Significantly, tangible UIs could increase users' perception of space and time by presenting the invisible micro-world and showing long-term slow changes quickly within a limited time.

4.3.2 Embodied Facilitation as Design Decisions to Support Collaboration

There is the proximal and full embodiment. Full embodiment is the most restrictive case where the "user provides input and receives output from the same tangible object" [82, p. 6]. Whereas proximal embodiment only has the input to be tangible. Learning sciences states that knowledge and mental concepts do not exist "irrespective of the organisms who apprehend them" but are rooted in the "situated, spatial-dynamical, kinesiological, and somatic phenomenology of the person" [1, p. 301]. In this sense, acquiring knowledge, i.e., the learning process, is a multimodal process with a somatic component. Embodied systems can facilitate and enhance this process. Hornecker [54, p. 145] suggested that *embodied facilitation* can be used to tie embodied system features to the pedagogical notion of learning as a somatic process. Embodied systems can be designed to enforce social configurations and guide users' behavior by facilitating some movements and hindering others. Therefore, they shape how we collaborate; they can induce us to collaborate or make us refrain from collaboration.

We can understand embodied facilitation as a set of design choices explicitly using physical and spatial surroundings and restrictions to support the bodily dimension of learning and synchronous collaboration. Users can physically engage in the tangible collaborative environment. In the physical setup, users tend to participate together more, which facilitates in-group collaboration and participation in activities. A shared tangible UI makes group members better aware of the group process and feedback. For example, some designs for peripheral interactions can reduce cognitive loads. In our *FlipCards* [P10] and *Chilego* [P10] studies, we designed peripheral information visualization to help users to take actions for better collaboration.

4.3.3 Manipulating and Creating Resources with Appropriate Task Difficulties and Intuitive Actions

The increasing diversity of resources can inspire ideas, while limited choices can help users focus on collaboration. Therefore, we should avoid too much or too complicated computational-enriched medium, which might frustrate users with little knowledge. For example, all my tangible designs for positive interdependence (i.e., *SpellBoard* [P7], *MemorINO* [P2], and *CollabMaze* [P6]), we simplified resource designs on purpose to have an appropriate task difficulty for participants. It was mainly because our participants were children, which was a necessary consideration for them. However, it also applies to other users because we design the resources to scaffold users to collaborate, not to increase their external cognitive loads. For example, if our target users have protanopia, we should avoid using red and blue colors in the design of tasks or physical appearance.

Tangible UIs could shorten the distance between interaction input and output and allow users to manipulate and create things with more unconscious and intuitive actions. It is a unique characteristic of tangible UIs to have an intuitive interaction. Therefore, we should particularly consider such design advantages facilitating collaboration. We can think with interactive metaphors and gamification to have intuitive actions. For example, in our *FlipCards* [P10], we stimulated the flashcard actions to engage users in the process. Because such "flip" action connects the user with their existing learning experience. In addition, the lightbox with an exciting and easy-understanding design also helps users concentrate on their tasks.

4.4 Limitations

It is worth discussing that my current studies have four limitations: First, we tested positive interdependence tangible prototypes (i.e., *SpellBoard* [P7], *MemorINO* [P2], and *CollabMaze* [P6]) only with children. The same is for shared attention tangible prototypes (i.e., *FlipCards* [P10], *Chilego* [P10], and *Study Marbles* study [P3]), whose participants were not children. Such inconsistency in experimental design might influence the generalization of our study results. In other words, we might need to redesign some of our interactions or interfaces when our target user groups change. Let us take *SpellBoard* as an example, a tangible device for children to learn German spelling. Some adults, e.g., international students, might also be interested in using it. However, we might need to redesign the graphic UI because we currently use children-friendly and cartoon designs. For adults, it might be better to use more life-related scenarios.

Second, my thesis title is "Tangible User Interfaces to Support Collaborative Learning". However, it does not explicitly describe how my thesis improves "learning"; instead, it is more for collaboration. Learning is mentioned, and most prototypes have a learning context. Unfortunately, it is neither defined nor specific learning properties that are elaborated explicitly that should be supported. From a learning science perspective, my research might fail to meet their expectations.

Third, we only did lab studies and did not test our prototypes in a naturally collaborative environment, e.g., group work in the classroom or working place. In a lab study, the motivation for users to use the prototypes was not intrinsic. The users rely more on extrinsic motivations, e.g., interest in new technology, to participate in the activities. Such differences might affect experimental results, such as the novelty effect and a high sense of immersion. This might also influence the generalization of our study results.

Finally, we provided a design process from theory foundation to prototype development without specific decision-making descriptions. We consistently get feedback from the targeted users or their related persons by conducting multiple user studies. Therefore, our guidelines act more likely as a design framework, not a handbook. However, suppose future researchers want to develop a new tangible UI for a new context. In that case, they will still encounter problems, such as not knowing how to design the interaction and collaborative activities.

4.5 Takeaways

RQ3: What are the implications of tangible user interfaces embedded with positive interdependence or shared attention on collaboration?

When a tangible UI is embedded with **positive interdependence** for collaboration, there are three mechanisms: **a**) an interactive and physical space for interdependence, **b**) physical representation with knowledge externalization for collaboration, and **c**) resource, interface, and interaction interdependence.

When a tangible UI is embedded with **shared attention** for collaboration, there are three mechanisms: **a**) a connected interactive space, **b**) information and interaction visualization to attract users' attention and **c**) an interactive loop from attention to action.

In general, physical space and embodied interaction are two typical characteristics of tangible UIs. In addition, to improve collaboration, tangible UIs provide object-driven perception, embodied facilitation, and intuitive interaction.

5
CONCLUSION

> *Representations are stand-ins for actual objects. An agent is in continuous contact with the object with which it needs to interact. If an agent is in continuous contact with the objects with which it needs to interact, then it doesn't require stand-ins for these objects.*
>
> **– Shapiro [129] (p. 191)**

Collaboration without scripting and orchestration is hard to be successful. Technologies, especially tangible UIs, show good advantages in supporting collaboration. My thesis explored how we can design and develop tangible UIs for collaboration. Initially, I investigated tangible design space for collaboration. Then, from theory, design principles, and method, I showed how to design and develop tangible UIs for positive interdependence and shared attention, which is essential for good collaboration.

By presenting three projects for positive interdependence and three for shared attention, I got **two key findings**: First, participants in our positive interdependence projects had reasonable enjoyment, engagement, and collaboration. Tangible UIs with positive interdependence design imply: **a**) an interactive and physical space for interdependence, **b**) physical representation with knowledge externalization for collaboration, and **c**) resource, interface, and interaction interdependence. Second, participants in the shared attention projects liked the tangible prototypes and had good concentration. Tangible UIs with shared attention design implies **a**) a connected interactive space, **b**) information and interactive visualization to attract users' attention, and **c**) an interactive loop from attention to action.

My thesis dug into rationales and actual developments of tangible technologies to benefit collaboration. My research results show how tangible design can improve the collaborative experience. Overall, my doctoral thesis has three contributions. First, I provided a design space framework for tangible UI designs and elaborated practical design guidelines (from theory, principle, and approach to actual prototype development). Second, my students and I designed and developed sixteen tangible prototypes to see the real effects of tangible UIs. Finally, I discussed the insights of tangible mechanisms for positive interdependence and shared attention.

Collaboration is a big topic. My thesis study only investigated positive interdependence and shared attention in collaboration. For future work, we can also consider other potentials of tangible UIs for collaboration, such as **object ownership, interpersonal connectedness, and tangible interaction in virtual reality**. Unlike other interfaces, object ownership is a unique feature of tangible UIs. Users not just interact with it but also sense having it. Except as a tool, we can also design tangible UI as wearable devices, which is helpful for ubiquitous collaboration. In addition, tangible UIs are suitable for creating personal connectedness between users, especially for remote collaborative users. In the future, remote collaboration will become more and more common. Therefore, it is essential to improve the remote collaboration experience, where the users do not just rely on video conferencing systems or collaborative online platforms to collaborate. Furthermore, tangible UIs have unique advantages to being a remote group orchestration tool. Finally, virtual reality opens a new world for users to collaborate with more and more applications. However, the interaction in virtual reality is still mainly by controlling handles. It is appropriate for some scenarios, such as handle-based interaction in the game. However, tangible UIs might provide good potential if the interaction needs specific interfaces or haptic feedback. Therefore, tangible interaction in the virtual is an exciting research topic.

List of Figures

List of Tables

References

[1] Abrahamson, D. and Lindgren, R. “Embodiment and Embodied Design.” In: *The Cambridge Handbook of the Learning Sciences*. 3rd ed. Cambridge Handbooks in Psychology. Cambridge University Press, 2022, pp. 301–320. DOI: 10.1017/9781108888295.019.

[2] Akkil, D., Thankachan, B., and Isokoski, P. “I See What You See: Gaze Awareness in Mobile Video Collaboration.” In: *Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications*. ETRA ’18. Association for Computing Machinery, 2018. DOI: 10.1145/3204493.3204542.

[3] Alavi, H. S. and Dillenbourg, P. “An Ambient Awareness Tool for Supporting Supervised Collaborative Problem Solving.” In: *IEEE Transactions on Learning Technologies* 5.3 (2012), pp. 264–274. DOI: 10.1109/TLT.2012.7.

[4] Alavi, H. S., Dillenbourg, P., and Kaplan, F. “Distributed Awareness for Class Orchestration.” In: *Learning in the Synergy of Multiple Disciplines*. Ed. by U. Cress, V. Dimitrova, and M. Specht. Springer Berlin Heidelberg, 2009, pp. 211–225.

[5] Anderson, T. and Shattuck, J. “Design-based Research: A Decade of Progress in Education Research?” In: *Educational Researcher* 41.1 (2012), pp. 16–25.

[6] Antle, A. and Wise, A. “Getting down to details: Using learning theory to inform tangibles research and design for children.” In: *Interacting with Computers* 25 (2013), pp. 1–20. DOI: 10.1093/iwc/iws007.

[7] Antle, A. N., Bevans, A., Tanenbaum, T. J., Seaborn, K., and Wang, S. “Futura: Design for Collaborative Learning and Game Play on a Multi-Touch Digital Tabletop.” In: *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’11. Association for Computing Machinery, 2010, pp. 93–100. DOI: 10.1145/1935701.1935721.

[8] Antle, A. N. and Wise, A. F. “Getting Down to Details: Using Theories of Cognition and Learning to Inform Tangible User Interface Design.” In: *Interacting with Computers* 25.1 (2013), pp. 1–20. DOI: 10.1093/iwc/iws007.

[9] Baldassarri, S., Passerino, L., Ramis, S., Riquelme, I., and Perales, F. J. “Videogame-Based Case Studies for Improving Communication and Attention in Children with ASD.” In: *Proceedings of the XIX International Conference on Human Computer Interaction*. Interacción 2018. Association for Computing Machinery, 2018. DOI: 10.1145/3233824.3233846.

[10] Barsalou, L. “Grounded cognition.” In: *Annual Review of Psychology* 59.1 (2008), pp. 617–645.

[11] Baudisch, P., Becker, T., and Rudeck, F. “Lumino: Tangible Blocks for Tabletop Computers Based on Glass Fiber Bundles.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’10. Association for Computing Machinery, 2010, pp. 1165–1174. DOI: 10.1145/1753326.1753500.

[12] Baurley, S., Petreca, B., Selinas, P., Selby, M., and Flintham, M. “Modalities of Expression: Capturing Embodied Knowledge in Cooking.” In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’20. Association for Computing Machinery, 2020, pp. 785–797. DOI: 10.1145/3374920.3375005.

[13] Beutelspacher, A. Kryptologie: Eine Einführung in die Wissenschaft vom Verschlüsseln, Verbergen und Verheimlichen. Ohne alle Geheimniskrämerei, aber nicht ohne hinterlistigen Schalk, dargestellt zum Nutzen und Ergötzen des allgemeinen Publikums. Friedr. Vieweg & Sohn Verlag, 2007, p. 10. DOI: 10.1007/978-3-658-05976-7.

[14] Bigelow, A. E. “The Development of Joint Attention in Blind Infants.” In: *Development and Psychopathology* 15.2 (2003), pp. 259–275. DOI: 10.1017/S0954579403000142.

[15] Brennan, S. E., Chen, X., Dickinson, C. A., Neider, M. B., and Zelinsky, G. J. “Coordinating Cognition: The Costs and Benefits of Shared Gaze During Collaborative Search.” In: *Cognition* 106.3 (2008), pp. 1465–1477. DOI: https://doi.org/10.1016/j.cognition.2007.05.012.

[16] Brewer, J., Williams, A., and Dourish, P. “A Handle on What’s Going on: Combining Tangible Interfaces and Ambient Displays for Collaborative Groups.” In: *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*. TEI ’07. Association for Computing Machinery, 2007, pp. 3–10. DOI: 10.1145/1226969.1226971.

[17] Brooke, J. “SUS: A Quick and Dirty Usability scale.” In: *Usability Evaluation in Industry* 189 (1995).

[18] Brown, E. and Cairns, P. “A Grounded Investigation of Game Immersion.” In: *CHI ’04 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’04. Association for Computing Machinery, 2004, pp. 1297–1300. DOI: 10.1145/985921.986048.

[19] Butterworth, G. and Jarrett, N. “What Minds Have in Common is Space: Spatial Mechanisms Serving Joint Visual Attention in Infancy.” In: *British Journal of Developmental Psychology* 9.1 (1991), pp. 55–72. DOI: https://doi.org/10.1111/j.2044-835X.1991.tb00862.x.

[20] Cathcart, A., Greer, D., and Neale, L. “Learner-focused evaluation cycles: facilitating learning using feedforward, concurrent and feedback evaluation.” In: *Assessment & Evaluation in Higher Education* 39.7 (2014), pp. 790–802. DOI: 10.1080/02602938.2013.870969. eprint: https://doi.org/10.1080/02602938.2013.870969.

[21] Cha, Y., Nam, S., Yi, M. Y., Jeong, J., and Woo, W. “Augmented Collaboration in Shared Space Design with Shared Attention and Manipulation.” In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST ’18 Adjunct. Association for Computing Machinery, 2018, pp. 13–15. DOI: 10.1145/3266037.3266086.

[22] Chen, R., Chen, P.-J. (, Feng, R., Liu, Y. (, Wu, A., and Mazalek, A. “SciSketch: A Tabletop Collaborative Sketching System.” In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’14. Association for Computing Machinery, 2014, pp. 247–250. DOI: 10.1145/2540930.2540973.

[23] Cheng, S., Wang, J., Shen, X., Chen, Y., and Dey, A. "Collaborative Eye Tracking based Code Review Through Real-time Shared Gaze Visualization." In: *Frontiers of Computer Science* 16.3 (2021), p. 163704. DOI: 10.1007/s11704-020-0422-1.

[24] Chew, L., Cochrane, K. A., Hespanhol, L., and Loke, L. "Sounds of Infinity: Playful Illusions with Performative Interaction." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. Association for Computing Machinery, 2020, pp. 669–675. DOI: 10.1145/3374920.3375289.

[25] Collazos, C. A., Guerrero, L. A., Pino, J. A., and Ochoa, S. F. "Collaborative Scenarios to Promote Positive Interdependence among Group Members." In: *International Conference on Collaboration and Technology*. Springer. 2003, pp. 356–370.

[26] D'Angelo, S. and Gergle, D. "Gazed and Confused: Understanding and Designing Shared Gaze for Remote Collaboration." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Association for Computing Machinery, 2016, pp. 2492–2496. DOI: 10.1145/2858036.2858499.

[27] D'Angelo, S. and Schneider, B. "Shared Gaze Visualizations in Collaborative Interactions: Past, Present and Future." In: *Interacting with Computers* 33.2 (2021), pp. 115–133. DOI: 10.1093/iwcomp/iwab015.

[28] Deng, X., Wang, D., and Jin, Q. "CoProStory: a tangible programming tool for children's collaboration." In: (2019).

[29] Dillenbourg, P. and Evans, M. "Interactive Tabletops in Education." In: *International Journal of Computer-Supported Collaborative Learning* 6.4 (2011), pp. 491–514. DOI: 10.1007/s11412-011-9127-7.

[30] Dillenbourg, P., Järvelä, S., and Fischer, F. "The Evolution of Research on Computer-Supported Collaborative Learning." In: *Technology-Enhanced Learning: Principles and Products*. Ed. by N. Balacheff, S. Ludvigsen, T. de Jong, A. Lazonder, and S. Barnes. Springer Netherlands, 2009, pp. 3–19. DOI: 10.1007/978-1-4020-9827-7_1.

[31] Dillenbourg, P. and Jermann, P. "Technology for Classroom Orchestration." In: *New Science of Learning: Cognition, Computers and Collaboration in Education*. Ed. by M. S. Khine and I. M. Saleh. Springer New York, 2010, pp. 525–552. DOI: 10.1007/978-1-4419-5716-0_26.

[32] Dillenbourg, P., Zufferey, G., Alavi, H., Jermann, P., Do-Lenh, S., Bonnard, Q., Cuendet, S., and Kaplan, F. "Classroom Orchestration: The Third Circle of Usability." In: (2011), pp. 510–517. DOI: https://doi.dx.org/10.22318/cscl2011.510.

[33] Do, L. H. S. Supporting Reflection and Classroom Orchestration with Tangible Tabletops. Tech. rep. 2012. DOI: 10.5075/epfl-thesis-5313.

[34] Esteves, A., Hoven, E. van den, and Oakley, I. "Physical Games or Digital Games? Comparing Support for Mental Projection in Tangible and Virtual Representations of a Problem-Solving Task." In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI '13. Association for Computing Machinery, 2013, pp. 167–174. DOI: 10.1145/2460625.2460651.

[35] Faiola, A., Newlon, C., Pfaff, M., and Smyslova, O. “Correlating the Effects of Flow and Telepresence in Virtual Worlds: Enhancing Our Understanding of User Behavior in Game-based Learning.” In: *Computers in Human Behavior* 29.3 (2013), pp. 1113–1121. DOI: https://doi.org/10.1016/j.chb.2012.10.003.

[36] Fan, M., Antle, A. N., Neustaedter, C., and Wise, A. F. “Exploring How a Co-Dependent Tangible Tool Design Supports Collaboration in a Tabletop Activity.” In: *Proceedings of the 18th International Conference on Supporting Group Work*. GROUP ’14. Association for Computing Machinery, 2014, pp. 81–90. DOI: 10.1145/2660398.2660402.

[37] Fischer, F., Kollar, I., Stegmann, K., and Wecker, C. “Toward a Script Theory of Guidance in Computer-Supported Collaborative Learning.” In: *Educational Psychologist* 48.1 (2013), pp. 56–66. DOI: 10.1080/00461520.2012.748005.

[38] Forssman, L., Ashorn, P., Ashorn, U., Maleta, K., Matchado, A., Kortekangas, E., and Leppänen, J. M. “Eye-tracking-based Assessment of Cognitive Function in Low-resource Settings.” In: *Archives of Disease in Childhood* 102.4 (2017), pp. 301–302. DOI: 10.1136/archdischild-2016-310525.

[39] Frayling, C. Research in Art and Design. Vol. 1. 1. Royal College of Art Research Papers, 1994. https://researchonline.rca.ac.uk/id/eprint/384.

[40] Fredricks, J. A., Blumenfeld, P. C., and Paris, A. H. “School Engagement: Potential of the Concept, State of the Evidence.” In: *Review of Educational Research* 74.1 (2004), pp. 59–109. DOI: 10.3102/00346543074001059.

[41] Frykedal, K. F. and Chiriac, E. H. “Student Collaboration in Group Work: Inclusion as Participation.” In: *International Journal of Disability, Development and Education* 65.2 (2018), pp. 183–198. DOI: 10.1080/1034912X.2017.1363381. eprint: https://doi.org/10.1080/1034912X.2017.1363381.

[42] Fu, F.-L., Su, R.-C., and Yu, S.-C. “EGameFlow: A scale to measure learners’ enjoyment of e-learning games.” In: *Computers & Education* 52.1 (2009), pp. 101–112. DOI: https://doi.org/10.1016/j.compedu.2008.07.004.

[43] Garcia-Sanjuan, F., Jurdi, S., Jaen, J., and Nacher, V. “Evaluating a tactile and a tangible multi-tablet gamified quiz system for collaborative learning in primary education.” In: *Computers & Education* 123 (2018), pp. 65–84. DOI: https://doi.org/10.1016/j.compedu.2018.04.011.

[44] Gelsomini, F., Kanev, K., Barneva, R., Bottoni, P., Tatsuki, D. H., and Roccaforte, M. “BYOD Collaborative Storytelling in Tangible Technology-Enhanced Language Learning Settings.” In: *Mobile Technologies and Applications for the Internet of Things*. Ed. by M. E. Auer and T. Tsiatsos. Springer International Publishing, 2019, pp. 22–33.

[45] Gennari, R., Melonio, A., and Rizvi, M. “Evolving Tangibles for Children’s Social Learning through Conversations: Beyond TurnTalk.” In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’18. Association for Computing Machinery, 2018, pp. 368–375. DOI: 10.1145/3173225.3173248.

[46] Giraud, T., Ravenet, B., Tai Dang, C., Nadel, J., Prigent, E., Poli, G., Andre, E., and Martin, J.-c. ““Can You Help Me Move This over There?”: Training Children with ASD

to Joint Action through Tangible Interaction and Virtual Agent." In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Association for Computing Machinery, 2021. DOI: 10.1145/3430524.3440646.

[47] González-González, C. S., Guzmán-Franco, M. D., and Infante-Moro, A. "Tangible Technologies for Childhood Education: A Systematic Review." In: *Sustainability* 11.10 (2019). DOI: 10.3390/su11102910.

[48] Greenberg, S., Gutwin, C., and Cockburn, A. "Awareness through fisheye views in relaxed-WYSIWIS groupware." In: *Graphics interface*. Vol. 96. Citeseer. 1996, pp. 28–38.

[49] Haj-Mohamadi, P., Fles, E. H., and Shteynberg, G. "When Can Shared Attention Increase Affiliation? On the Bonding Effects of Co-experienced Belief Affirmation." In: *Journal of Experimental Social Psychology* 75 (2018), pp. 103–106. DOI: https://doi.org/10.1016/j.jesp.2017.11.007.

[50] Hendry, G. D., Ryan, G., and Harris, J. "Group problems in problem-based learning." In: *Medical Teacher* 25.6 (2003), pp. 609–616.

[51] Hobson, J. A. and Hobson, R. P. "Identification: The Missing Link Between Joint Attention and Imitation?" In: *Development and Psychopathology* 19.2 (2007), pp. 411–431. DOI: 10.1017/S0954579407070204.

[52] Horn, M. S., Crouser, R. J., and Bers, M. U. "Tangible interaction and learning: the case for a hybrid approach." In: *Personal and Ubiquitous Computing* 16.4 (2012), pp. 379–389. DOI: 10.1007/s00779-011-0404-2.

[53] Hornecker, E. "A Design Theme for Tangible Interaction: Embodied Facilitation." In: *ECSCW 2005*. Ed. by H. Gellersen, K. Schmidt, M. Beaudouin-Lafon, and W. Mackay. Springer Netherlands, 2005, pp. 23–43.

[54] Hornecker, E. "A Design Theme for Tangible Interaction: Embodied Facilitation." In: *Proceedings of the Ninth Conference on European Conference on Computer Supported Cooperative Work*. ECSCW'05. Springer-Verlag, 2005, pp. 23–43.

[55] Hornecker, E. and Buur, J. "Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Association for Computing Machinery, 2006, pp. 437–446. DOI: 10.1145/1124772.1124838.

[56] Ishii, H. and Ullmer, B. "Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms." In: *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*. CHI '97. Association for Computing Machinery, 1997, pp. 234–241. DOI: 10.1145/258549.258715.

[57] Jeong, H. and Hmelo-Silver, C. E. "Seven Affordances of Computer-Supported Collaborative Learning: How to Support Collaborative Learning? How Can Technologies Help?" In: *Educational Psychologist* 51.2 (2016), pp. 247–265. DOI: 10.1080/00461520.2016.1158654.

[58] Jing, A., May, K., Lee, G., and Billinghurst, M. "Eye See What You See: Exploring How Bi-Directional Augmented Reality Gaze Visualisation Influences Co-Located Symmetric Collaboration." In: *Frontiers in Virtual Reality* 2 (2021), pp. 1–17.

[59] Johnson, D. W. and Johnson, R. T. "An Educational Psychology Success Story: Social Interdependence Theory and Cooperative Learning." In: *Educational Researcher* 38.5 (2009), pp. 365–379. DOI: 10.3102/0013189X09339057. eprint: https://doi.org/10.3102/0013189X09339057.

[60] Johnson, D. W. and Norem-Hebeisen, A. A. "A Measure of Cooperative, Competitive, and Individualistic Attitudes." In: *Journal of Social Psychology* 109.2 (1979), pp. 253–261. DOI: 10.1080/00224545.1979.9924201.

[61] Kaendler, C., Wiedmann, M., Rummel, N., and Spada, H. "Teacher Competencies for the Implementation of Collaborative Learning in the Classroom: A Framework and Research Review." In: *Educational Psychology Review* 27.3 (2015), pp. 505–536. DOI: 10.1007/s10648-014-9288-9.

[62] Kaspersen, M. H., Bilstrup, K.-E. K., and Petersen, M. G. "The Machine Learning Machine: A Tangible User Interface for Teaching Machine Learning." In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Association for Computing Machinery, 2021. DOI: 10.1145/3430524.3440638.

[63] Kazanidis, I., Palaigeorgiou, G., and Bazinas, C. "Dynamic Interactive Number Lines for Fraction Learning in a Mixed Reality Environment." In: *2018 South-Eastern European Design Automation, Computer Engineering, Computer Networks and Society Media Conference (SEEDA_CECNSM)*. IEEE. 2018, pp. 1–5. DOI: 10.23919/SEEDA-CECNSM.2018.8544927.

[64] Khodr, H., Kianzad, S., Johal, W., Kothiyal, A., Bruno, B., and Dillenbourg, P. "AlloHaptic: Robot-Mediated Haptic Collaboration for Learning Linear Functions." In: *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE. 2020, pp. 27–34.

[65] Kirschner, F., Paas, F., Kirschner, P. A., and Janssen, J. "Differential effects of problem-solving demands on individual and collaborative learning outcomes." In: *Learning and Instruction* 21.4 (2011), pp. 587–599. DOI: https://doi.org/10.1016/j.learninstruc.2011.01.001.

[66] Kirsh, D. and Maglio, P. "On Distinguishing Epistemic from Pragmatic Action." In: *Cognitive Science* 18.4 (1994), pp. 513–549. DOI: https://doi.org/10.1016/0364-0213(94)90007-8.

[67] Kollar, I. and Fischer, F. "Orchestration Is Nothing Without Conducting – But Arranging Ties the Two Together!: A response to Dillenbourg (2011)." In: *Computers & Education* 69 (2013), pp. 507–509. DOI: https://doi.org/10.1016/j.compedu.2013.04.008.

[68] Kosmas, P. and Zaphiris, P. "Embodied Interaction in Language Learning: Enhancing Students' Collaboration and Emotional Engagement." In: *Human-Computer Interaction – INTERACT 2019*. Ed. by D. Lamas, F. Loizides, L. Nacke, H. Petrie, M. Winckler, and P. Zaphiris. Springer International Publishing, 2019, pp. 179–196.

[69] Koushik, V., Guinness, D., and Kane, S. K. "StoryBlocks: A Tangible Programming Game To Create Accessible Audio Stories." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Association for Computing Machinery, 2019, pp. 1–12. DOI: 10.1145/3290605.3300722.

[70] Laal, M. "Positive Interdependence in Collaborative Learning." In: *Procedia - Social and Behavioral Sciences* 93 (2013). 3rd World Conference on Learning, Teaching and Educational Leadership, pp. 1433–1437. DOI: https://doi.org/10.1016/j.sbspro.2013.10.058.

[71] Laal, M. and Ghodsi, S. M. "Benefits of collaborative learning." In: *Procedia - Social and Behavioral Sciences* 31 (2012). World Conference on Learning, Teaching Administration - 2011, pp. 486–490. DOI: https://doi.org/10.1016/j.sbspro.2011.12.091.

[72] Lee, K. T. "Use of Tangible Learning in STEM Education." In: *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications*. SA '16. Association for Computing Machinery, 2016. DOI: 10.1145/2999508.3008582.

[73] Lefeuvre, K., Totzauer, S., Storz, M., Kurze, A., Bischof, A., and Berger, A. "Bricks, Blocks, Boxes, Cubes, and Dice: On the Role of Cubic Shapes for the Design of Tangible Interactive Devices." In: *Proceedings of the 2018 Designing Interactive Systems Conference*. DIS '18. Association for Computing Machinery, 2018, pp. 485–496. DOI: 10.1145/3196709.3196768.

[74] Leithinger, D., Follmer, S., Olwal, A., and Ishii, H. "Physical Telepresence: Shape Capture and Display for Embodied, Computer-Mediated Remote Collaboration." In: *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. UIST '14. Association for Computing Machinery, 2014, pp. 461–470. DOI: 10.1145/2642918.2647377.

[75] Do-Lenh, S., Jermann, P., Cuendet, S., Zufferey, G., and Dillenbourg, P. "Task Performance vs. Learning Outcomes: A Study of a Tangible User Interface in the Classroom." In: *Sustaining TEL: From Innovation to Learning and Practice*. Ed. by M. Wolpers, P. A. Kirschner, M. Scheffel, S. Lindstaedt, and V. Dimitrova. Springer Berlin Heidelberg, 2010, pp. 78–92.

[76] Lenz, E., Diefenbach, S., and Hassenzahl, M. "Aesthetics of Interaction: A Literature Synthesis." In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*. NordiCHI '14. Association for Computing Machinery, 2014, pp. 628–637. DOI: 10.1145/2639189.2639198.

[77] Li, Y., Kothiyal, A., Weber, T., Rossmy, B., Mayer, S., and Hussmann, H. "Designing Tangible as an Orchestration Tool for Collaborative Activities." In: *Multimodal Technologies and Interaction* 6.5 (2022). DOI: 10.3390/mti6050030.

[78] Lin, Y.-R., Keegan, B., Margolin, D., and Lazer, D. "Rising Tides or Rising Stars?: Dynamics of Shared Attention on Twitter during Media Events." In: *PLOS ONE* 9.5 (2014), pp. 1–12. DOI: 10.1371/journal.pone.0094093.

[79] Lo, D. and Lee, A. "Click: Using Smart Devices For Physical Collaborative Coding Education." In: *Proceedings of the TEI '16: Tenth International Conference on Tangible,*

Embedded, and Embodied Interaction. TEI '16. Association for Computing Machinery, 2016, pp. 500–505. DOI: 10.1145/2839462.2856522.

[80] Manches, A., O'Malley, C., and Benford, S. "Physical Manipulation: Evaluating the Potential for Tangible Designs." In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. TEI '09. Association for Computing Machinery, 2009, pp. 77–84. DOI: 10.1145/1517664.1517688.

[81] Maquil, V., Moll, C., Schwartz, L., and Hermen, J. "Kniwwelino: A Lightweight and WiFi Enabled Prototyping Platform for Children." In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '18. Association for Computing Machinery, 2018, pp. 94–100. DOI: 10.1145/3173225.3173275.

[82] Markova, M., Wilson, S., and Stumpf, S. "Tangible User Interfaces for Learning." In: *International Journal of Technology Enhanced Learning* 4 (2012), pp. 139–155. DOI: 10.1504/IJTEL.2012.051578.

[83] Markova, M. S., Wilson, S., and Stumpf, S. "Tangible User Interfaces for Learning." In: *International Journal of Technology Enhanced Learning* 4.3-4 (2012), pp. 139–155. DOI: 10.1504/IJTEL.2012.051578.

[84] Marshall, P. "Do Tangible Interfaces Enhance Learning?" In: *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*. TEI '07. Association for Computing Machinery, 2007, pp. 163–170. DOI: 10.1145/1226969.1227004.

[85] Marshall, P., Fleck, R., Harris, A., Rick, J., Hornecker, E., Rogers, Y., Yuill, N., and Dalton, N. S. "Fighting for Control: Children's Embodied Interactions When Using Physical and Digital Representations." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Association for Computing Machinery, 2009, pp. 2149–2152. DOI: 10.1145/1518701.1519027.

[86] Matthews, S., Viller, S., and Boden, M. A. ""... And We Are the Creators!" Technologies as Creative Material." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. Association for Computing Machinery, 2020, pp. 511–518. DOI: 10.1145/3374920.3374980.

[87] Matviienko, A., Rauschenberger, M., Cobus, V., Timmermann, J., Müller, H., Fortmann, J., Löcken, A., Trappe, C., Heuten, W., and Boll, S. "Deriving Design Guidelines for Ambient Light Systems." In: *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia*. MUM '15. Association for Computing Machinery, 2015, pp. 267–277. DOI: 10.1145/2836041.2836069.

[88] Maurer, B., Lankes, M., Stiglbauer, B., and Tscheligi, M. "EyeCo: Effects of Shared Gaze on Social Presence in an Online Cooperative Game." In: *Entertainment Computing - ICEC 2016*. Ed. by G. Wallner, S. Kriglstein, H. Hlavacs, R. Malaka, A. Lugmayr, and H.-S. Yang. Springer International Publishing, 2016, pp. 102–114.

[89] Mazalek, A., Davenport, G., and Ishii, H. "Tangible Viewpoints: A Physical Approach to Multimedia Stories." In: *Proceedings of the Tenth ACM International Conference on Multimedia*. MULTIMEDIA '02. Association for Computing Machinery, 2002, pp. 153–160. DOI: 10.1145/641007.641037.

[90] Mironcika, S., Schipper, A. de, Brons, A., Toussaint, H., Kröse, B., and Schouten, B. "Smart Toys Design Opportunities for Measuring Children's Fine Motor Skills Development." In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '18. Association for Computing Machinery, 2018, pp. 349–356. DOI: 10.1145/3173225.3173256.

[91] Morrison-Smith, S., Chilton, L. B., and Ruiz, J. "AmbiTeam: Enabling Awareness of Remote Team Activities Using Ambient Displays." In: *XRDS* 28.2 (2022), pp. 60–65. DOI: 10.1145/3495265.

[92] Müller, H., Fortmann, J., Hesselmann, T., Poppinga, B., Henze, N., Heuten, W., and Boll, S. "AmbiX: Designing Ambient Light Information Displays." In: *Proceedings of the Designing Interactive Systems Conference at DIS*. 2012.

[93] Müller, H., Löcken, A., Heuten, W., and Boll, S. "Sparkle: An Ambient Light Display for Dynamic off-Screen Points of Interest." In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*. NordiCHI '14. Association for Computing Machinery, 2014, pp. 51–60. DOI: 10.1145/2639189.2639205.

[94] Mundy, P., Sullivan, L., and Mastergeorge, A. M. "A Parallel and Distributed-processing Model of Joint Attention, Social Cognition and Autism." In: *Autism Research* 2.1 (2009), pp. 2–21. DOI: https://doi.org/10.1002/aur.61.

[95] Narumi, T., Hiyama, A., Tanikawa, T., and Hirose, M. "Inter-Glow: Interaction by Controlling Light." In: *Proceedings of the International Conference on Advances in Computer Entertainment Technology*. ACE '07. Association for Computing Machinery, 2007, pp. 276–277. DOI: 10.1145/1255047.1255123.

[96] Nonnis, A. and Bryan-Kinns, N. "Olly: A Tangible for Togetherness." In: *International Journal of Human-Computer Studies* 153 (2021), p. 102647. DOI: https://doi.org/10.1016/j.ijhcs.2021.102647.

[97] O'Malley, C. and Stanton Fraser, D. Literature Review in Learning with Tangible Technologies. A NESTA Futurelab Research report - report 12. 2004.

[98] Occhialini, V., Essen, H. van, and Eggen, B. "Design and Evaluation of an Ambient Display to Support Time Management during Meetings." In: *Human-Computer Interaction – INTERACT 2011*. Ed. by P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler. Springer Berlin Heidelberg, 2011, pp. 263–280.

[99] Okerlund, J., Segreto, E., Grote, C., Westendorf, L., Scholze, A., Littrell, R., and Shaer, O. "SynFlo: A Tangible Museum Exhibit for Exploring Bio-Design." In: *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '16. Association for Computing Machinery, 2016, pp. 141–149. DOI: 10.1145/2839462.2839488.

[100] Patten, J. and Ishii, H. "A Comparison of Spatial Organization Strategies in Graphical and Tangible User Interfaces." In: *Proceedings of DARE 2000 on Designing Augmented Reality Environments*. DARE '00. Association for Computing Machinery, 2000, pp. 41–50. DOI: 10.1145/354666.354671.

[101] Perugia, G., Paetzel-Prüsmann, M., Alanenpää, M., and Castellano, G. “I Can See It in Your Eyes: Gaze as an Implicit Cue of Uncanniness and Task Performance in Repeated Interactions With Robots.” In: *Frontiers in Robotics and AI* 8 (2021). DOI: 10.3389/frobt.2021.645956.

[102] Peters, C., Castellano, G., and Freitas, S. de. “An Exploration of User Engagement in HCI.” In: *Proceedings of the International Workshop on Affective-Aware Virtual Agents and Social Robots*. AFFINE ’09. Association for Computing Machinery, 2009. DOI: 10.1145/1655260.1655269.

[103] Pihlajaniemi, H., Österlund, T., and Herneoja, A. “Urban Echoes: Adaptive and Communicative Urban Lighting in the Virtual and the Real.” In: *Proceedings of the 2nd Media Architecture Biennale Conference: World Cities*. MAB ’14. Association for Computing Machinery, 2014, pp. 48–57. DOI: 10.1145/2682884.2682888.

[104] Piper, B., Ratti, C., and Ishii, H. “Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’02. Association for Computing Machinery, 2002, pp. 355–362. DOI: 10.1145/503376.503439.

[105] Premo, J., Cavagnetto, A., and Davis, W. B. “Promoting Collaborative Classrooms: The Impacts of Interdependent Cooperative Learning on Undergraduate Interactions and Achievement.” In: *CBE—Life Sciences Education* 17.2 (2018), ar32. DOI: 10.1187/cbe.17-08-0176.

[106] Price, S. “A Representation Approach to Conceptualizing Tangible Learning Environments.” In: *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*. TEI ’08. Association for Computing Machinery, 2008, pp. 151–158. DOI: 10.1145/1347390.1347425.

[107] Price, S. and Jewitt, C. “A Multimodal Approach to Examining ’embodiment’ in Tangible Learning Environments.” In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’13. Association for Computing Machinery, 2013, pp. 43–50. DOI: 10.1145/2460625.2460632.

[108] Price, S. and Rogers, Y. “Let’s get physical: The learning benefits of interacting in digitally augmented physical spaces.” In: *Computers & Education* 43.1 (2004). 21st Century Learning: Selected Contributions from the CAL 03 Conference, pp. 137–151. DOI: https://doi.org/10.1016/j.compedu.2003.12.009.

[109] Prieto, L. P., Holenko Dlab, M., Gutiérrez, I., Abdulwahed, M., and Balid, W. “Orchestrating Technology Enhanced Learning: A Literature Review and A Conceptual Framework.” In: *International Journal of Technology Enhanced Learning* 3.6 (2011), pp. 583–598.

[110] Rahimabad, R. M. and Rezvani, M. H. “Identifying Factors Affecting the Immersion and Concentration of Players in Serious Games.” In: *2020 International Serious Games Symposium (ISGS)*. 2020, pp. 61–67. DOI: 10.1109/ISGS51981.2020.9375239.

[111] Raudanjoki, Ö., Genç, Ç., Hurtig, K., and Häkkilä, J. “ShadowSparrow: An Ambient Display for Information Visualization and Notification.” In: *19th International Con-*

ference on Mobile and Ubiquitous Multimedia. MUM 2020. Association for Computing Machinery, 2020, pp. 351–353. DOI: 10.1145/3428361.3431197.

[112] Read, J. C. and MacFarlane, S. "Using the Fun Toolkit and Other Survey Methods to Gather Opinions in Child Computer Interaction." In: *Proceedings of the 2006 Conference on Interaction Design and Children*. IDC '06. Association for Computing Machinery, 2006, pp. 81–88. DOI: 10.1145/1139073.1139096.

[113] Reyes-Flores, A., Mezura-Godoy, C., and Benıtez-Guerrero, E. "Modeling Interactions for a Tangible System to Support Collaborative Learning through Social Regulation." In: *8th Mexican Conference on Human-Computer Interaction*. MexIHC' 21. Association for Computing Machinery, 2021. DOI: 10.1145/3492724.3492728.

[114] Rheden, V. van, Maurer, B., Smit, D., Murer, M., and Tscheligi, M. "LaserViz: Shared Gaze in the Co-Located Physical World." In: *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '17. Association for Computing Machinery, 2017, pp. 191–196. DOI: 10.1145/3024969.3025010.

[115] Roger, T. and Johnson, D. W. "An overview of cooperative learning." In: *Creativity and collaborative learning* (1994), pp. 1–21.

[116] Rogers, Y. "Interaction Design Gone Wild: Striving for Wild Theory." In: *Interactions* 18.4 (2011), pp. 58–62. DOI: 10.1145/1978822.1978834.

[117] Roschelle, J. and Teasley, S. D. "The Construction of Shared Knowledge in Collaborative Problem Solving." In: *Computer Supported Collaborative Learning*. Ed. by C. O'Malley. Springer Berlin Heidelberg, 1995, pp. 69–97.

[118] Roschelle, J. and Teasley, S. D. "The Construction of Shared Knowledge in Collaborative Problem Solving." In: *Computer Supported Collaborative Learning*. Ed. by C. O'Malley. Springer Berlin Heidelberg, 1995, pp. 69–97.

[119] Rygh, K. "Designing tangible tools to support collaboration in the co-design of healthcare services." In: *ServDes2018: Service Design Proof of Concept-Proceedings of the ServDes2018 Conference, Milano, 18-20 June*. Linköping University Electronic Press. 2018.

[120] Sabuncuoglu, A. "Tangible Music Programming Blocks for Visually Impaired Children." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. Association for Computing Machinery, 2020, pp. 423–429. DOI: 10.1145/3374920.3374939.

[121] Scardamalia, M. and Bereiter, C. Knowledge building: Theory, pedagogy, and technology. na, 2006.

[122] Schlösser, C. and Harrer, A. "Exploring the Impact of Gaze Sharing on Collaboration During a Co-Construction Task." In: *2019 IEEE 19th International Conference on Advanced Learning Technologies (ICALT)*. Vol. 2161-377X. 2019, pp. 131–133. DOI: 10.1109/ICALT.2019.00046.

[123] Schneider, B., Jermann, P., Zufferey, G., and Dillenbourg, P. "Benefits of a tangible interface for collaborative learning and interaction." In: *IEEE Transactions on Learning Technologies* 4.3 (2010), pp. 222–232. DOI: 10.1109/TLT.2010.36.

[124] Schneider, B. and Pea, R. "Real-Time Mutual Gaze Perception Enhances Collaborative Learning and Collaboration Quality." In: *Educational Media and Technology Yearbook: Volume 40*. Ed. by M. Orey and R. M. Branch. Springer International Publishing, 2017, pp. 99–125. DOI: 10.1007/978-3-319-45001-8_7.

[125] Schneider, B., Sharma, K., Cuendet, S., Zufferey, G., Dillenbourg, P., and Pea, R. "Leveraging Mobile Eye-trackers to Capture Joint Visual Attention in Co-located Collaborative Learning Groups." In: *International Journal of Computer-Supported Collaborative Learning* 13.3 (2018), pp. 241–261. DOI: 10.1007/s11412-018-9281-2.

[126] Schneider, B., Sharma, K., Cuendet, S., Zufferey, G., Dillenbourg, P., and Pea, R. "Using Mobile Eye-Trackers to Unpack the Perceptual Benefits of a Tangible User Interface for Collaborative Learning." In: *ACM Trans. Comput.-Hum. Interact.* 23.6 (2016). DOI: 10.1145/3012009.

[127] Schneider, B., Sharma, K., Cuendet, S., Zufferey, G., Dillenbourg, P., and Pea, R. D. "3D Tangibles Facilitate Joint Visual Attention in Dyads." In: International Society of the Learning Sciences, 2015, pp. 158–165.

[128] Shaer, O. Tangible User Interfaces: Past, Present, and Future Directions. Vol. 3. 1-2. Now Publishers, 2009, pp. 1–137. DOI: 10.1561/1100000026.

[129] Shapiro, L. Embodied cognition. Routledge, 2019.

[130] Shteynberg, G. "A Collective Perspective: Shared Attention and The Mind." In: *Current Opinion in Psychology* 23 (2018). Shared Reality, pp. 93–97. DOI: https://doi.org/10.1016/j.copsyc.2017.12.007.

[131] Shteynberg, G. "Shared Attention." In: *Perspectives on Psychological Science* 10.5 (2015). PMID: 26385997, pp. 579–590. DOI: 10.1177/1745691615589104.

[132] Shteynberg, G. "Shared Attention at the Origin: On the Psychological Power of Descriptive Norms." In: *Journal of Cross-Cultural Psychology* 46.10 (2015), pp. 1245–1251. DOI: 10.1177/0022022115600260.

[133] Shteynberg, G. Social Attention Theory: A New Look at Knowledge Formation in Groups. University of Maryland, College Park, 2009.

[134] Siposova, B. and Carpenter, M. "A New Look at Joint Attention and Common Knowledge." In: *Cognition* 189 (2019), pp. 260–274. DOI: https://doi.org/10.1016/j.cognition.2019.03.019.

[135] So, H.-J. and Brush, T. A. "Student Perceptions of Collaborative Learning, Social Presence and Satisfaction in a Blended Learning Environment: Relationships and Critical Factors." In: *Computers & Education* 51.1 (2008), pp. 318–336. DOI: https://doi.org/10.1016/j.compedu.2007.05.009.

[136] Speelpenning, T., Antle, A. N., Doering, T., and Hoven, E. van den. "Exploring How Tangible Tools Enable Collaboration in a Multi-touch Tabletop Game." In: *Human-Computer Interaction – INTERACT 2011*. Ed. by P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler. Springer Berlin Heidelberg, 2011, pp. 605–621.

[137] Speelpenning, T., Antle, A. N., Doering, T., and Hoven, E. van den. "Exploring How Tangible Tools Enable Collaboration in a Multi-touch Tabletop Game." In: *Human-Computer Interaction – INTERACT 2011*. Ed. by P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler. Springer Berlin Heidelberg, 2011, pp. 605–621.

[138] Stanton, D., Bayon, V., Neale, H., Ghali, A., Benford, S., Cobb, S., Ingram, R., O'Malley, C., Wilson, J., and Pridmore, T. "Classroom Collaboration in the Design of Tangible Interfaces for Storytelling." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '01. Association for Computing Machinery, 2001, pp. 482–489. DOI: 10.1145/365024.365322.

[139] Steinfeld, A., Jenkins, O. C., and Scassellati, B. "The Oz of Wizard: Simulating the Human for Interaction Research." In: *Proceedings of the 4th ACM/IEEE International Conference on Human Robot Interaction*. HRI '09. Association for Computing Machinery, 2009, pp. 101–108. DOI: 10.1145/1514095.1514115.

[140] Svanaes, D. and Verplank, W. "In Search of Metaphors for Tangible User Intefaces." In: *Proceedings of DARE 2000 on Designing Augmented Reality Environments*. DARE '00. Association for Computing Machinery, 2000, pp. 121–129. DOI: 10.1145/354666.354679.

[141] Takahashi, R., Suzuki, H., Chew, J. Y., Ohtake, Y., Nagai, Y., and Ohtomi, K. "A System for Three-dimensional Gaze Fixation Analysis Using Eye Tracking Glasses." In: *Journal of Computational Design and Engineering* 5.4 (2017), pp. 449–457. DOI: 10.1016/j.jcde.2017.12.007.

[142] Tsui, K. M., Desai, M., Yanco, H. A., and Uhlik, C. "Exploring Use Cases for Telepresence Robots." In: *2011 6th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 2011, pp. 11–18. DOI: 10.1145/1957656.1957664.

[143] Van Dijk, E. M., Lingnau, A., and Kockelkorn, H. "Measuring Enjoyment of An Interactive Museum Experience." In: *Proceedings of the 14th ACM International Conference on Multimodal Interaction*. 2012, pp. 249–256.

[144] Verweij, D., Bakker, S., and Eggen, B. "FireFlies2: Interactive Tangible Pixels to Enable Distributed Cognition in Classroom Technologies." In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ISS '17. Association for Computing Machinery, 2017, pp. 260–269. DOI: 10.1145/3132272.3134122.

[145] Villanueva, A., Zhu, Z., Liu, Z., Wang, F., Chidambaram, S., and Ramani, K. "ColabAR: A Toolkit for Remote Collaboration in Tangible Augmented Reality Laboratories." In: *Proc. ACM Hum.-Comput. Interact.* 6.CSCW1 (2022). DOI: 10.1145/3512928.

[146] Wang, F. and Burton, J. K. "Collaborative learning problems and identity salience: A mixed methods study." In: *Journal of Educational Technology Development and Exchange (JETDE)* 3.1 (2010), p. 1.

[147] Wang, H.-C., Rosé, C. P., and Chang, C.-Y. “Agent-based dynamic support for learning from collaborative brainstorming in scientific inquiry.” In: *International Journal of Computer-Supported Collaborative Learning* 6.3 (2011), p. 371. DOI: 10.1007/s11412-011-9124-x.

[148] Wang, Q. “Design and evaluation of a collaborative learning environment.” In: *Computers & Education* 53.4 (2009). Learning with ICT: New Perspectives on Help Seeking and Information Searching, pp. 1138–1146. DOI: https://doi.org/10.1016/j.compedu.2009.05.023.

[149] Weiser, M. “The Computer for the 21st Century.” In: *SIGMOBILE Mob. Comput. Commun. Rev.* 3.3 (1999), pp. 3–11. DOI: 10.1145/329124.329126.

[150] Wise, A., Antle, A., Warren, J., May, A., Fan, M., and Macaranas, A. “What Kind of World Do You Want to Live In? Positive Interdependence and Collaborative Processes in the Tangible Tabletop Land-use Planning Game Youtopia.” In: *Exploring the Material Conditions of Learning*. Ed. by O. Lindwall, P. Hakkinen, T. Koschmann, P. Tchounikine, and S. Ludvigsen. Computer-Supported Collaborative Learning Conference, CSCL. International Society of the Learning Sciences (ISLS), 2015, pp. 236–243.

[151] Witmer, B. G., Jerome, C. J., and Singer, M. J. “The Factor Structure of the Presence Questionnaire.” In: *Presence: Teleoperators and Virtual Environments* 14.3 (2005), pp. 298–312. DOI: 10.1162/105474605323384654.

[152] Wobbrock, J. O. and Kientz, J. A. “Research Contributions in Human-Computer Interaction.” In: *Interactions* 23.3 (2016), pp. 38–44. DOI: 10.1145/2907069.

[153] Wohltjen, S. and Wheatley, T. “Eye Contact Marks the Rise and Fall of Shared Attention in Conversation.” In: *Proceedings of the National Academy of Sciences* 118.37 (2021), e2106645118. DOI: 10.1073/pnas.2106645118.

[154] Yang, Z., Jie, S., Shiqi, L., Ping, C., and Shengjia, N. “Tangible Interactive Upper Limb Training Device.” In: *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems*. DIS ’18 Companion. Association for Computing Machinery, 2018, pp. 1–5. DOI: 10.1145/3197391.3205403.

[155] Ying, F. T., Cai, J. X., Wang, Q., Tao, Y., Chen, C., Wang, Y. N., and Yao, C. “Cultural Design Method on Multi-Sensor Technology Design: A Case of Interactive Lamp Design.” In: *Mechatronics and Industrial Informatics*. Vol. 321. Applied Mechanics and Materials. Trans Tech Publications Ltd, 2013, pp. 553–557. DOI: 10.4028/www.scientific.net/AMM.321-324.553.

[156] Yu, J., Zheng, C., Tamashiro, M. A., Gonzalez-millan, C., and Roque, R. “CodeAttach: Engaging Children in Computational Thinking Through Physical Play Activities.” In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’20. Association for Computing Machinery, 2020, pp. 453–459. DOI: 10.1145/3374920.3374972.

[157] Zhou, Q., Suraworachet, W., Celiktutan, O., and Cukurova, M. “What Does Shared Understanding in Students’ Face-to-Face Collaborative Learning Gaze Behaviours “Look Like”?” In: *Artificial Intelligence in Education*. Ed. by M. M. Rodrigo, N. Matsuda, A. I. Cristea, and V. Dimitrova. Springer International Publishing, 2022, pp. 588–593.

[158] Zuckerman, O., Press, V. S., Barda, E., Megidish, B., and Erel, H. "Tangible Collaboration: A Human-Centered Approach for Sharing Control With an Actuated-Interface." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3517449.

Original Contributing Publications

The research within this thesis would not have been possible without my supervisor, colleagues, and the students I supervised. The following Table clarifies my and others' contributions to the included projects.

Table 5.1: Clarification of my and others' contributions to the publications included in my thesis.

	My Contributions	Others' Contributions
[P9]	I came up with the initial idea and conducted a literature review. I led the paper writing.	M. Liang, J. Preissing, N. Bachl, and M. Dutoit participated in reviewing the selected papers and collected the paper writing data from the reading. In addition, M. Liang helped write the finding session. T. Weber, S. Mayer, and H. Hussmann provided feedback on the work and the publication.
[P8]	I came up with the initial idea and developed the concept in two practical master courses where I was the main lecturer. I led the paper writing.	Seventeen master students who took our *Practical Tangible Light* courses at LMU Munich developed the tangible tools in the paper. *stayFOCUSed*: A. Ristic, S. Muser, A. Reda, and T. Lu; *Group Hexagon*: S. Bast, A. Gehlisch, L. Haller, and I. Klautke; *Tower*: H. Ha, M. Hussain, J. Herner, and V. Balzer; *Glowing Wand*: A. Pellhammer, J. Haudenschild, and S. Wackerl; *Remolight*: M. Liang and T. Mitrevska. B. Rossmy and T. Weber helped teach the courses together. A. Kothiyal, T. Weber, B. Rossmy, S. Mayer, and H. Hussmann provided feedback on the work and the publication.
[P6]	I developed the main idea and the individual project concepts, co-designed and co-implemented the two prototypes together with two bachelor students (Z. Zhao and S. Egger), and led the paper writing process.	Z. Zhao executed the *CollabMaze* experiment. S. Egger did *UnitRry* experiment. S. Mayer and Hussmann provided feedback on the work and the publication.
[P11]	I came up with the initial idea and conducted the literature review. I led the paper writing.	B. Rossmy and H. Hussmann provided feedback on the work and the publication.
[P1]	I developed the main idea and the project concept, co-designed and co-implemented the *TalkinGlass* prototype together with two bachelor students (N. Bachl and M. Dutoit), and led the paper writing process.	N. Bachl and M. Dutoit executed the experiment. T. Weber, S. Mayer, and H. Hussmann provided feedback on the work and the publication.

	My Contributions	Others' Contributions
[P2]	I developed the main idea and the project concept, co-designed and co-implemented the *MemorINO* prototype together with two bachelor students (S. Bachl and A. Luttringer), and led the paper writing process.	S. Bachl and A. Luttringer executed the experiment. T. Weber, S. Mayer, and H. Hussmann provided feedback on the work and the publication.
[P4]	I developed the main idea and the individual project concepts, co-designed and co-implemented the two prototypes together with one master student (N. Corz) and one student (T. Marschall), and led the paper writing process.	N. Corz executed the *Paint-Matics* experiment. T. Marschall did *Slimo* experiment. L. Hirsch helped the initial idea of *Paint-Matics*.
[P3]	I developed the main idea and the project concept, co-designed and co-implemented the *Study Marbles* prototype together with two master students (B. Bapisch and J. Phu), and led the paper writing process.	B. Bapisch and J. Phu executed the experiment. T. Weber and H. Hussmann provided feedback on the work and the publication.
[P13]	I developed the main idea and the project concept, co-designed and co-implemented the *GrouPen* prototype together with two master students (Y. Sun and T. Lu), and led the paper writing process.	Y. Sun and T. Lu executed the experiment. T. Weber and H. Hussmann provided feedback on the work and the publication.
[P14]	I developed the main idea. I provided feedback on the work and the publication. I led the paper writing process.	M. Liang conducted the literature review and wrote the paper draft. T. Weber and H. Hussmann provided feedback on the work and the publication.
[P12]	J. Slotta and I developed the main idea. I co-designed and co-implemented the experiment with D. Sommerhoff and led the paper writing process.	X. Wang helped design the experimental exercises. S. Ufer and J. Slotta provided feedback on the work and the publication.
[P5]	J. Slotta and I developed the main idea. I co-designed and co-implemented the experiment with J. Dai and led the paper writing process.	X. Wang helped design the experimental exercises. J. Slotta provided feedback on the work and the publication.
[P10]	I developed the main idea and the project concept, co-designed and co-implemented the *Chilego* prototype together with one master (S. Liu) and *FlipCards* prototype with one bachelor students (L. Nguyen), and led the paper writing process.	C. Ou did the data analysis, and T. Weber made the sketches in the paper and read the paper. S. Mayer provided feedback on the writing structure and did the proofreading. S. Strithroth provided feedback on the work and did manuscript proofreading.

	My Contributions	Others' Contributions
[P7]	I developed the main idea and the project concept, co-designed and co-implemented the *SpellBoard* prototype together with one master student (E. Harmat) and one bachelor student (M. Mayer), and led the paper writing process.	E. Harmat and M. Mayer executed the experiment. C. Ou did the data analysis and did manuscript proofreading.

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eidesstatt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 5. May 2023

Yanhong Li