A Meta-Analysis of Tangible Learning Studies from the TEI Conference

Yanhong Li*
yanhong.li@ifi.lmu.de
LMU Munich
Munich, Germany

Meng Liang*
meng.liang@campus.lmu.de
LMU Munich
Munich, Germany

Julian Preissing
julian.preissing@web.de
LMU Munich
Munich, Germany

Nadine Bachl
N.Bachl@campus.lmu.de
LMU Munich
Munich, Germany

Michelle Dutoit
M.Dutoit@campus.lmu.de
LMU Munich
Munich, Germany

Thomas Weber
thomas.weber@ifi.lmu.de
LMU Munich
Munich, Germany

Sven Mayer
info@sven-mayer.com
LMU Munich
Munich, Germany

Heinrich Hussmann
hussmann@ifi.lmu.de
LMU Munich
Munich, Germany

ABSTRACT

Tangible learning has received increasing attention. However, in the recent decade, it has no comprehensive overview. This study aimed to fill the gap and reviewed 92 publications from all the TEI conference proceedings (2007–2021). We analysed previous studies' characteristics (e.g., study purpose and interactive modalities) and elaborated on three common topics: collaborative tangible learning, tangibles' impacts on learning, and comparisons between tangibles and other interfaces. Three key findings were: (1) Tangibles impacted learning because it could scaffold learning, change learning behaviour, and improve learning emotion; (2) We should see the effectiveness of tangibles with rational and critical minds. (3) Some studies emphasised too much on the interaction of tangibles and ignored their metaphor meanings. For future work, we suggest avoiding an intensive cluster on collaboration and children and consider other valuable areas, e.g., tangibles for teachers, tangibles' social and emotional impacts on students, tangible interaction's meaning and metaphor.

CCS CONCEPTS

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

KEYWORDS

tangible learning, tangible interaction, tangible user interface, collaborative learning, children, TEI, TUI

ACM Reference Format:
Yanhong Li, Meng Liang, Julian Preissing, Nadine Bachl, Michelle Dutoit, Thomas Weber, Sven Mayer, and Heinrich Hussmann. 2022. A Meta-Analysis of Tangible Learning Studies from the TEI Conference. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'22), February 13–16, 2022, Daejeon, Republic of Korea.* ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3490149.3501313

1 INTRODUCTION

Tangible User Interface (TUI) has received interests to support learning and teaching, e.g., expanding learning opportunities [32], transforming traditional pedagogical approach [132], problem solving [40, 54, 148], programming [21, 88, 123, 133], and social communication [126]. As an emerging field of research, tangible learning is continuing to have more studies. In order to address the knowledge gap and focus future research efforts in this field, it is essential to have a comprehensive overview of the previous studies and current research state.

To date, there are 12 review papers about learning with tangible technologies. They were about children education [53, 112, 147, 149], abstract concept learning [14, 79, 123], and social interaction for the elderly [18]. The other three [83, 84, 99], which were performed in 2012, 2007, and 2004, summarised the theories, case studies and analytic framework of tangible learning. However, they fall short when it comes to topics, such as interactive modalities, collaborative learning, and tangible effects on learning. Moreover, in nearly 10 years, there was no comprehensive literature review. Thus, the recent literature on tangible learning has not been covered, and emerging topics are missing.

To close this gap, we set out to conduct a systematic literature review. We performed a systematic review of tangible learning studies published in the *ACM International Conference on Tangible, Embedded and Embodied Interaction* (TEI) conference, the most related and influenced tangible community. We conducted the review from January to August of 2021. Before reading the papers, we established a research framework to record the basic review information, e.g., publication year, participant, study purpose, and study findings. Each paper had two authors to read and enter the entries in this framework, then another different author analysed and summarised the final contents of each entry. In addition, we conducted a survey with 14 domain participants. We coded their answers into four themes: definition, advantage, challenge, and the best tangible learning application (with good examples). The purpose is to add authentic voices and avoid incomplete opinions dominated by publications.

With this paper, we contribute: provide a unique and insightful analysis of tangible learning studies from perspectives of the TEI

---

*Both authors contributed equally to this research.

TEI'22, February 13–16, 2022, Daejeon, Republic of Korea

ACM ISBN 978-1-4503-9147-4/22/02…$15.00
https://doi.org/10.1145/3490149.3501313

community. Previous literature reviews analysed TUIs' impact on learning from theoretical perspectives with little practical evidence. Our review summarised and analysed all the case studies published at the TEI conference since 2007 to show the real impact of TUI on learning. Beyond reporting prior findings, we additionally report on a survey with domain participants to extend our results beyond prior findings. Finally, we point out three issues and valuable future directions based on all the findings and expects' perspectives. We are trying to increase the visibility and the value of individual studies and to focus future research efforts in this field.

2 BACKGROUND

In the following, we highlight the domains TUI and tangible learning to set up the development and trend within the larger research space.

2.1 Tangible User Interface

At present, there is no consistent definition of TUI. Researchers understand it from different perspectives as system, representation, embedded technology, and computing paradigm. In the seminal work by Ishii and Ullmer [64], they defined TUI as a user interface that "augment the real physical world by coupling digital information to everyday physical objects and environment." Hornecker and Buur [61] understood it as "systems that rely on embodied interaction, tangible manipulation, physical representation of data, and embeddedness in real space". Later, Price [106] reckoned "Tangibles, in the form of physical artefacts embedded with wireless, sensor and actuator technologies, offer the opportunity to build on our everyday interaction and experience with the world." In 2013, Antle and Wise [8] defined it as "a computing paradigm in which the real world is augmented by embedding computation into physical objects and environments that are linked to digital representations." Markova et al. [83] point out, the lack of a clear definition could lead to an ambiguity whether a system was a TUI or just a system with tangible aspects. Therefore, Markova et al. [83] provided four criteria which a TUI must fulfil: (1) *Tangible Objects*: Contain one or more tangible objects as interactive devices; (2) *Embodiment*: Input and output are closely temporally and spatially related; (3) *Metaphor*: Digital and physical spaces are closely integrated; and (4) *Continuity*: Support continuous interactions [83]. This built on earlier TUI characteristics proposed by Ullmer and Ishii [138] as: "(1) Physical representations are computationally coupled to underlying digital information; (2) Physical representations embody mechanisms for interactive control; (3) Physical representations are perceptually coupled to actively mediated digital representations; and (4) The physical state of interface artefacts partially embodies the digital state of the system" [138].

2.2 Tangible Learning

Tangible learning used a combination of gesture, motion, or full-body interaction to convey knowledge. More importantly, tangible learning "emphasizes the use of the body in educational practice" [68]. Similarly, TUIs use the interaction with physical manipulatives and embodied metaphors to communicate abstract concepts. Here, TUIs embed technology in everyday objects and allow natural action such as grabbing, in the manner technology embedded in TUIs becomes ubiquitous [143]. Here as a skilled subjectivity, the human body enables learning and knowledge transfer [130]. Additionally, Wilson [144] describes that physical states and bodily structures influence all cognitive processes, further supporting learning. Thus, it is beneficial to learn by manipulating real physical objects, which results in haptic interactions and embodiment effects [84, 99]. This resembles the pedagogical approach of learning-by-doing. From the cognitive load theory perspective, understanding how tangible design might change how we perceive and think about learned concepts [106]. Embodiment in practice reduces the burden of learners' mental cognition and provides them with hands-on interactive experiences.

Learning with TUIs has three advantages. First, due to their playful and intuitive nature, TUIs have been seen as a new trend for teaching and learning. Tamim et al. [137] noted in their meta-analysis over the past 40 years that classrooms with digital technology had resulted in a remarkable increase in students' achievement. TUI, as a new technology, has been used in many fields, such as programming [21, 88, 133], storytelling [135, 136], and mathematics [47, 73, 124]. Second, it has a broad beneficiary group, which ranges from preschool to university. Meanwhile, some common TUIs are becoming easier to approach, e.g., paper [19, 133], blocks [66, 118], and robots [21, 45]. Finally, TUIs seem well suited for whole-class activities and discussion [58] and had the advantage to create pedagogical environments for collaboration and creativity [71]. Some previous studies have reviewed tangible objects [31, 36, 52, 62, 128]; however, few target the learning perspective [15, 121].

2.3 Summary

Tangible technologies have created a wealth of novel chances to support and improve learning. First, we want to establish an insightful overview conveying the characteristics of previous studies. In detail, we aim to address the following questions: which areas have used TUIs to support learning? How have these studies been conducted? Which kind of users and what contexts were common? Tangible learning was featured for embodied and active interaction. What were the actual interactive modalities in the review results? What were their influences on learning? In addition, after reviewing all the related studies, what are the common topics? What will be the most likely upcoming topics for future research in the next few years?

3 METHOD

Our investigation aims to perform a systematic literature review on all the tangible learning publications from the *ACM International Conference on Tangible, Embedded and Embodied Interaction* (TEI), first held in 2007. The publication types included paper, demo, work in progress, art exhibition, studio, graduate student consortium, and student design challenge.

A common approach to gathering a corpus of works in the first *Identification Phase* [92] of a literature review is a keyword search. However, we identified TEI to be the main venue for tangible learning publication. We started with 720 papers in the Identification phase. Thus, we went into the second phase, the *Screening*

Phase [92], with these 720 papers. We first went through all publications and made an initial selection based on their titles and abstracts. This resulted in 112 relevant publications. Second, two authors read each paper's entire content and excluded 20 publications based on two criteria: (1) the interaction is not tangible; (2) the purpose of tangible interaction is not mainly for learning. As shown in the Appendix (Table 9), our final data set contains 92 publications for review, which included 64 full papers and 28 extended abstract papers.

We established a research framework to record the basic review information, e.g., publication year, participant, study purpose, and study findings. For these, two authors entered each entry. Then, the first two authors checked and summarised them to finalise it. We picked up the "study findings" entries and discussed them to find the common topics in the findings. Here, we identified three common topics, which were shown frequently in the review results.

To add authentic voices and avoid incomplete opinions dominated by publications, we interviewed 14 domain participants. We used the convenience sampling method to recruit them. However, they were all qualified by being from one of the following pools of participants: (1) experts from education and Human-Computer Interaction (HCI), (2) human-computer interaction master students with a strong background in TUIs for learning; (3) educational PhD students who have teaching experience with technologies, such as interactive whiteboard and tablet. We received 4, 5, and 5 responses, respectively. For education experts and computer science master students, the questions were: (1) *Can you use one or two sentences to let me know your definition of tangible learning technology? If possible, can you give me one or two examples?* (2) *What are the three advantages of tangible learning from your perspective? Who may benefit from it most, and in which situation will it create the best benefits?* (3) *What are the three challenges of tangible learning that come to your mind?* For educational PhD students, we gave them the definition of tangible learning and showed them two tangible learning examples with videos first; Then, we asked them the questions: (1) *What are the three advantages of tangible learning from your perspective? Who may benefit from it most, and in which situation will it create the best benefits?*, and (2) *What are the three challenges of tangible learning that come to your mind?*

4 FINDINGS

Based on our literature review and the survey, we will introduce seven findings organised in three categories. First, characteristics of previous studies, which includes study purpose (Section 4.1), participant, context, research time & data resource (Section 4.2), and tangible interaction (Section 4.3); Second, common topics which were formed from all the 92 publications, which contains tangible collaborative learning (Section 4.5), TUIs' impacts on learning (Section 4.6), and comparative studies between TUI and other interface (Section 4.7). Finally, we report the results from our survey (Section 4.8).

4.1 Study Purpose

All the studies were classified into four contribution types [131]: material contribution, design contribution, technology contribution, and theoretical contribution. Most studies (68) were design contributions. Twenty-three studies were theoretical contributions, and the last one was a technology contribution. In addition, we categorised all studies into three study types: case study, exploration, and guidance. There were 27, 48, and 6, respectively.

To explore the applications of tangible learning, 95.65% of researchers developed TUI prototypes to show their research ideas. As shown in Table 2, we grouped them according to their primary purposes and introduced some good examples from each category, to get an overview.

The most common study purpose (24 studies) was to *facilitate collaborative learning*. For example, *SciSketch: A Tabletop Collaborative Sketching System* [25] developed *SciSketch* to allow collaborative sketching. There were 20 studies to *test or compare the TUI properties for learning*. We found that many tangible prototypes were compared to their digital counterparts. For example, Catala et al. [22] compared a digitally augmented tabletop with its physical version for collaborative creative tasks. One more instance was *How Does the Tangible Object Affect Motor Skill Learning?* [82], where the effects of similarity of physical and digital representations were analysed. Thirteen studies were explored to teach people programming [59], languages [65], writing [129], reading [110], musical skills [102] and proper behaviour/usage [3]. For example, in Hangul language [65], an interface with physical blocks was developed to help users learn Hangul characters. For writing skills [129], a prototype was designed to enable users to self-train their calligraphy skills by giving automatic feedback while writing. The study "Brush and learn: transforming tooth brushing behaviour through interactive materiality, a design exploration" [3] aimed to teach users the right brushing behaviour with a special toothbrush (used as a tangible interface).

Twelve studies focused on providing learners with an embodied learning environment or experience. It is important to note that they aimed to provide an experience (learn by doing) rather than have a specific learning goal as the outcome. One example could be seen in *IRelics: Designing a Tangible Interaction Platform for the Popularization of Field Archaeology* [76]. It provided an immersive experience into the world of archaeologists by allowing users to explore and discover virtual excavation sites with the aid of tangible tools. Similarly, Gläser et al. [49] made a virtual space for children and teenagers to conduct chemistry experiments without dangers. In addition, museums often designed equipment for visitors to have different learning experiences. Seven studies were designed to help people (particularly children) with learning difficulties or disabilities. For example, Dyslexia [6, 42] can cause problems with reading [43], writing and spelling [42]. For visually impaired children, TUIs can provide an affordable and accessible means to learn (e.g., music creation [117], Geometry [116]). Another six studies helped students with learning tasks in general. For example, Bakker et al. [12] presented two prototypes: *Caw Clock* and *NoteLet. Caw Clock* was designed to support time awareness for teachers and students by visualising the time. *NoteLet* was a device to help teachers observe and document unintentional behaviour of children.

Finally, there were 10 studies either had no prototypes or did not fit into previous categories. For example, Gennari et al. [46] studied how to scaffold turn-sharing norms in small group conversations for primary school children. Patel et al. [101] explored the freedom and

Table 1: Numbers of tangible learning studies in the TEI conference.

TEI	'21	'20	'19	'18	'17	'16	'15	'14	'13	'12	'11	'10	'09	'08	'07	In all
All papers	40	37	36	37	41	45	63	46	48	42	65	54	70	46	50	**720**
First select	2	4	5	12	5	7	14	7	10	15	6	4	7	4	10	**112 (15.56%)**
Final select	2	4	4	10	3	6	11	7	9	9	6	6	5	2	8	**92 (12.78%)**

spontaneity among the audience, performers, interactive prototypes and theatrical space.

4.2 Participant, Context, Research Time & Data Resource

Out of the 92 publications, 67 have performed user studies. Regarding their **participants**, 55 studies had homogeneous participants. More specifically, *children were the main participants for studies*, with 40. Then, 15 studies were for adults (7 for university students, 2 for teachers, and 1 for experts), and 5 for teenagers. Twelve studies had heterogeneous participants (5 for children and adults, 3 for children and teachers, 1 for children and caregivers, 1 for children, parents and museum staff, 1 for families, and 1 for children, teenagers and teachers). The number of participants ranged from 2 to 240. Most studies (55) had participants below 50; 12 were between 50 and 100. There were 1.27 more females than males. Regarding the **context**, most studies 34) were conducted in school. In addition, seven were in museums, and three were in rehabilitation centres. The remaining studies were conducted in other places, such as learning centres, labs, workshops, and homes.

Regarding the **experiment duration**, 54 of them conducted only one experiment (from less than 10 minutes to 3 hours), 11 multiple experiments (from 4 days to 10 months), and two did not mention the time the experiment took. Twenty-two studies had a study duration of less than 1 hour. More specifically, five studies were conducted in less than 10 minutes, 8 were less than 30 minutes, 9 were less than 1 hour, and the other 3 were less than 1 month.

In the studies, researchers collected various **data** using different **methods**. Most data gathered were qualitative data (60) and the rest were quantitative (23). The most used mediums of documenting data were observations, interviews, and questionnaires. The least used method was self-documentation, usability scale and "again and again table" format, which were all used once.

Table 2: Primary study purposes of the reviewed results.

Primary study purposes	Count	Examples
Facilitate collaborative learning	24	[25]
Test or compare tangible properties (e.g., embodied) for learning	20	[22, 82]
Teach skills (e.g., programming, language, playing music)	13	[3, 65, 129]
Provide an embodied learning environment or experience	12	[49, 76]
Help people with learning difficulties or disabilities (e.g., Dyslexia and visually impaired)	7	[6, 42, 117]
Support teaching	6	[12]
Others	10	[46, 101]

4.3 Tangible Interaction: Input & output

To understand the tangible interaction, we analysed input and output methods used in the review results. As shown in Figure 1a, input methods used in the review results were summarised into five categories: (1) *Object + Body-based/ Gesture* (17.02% studies), focusing on human gesture, movement, and other body-based interactions; (2) *Object + Phone/ GUI (Graphic User Interface)/ Projector* (15.96%), using physical objects with an additional GUI, e.g., projector and phone; (3) *Object + Interactive board/ Tabletop/ Write-board/ Tablet* (25.53%),which usually had tokens on a surface; (4) *Object + assembling/ Structuring* (9.57%), referring to digital augmented tangibles that could be constructed or assembled; and (5) *Object manipulation* (31.91%), interacting with one or several physical objects. As shown in Figure 1b, we could find three features: First, between 2007 and 2015, the combination of physical objects and interactive board, tabletop, write-board, and tablet was a popular research focus; Second, from 2010 to 2018, researchers were more interested in user's body gestures and movements. Finally, a few studies took advantage of the composability of the physical objects and supported users to construct and assemble tangibles.

Regarding the output modality, there mainly were three types: visuospatial, audial, and haptic. As shown in Figure 2 and Table 3, most studies (40 publications) had visuospatial as only output, and 39 used the combination of vision and other perceptions. Visual and auditory were the most common feedback combinations (20), 12 used visual and tactile feedback, and one used audio and haptic feedback simultaneously. In addition, since 2014, eight studies [6, 13, 20, 42, 63, 97, 101, 148] have tried to incorporate all three modalities into their interaction design. However, only 4 [10, 87, 114, 117] were auditory and 2 [3, 82] tactile feedback.

Table 3: Output modality in the review results.

Modalities	Count	Reference
Visuospatial (V)	40	[1, 2, 4, 22, 24–26, 28, 29, 34, 35, 37, 39, 40, 46, 48, 50, 51, 57, 59, 67, 75, 81, 89–91, 95, 96, 98, 105, 107–109, 111, 115, 120, 122, 125, 134, 141]
Audial (A)	4	[10, 87, 114, 117]
Haptic (H)	2	[3, 82]
V + A	20	[5, 7, 11, 12, 17, 41, 43, 44, 55, 56, 60, 65, 69, 86, 110, 129, 140, 142, 145, 146]
V + H	12	[23, 27, 30, 49, 54, 72, 74, 76, 85, 100, 104, 119]
A + H	3	[63, 102, 116]
V + A + H	7	[6, 13, 20, 42, 97, 101, 148]

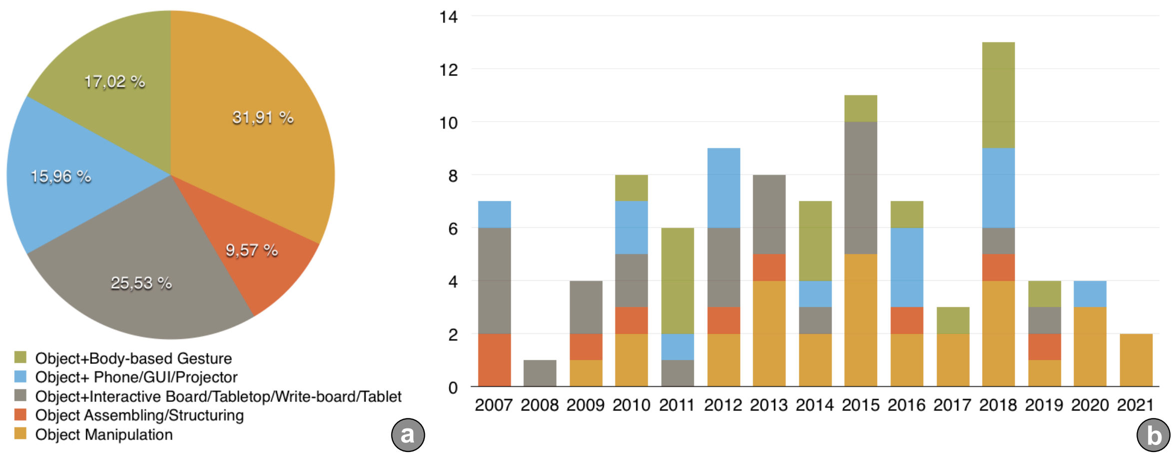

Figure 1: Tangible input methods used in the review results (a. Method distribution; b. Year distribution)

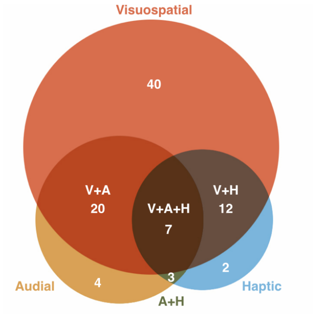

Figure 2: Output modality in the review results.

4.4 Materials Used for TUI

We found three main considerations to build TUI prototypes in the surveyed papers: production, usability, and learning application. For production, research considered more about the cost and convenience, which made them usually use wood [17, 24, 42, 44, 46, 55, 102, 141] or acrylic [2, 5, 6, 65, 75, 90, 107, 120]. In addition, TUI researchers usually selected appropriate materials based on the component's function. For example, using wood [5, 28, 86, 109, 120] and metal [3] to support the structure, soft fabric [57, 141] or transparent acrylic [5, 6] as a surface, and foam [23, 30, 82] as the filler. Researchers used paper [29, 35, 37, 54, 97] and modelling clay [30] to build preliminary and more sophisticated models due to their plasticity.

To increase tangibles' usability, researchers also used materials and objects from daily life to develop tangible prototypes, e.g., gloves [63], piano [145], torch [107], skateboard [109]. In addition, using tools like injection syringe [122] and laboratory flack [98] helped students to transfer the knowledge and more accessible to apply them in practice. Interestingly, materials suitable for wearable prototypes were used to design peripheral tools to avoid interfering with participants to complete the main tasks [4, 63, 101]. For instance, in *ClassBeacons* [4], an adjustable Velcro structure was used to ensure the garment was suitable for different teachers. Moreover, the material texture was another factor that was considered for TUI design. Some studies [22, 39, 142] used 2D icons and labels or even 3D shapes [23, 117] to distinguish different tangibles. However, Tactile Letters [42] explored the design space of materials by using different textures to help users distinguish different tangible letters for learning to read.

For learning applications, specific learning content and task may have constraints on materials selection. For example, when using TUIs to learn the optical properties in physics classes, the properties like refraction, reflection may affect students' understanding and experience of learning [96]. In addition, children's safety needs to be considered. For instance, we should avoid using tangibles which had sharp edges and might be eaten by mistake [65]. In addition, some researchers used everyday materials, like paper, because such prototypes have the advantage to be scalable and customised easily for different age groups [54]. Finally, a number of studies [117] had no special materials requirements because they aimed to make TUIs to be easily duplicated and widely used in teaching practice.

4.5 Tangible Collaborative Learning

As shown in study purpose, 24 studies' purpose was to enable and facilitate collaborative learning. To achieve this, as shown in Table 4, TUIs had three different collaborative mechanisms: sharing resources, multi-touch interaction, and single-touch interaction. For shared resources, different resources required to complete a task were divided among group members to prevent one person from taking over the whole activity. For example, *Futura* [5], a tabletop game, gave participants decision-makers in different perspectives for planning land use to support the growing population and sustainable environment. By incorporating multi-touch interaction, TUIs can offer multiple tangible objects to be interacted with. For instance, *BacPack* [75], a tangible museum exhibit, provided multiple tangible tokens for visitors to explore bio-design. Here, they designed single-touch interactions making participants have to take turns fostering collaboration. For example, *CodeAttach* [148]

Table 4: Collaborative mechanisms of TUI designs in the review results.

Mechanisms	Count	References
Share resources	3	[5, 87, 98]
Multi-touch interaction	16	[1, 11, 22, 25, 40, 46, 54, 67, 74, 75, 81, 91, 107, 108, 140, 146]
Single-touch interaction	5	[48, 56, 65, 86, 148]

Table 5: Group sizes for collaborative interaction in the review results.

Group size	Count	References
Pair (2)	9	[22, 25, 56, 67, 81, 91, 108, 140, 146]
Small group (3-5)	12	[1, 5, 40, 46, 48, 54, 65, 74, 75, 87, 98, 107]
Large group (6+)	3	[11, 86, 148]

attached everyday objects for playing physical games together via interacting with only one tangible interface.

We found a diverse number of people who could take part in collaborative interaction. As shown in Table 5, we divided them into three categories: pair (2 participants), small group (3-5), and large group (6+). For pairs, studies used a game, e.g., *tangible jigsaw puzzle* [146], in which the pairs had to complete problem-solving tasks. For small groups, the interactive designs were supposed to include all the participants. Esteves et al. [40] proposed a tangible *four-in-a-row* game board for three players. In addition, some TUIs were designed to be suitable for small groups as well as single learners. For instance, *Code Bits* [54] is a tangible toolkit for computational thinking, with which individual players or groups could be defined by placing tangible paper bits on the table. Code could then be executed by using a mobile application. On the other hand, Martinez et al. [86] proposed a TUI for large groups, where eight participants could stand in a circle and discuss a special topic by passing around a tangible token to talk.

As shown in Table 6, we found four different contexts for tangible collaborative interaction. *Exploration* means to explore and learn a topic presented or guided by TUIs. For example, Price et al. [108] allowed learners to explore light behaviours. *Problem solving* referred to participants completing a task with TUIs. For example, in *TagTiles* [140] (a tangible board game), all participants were asked to reproduce a pattern from a central display with tiles. *Skill development* could be language learning or machine learning, e.g., *LinguaBytes* [56] helped non- or hardly speaking children to improve their language development. Finally, TUIs could act as a medium for communication. *TurnTalk* [46] is a visualising example; it presented turn-taking norms during conversations and simultaneously offered participants the possibility to reflect on their actions.

Participants were willing to collaborate instead of working alone during tangible learning activities [120]. For example, children were observed to develop rules and turn-taking strategies on their own [26]. They could collaborate synchronously or asynchronously [120] and in different ways, such as working together or in parallel [22]. It has been shown that TUIs can create more opportunities for collaboration than multi-touch interaction [75] because TUIs' configuration and function design influenced users' communication and collaborative style. More specifically, we found the following five contributing reasons. (1) Good visibility and externalisation. For instance, in the museum, although the negotiating control was centred, the content could be easily shared among a group of visitors [60]. (2) Participants' position (e.g., opposite, adjacent, moving) impacted their actions, activities, and talking between each other [60]. (3) Flexibility of the TUI design fostered intended role play and role switching [5]. (4) Shareable TUI tools motivated social engagement [89]. (5) Integrating physical objects and digital representation increased children's social learning. For instance, *LinguaBytes* [56] provided non-or hardly speaking children the opportunity to express, communicate, and learn and improve their social and emotional development.

Table 6: Contexts for collaborative tangible interaction in the review results.

Contexts	Count	References
Exploration	8	[1, 5, 48, 75, 87, 98, 107, 108]
Problem solving	8	[22, 40, 54, 74, 81, 140, 146, 148]
Skill development	4	[56, 65, 67, 91]
Communication	4	[11, 25, 46, 86]

Besides collaboration among peers, some studies also found it promoted collaboration between parents and their children because "an adult's reaction to children's behaviour is important" [101]. Bonani et al. [17] indicated that required adult support allowing them to gain a better understanding. For example, caretakers could scaffold children while leaving enough space for surprises and challenges [101]. In *Ghost Hunter*, parents provided their children with physical assistance and conceptual elaboration, which helped them find electricity consumption sources [13]. *Futura* [5] showed that grouping children with their parents encouraged collaboration. TUIs encouraged educational conversations between adults and children, which helped their interactions with the system conversely [60] and the discussion [72].

4.6 TUIs' Impacts on Learning

More than 26 studies found TUI had a positive impact on learning. In the review results, there were four applications. First, programming was one of the popular subjects. By using coding to create new physical activities or change rules of existing activities [148], TUI helped children foster their computational thinking [59, 142]. Second, it helped learners learn the correct gesture for instruments (e.g., piano) playing [145] and tooth brushing [3]. Third, it assisted learners to understand complex knowledge, e.g., veterinary concepts [29], bio-design operations [98], ecological strategies [50], and gene editing basics [141]. Finally, it raised children's awareness of energy-saving and sustainability [5]. As shown in Table 7, we summarised TUI effects on learning into three impacting themes: (1) scaffold learning, (2) influence learners' behaviours, and (2) affect their emotions.

4.6.1 Scaffold Learning. As shown in Table 7, scaffold learning has some impacts on learning. *Helping children understand knowledge*

Table 7: The survey papers grouped by the impact on learning.

Impacts	Dimensions	Examples	Ref.
Scaffold Learning	Concept understanding	Get insights from an expert view Correct previous misunderstandings Consolidate ideas and test a hypothesis Bridge time and size scale	[23] [90] [90] [98]
	Cognition	Support an imitation Foster epistemic actions and reduce cognitive costs Improve meta-cognition	[114] [40] [120, 145]
	Task perform	Simplify tasks Enable spatial complementary actions Support an integrated motor-cognitive process	[119, 148] [7] [7]
	Tolerance of errors	Flexible, reconfigurable and low-cost prototype	[95]
	Creativity	Foster an ideation and divergent thinking	[87]
	Self-regulation	Exposed structure explicitly Visible infrastructure and allow to umassemble and reconstruct	[96] [87]
Learning Behaviour	Attention	Extend attention spans Increase focus and considerations	[56] [96]
	Control	Empower with self-control and sense of ownership Increase the control of time	[148] [55]
	Expression	Facilitate more communication with surroundings Strengthen the storytelling and narrative Help to convey sophisticated ideas	[55, 89] [5, 115] [96]
Learning Emotion	Engagement	Foster explorations and improvisations	[56]
	Enjoyment	Make it more interesting Fun, tactile and embodied	[76] [101]
	Immersion	Provide a direct, personal and immersive experience Create a close relationship with the avatars Facilitate children's experiments in the real world	[17] [50] [1]
	Confidence	Positive impact on self-esteem and self-confidence Build a confidence and trust with the teacher	[56] [95]

concepts: The review results showed TUIs had helped children and teenagers learn concepts in different fields, e.g., music [10], mathematics [89], gravitational force [89], principles of physics [90], and popularisation of archaeology [76]. We summarised the reasons came from: first, TUIs allowed students to get insights from an expert view, e.g., *SpinalLog* [23], which provided passive haptic feedback combined with immediate visual feedback, showed in immersive interaction the high fidelity of physical shape had little impact on task performance but was praised in participants' comments. Second, TUIs could correct children's previous misunderstandings and allow them to use a concrete object to design and test their hypothesis [90], which at the same time could be shared with others. Finally, it bridged time and size scale, e.g., *SynFlo* [98] represented a complex biological creation by integrating authentic tangibles, which enabled children to do biological creation through observation, parent intervention, and peer collaboration.

Scaffolding cognition. Compared to traditional GUIs, tangible interaction is more intuitive and straightforward [20]. For instance, *COMB* [114] showed that physical shapes as a meaningful indicator of functionality could support children's imitation, which was regarded as an important behaviour for early learning. In addition, by coupling physical objects with digital content, TUI fostered epistemic actions, which allowed users to reduce their cognitive cost [40]. Physical actions and manipulations facilitated tangible thinking [126] and enabled learners to use external resources to understand the current state [40] and simplify the problem-solving process [70]. Finally, TUIs improved meta-cognition, i.e., self-reflection and self-explanation, which was very important for learning. For instance, compared with mouse and touchscreen interfaces, TUIs as closer interfaces could foster reflection and planning, making them more suitable for problem-solving tasks [34]. *MirrorFugue* [145] enabled piano learners to reflect on their playing gestures by watching and imitating others. *Process Pad* scaffolded explanation to help children learn to explain [120].

Simplifying tasks. TUI was good at simplifying tasks, e.g., enabling complementary spatial action to support integrated motor-cognitive processes [7]. With *CodeAttach* [148], limited connecting possibilities of coding blocks made it easier for young children to learn to program; *Touch Wire* [119] used a TUI to emphasise the most important components to simplify the circuit-building process and hide complex features until children were equipped with enough knowledge. *Increasing tolerance of risks or errors*: TUIs increased the tolerance of risks and errors in the learning process, which allowed learners to gain familiarity with concepts and operations. For example, after experimenting independently with flexible, reconfigurable tangible lighting proxies [95], students learned to control equipment and related hardware and software knowledge without worrying about breaking expensive equipment.

Promoting children and teenagers' creativity. Four studies mentioned that interacting with tangibles had a positive effect on children's and teenagers' creativity [22, 87, 95, 96]. TUIs provided children opportunities for risk-taking and exploration, enabling them to "flex their creative skills with tangibles." This was a good method to foster their ideation and divergent thinking [87]. For instance, *Tangible Lighting Proxies* [95] were used in the K-12 creative arts classroom to allow students to learn the design and operation of stage lighting by experimenting with different possible configurations. When children developed their own narrative material, they were more engaged and creative [96].

Encouraging self-exploration, self-correction, and self-regulated learning. TUIs encouraged children's self-exploration, self-correction and self-regulated learning, especially when the structure of TUIs was explicitly exposed [96]. The tangible installation structure extracted curiosity and conveyed system operations to very young children. For instance, in the Digital Dream Lab [96], children could explore and comprehend the system's operating principles by peering through transparent windows into the tabletop. This design aimed to improve "the walk-up usability of the tangible system" for younger learners. In addition, unassembled objects prompted children's understanding to provide a kind of curiosity about how things work in the world [94]. For example, Matthews et al. [87] pointed out that it was a challenge or even an obstacle for novices to use the tangible system as a design material to implement their ideas. It was better to show the infrastructure and design of the TUIs that not only enabled children to decipher the problem quickly and supported them to unassembled and reconstruct to explore the possible solutions. Rossmy and Wiethoff [114] also mentioned that "the ability to detect and correct false mental models can be seen as beneficial for self-regulated learning."

4.6.2 Impact on Learners' Behaviour.

In addition to making it easier to learn, researchers have also found the effects of TUI on learners' behaviours, such as attention, control, and expression.

Attention. Children's attention span was found to be longer in a tangible and playful interaction style [56]. For children to explore programmatic concepts, Hyunjoo Oh et al. [96] developed *Tabletop Puzzle Blocks* to allow them to create scenarios while playing with puzzle blocks. In this case, children's focus and concentration were increased. Therefore, interactive installation could provide responsive and direct feedback to engage younger learners. In the classroom, *Caw Clock* [12], a TUI at the periphery of teachers' attention, supported time awareness without interfering with the everyday routine.

Control. TUIs empowered children with self-control and a sense of ownership [148], which benefited their initiative and imagination [56]. For example, the design of *LinguaBytes* [56] involved children in activities typically conducted by their teachers or parents, such as setting up the system through placing the story module and programming their toy's RFID label. Moreover, manipulating TUIs slowed down the interaction to better control time for students and teachers [55].

Expression. Many studies indicated that the performative aspects of tangible interaction provided children and adolescents with a powerful medium for self-expression [89] and facilitated more communication with their surroundings. More specifically, tangibles gave children more opportunities for facial, gestural, and verbal expressions [55] as well as strengthened their storytelling and narrative [5, 115] during game play or even in the mathematics curriculum [89]. In addition, *The Digital Dream Lab*, jigsaw puzzle pieces, enabled children to convey sophisticated ideas [96]. Finally, for *others*, TUI was also used as persuasive technology to train certain performance skills, such as healthy habits, because of the direct feedback and influences on behaviours. For example, an active tooth-brushing [3] helped users significantly distinguish the right and wrong tooth-brushing actions.

4.6.3 Impact on Learners' Emotion.

Except for the usability of the interface and learning effects, some studies were more focused on the quality of the overall experience [13]. The interactive experience could influence students' concepts understanding [27]. It had an effective or emotional influence on learning, such as engagement, initiative, playfulness, enjoyment, immersion, and confidence.

More than 19 studies in the review results showed that learners were more active or engaged when using TUIs [148], e.g., narrative material development [96], mini-game and quiz [72]. For instance, children said they liked the tangible game very much [142] and were willing to repeat the learning experience [17]. It showed that high engagement with TUI "benefits for critical thinking, problem-solving and also supporting active learning" [26] and fostered exploration and improvisation, which gave children more initiative for learning [56]. Eight studies found participants enjoy tangible learning experiences [5, 29, 56, 76, 101, 110, 115, 141], even though sometimes the tangible task was too difficult for them [91]. Compared to screen-focused interaction, TUIs were more interesting [76] and appealing to children [56] because the multi-sensory and ambiguous aspects of TUIs were fun, and had tactile, embodied interactions and patterns [101], e.g., story creating [56] and activities on the theatre stage [101].

TUI enabled children to be more immersed in in-class learning and other contexts like museums. Hornecker [60] designed a contextually embedded system, which provided children with a direct, personal, and immersive experience in the Natural History Museum in Berlin. In the *Hunger Games* [50], children had a close relationship with the avatars and formed a strong sense of ownership [50]. Some of them even imagined themselves as natural animals and mimicked their behaviours during the game. Moreover, physical setups augmented with digital settings provided a multi-sensory tangible interface to facilitate children's experiments in the real world and even go beyond reality [1]. Finally, TUIs helped to build children's confidence and trust with teachers [95]. For instance, with the help of *LinguaBytes* [56], disabled children could play as well as normal peers in the language learning application, which positively impacted their self-esteem and confidence.

4.7 Comparative Studies: TUI and Other Interfaces

As shown in Table 8, we found eight comparative studies in the review results. Before 2012, researchers focused more on TUIs' digital characteristics. One of the main research interests was to compare purely physical interaction with digitally augmented TUIs, which were shown to promote children's motivation and creativity. For example, Catala et al. [22] found that the interaction with a TUI produced more ideas and balanced the interaction better. However, since 2013, more researchers have begun to see the advantages of TUI's natural physical properties on learning. It was compared to screen-based interfaces interaction, such as mouse-controlled or touch-controlled GUI. There were three advantages of TUIs. First, TUIs brought motor-cognitive benefits in spatial problem-solving tasks. As Antle and Wang's study [7] showed, TUIs facilitated tactile and 3D interaction, which simplified epistemic strategies. Second, intuitive tangible interaction increased efficiency. Donahue et al. [34] showed that children who used TUIs were significantly more efficient than using mouses. Finally, TUIs afforded instantiation of problem-solving. In other words, "meaningful physical representation of a problem space can improve user performance" [40].

Children showed different behaviours when using tangible interaction methods. For example, both digital and tangible representations could be used to study ancient Egyptian sculptures. However, educational technologies and interaction styles would influence their learning process and outcome [105]. Loparev et al. [75] showed that children tended to focus on the design problem and paid more attention when using a TUI to process and context.

4.8 Survey Results

We coded the survey results from domain participants, developers and teachers. Based on the survey questions, we categorised the answers into four aspects: definition, advantages, challenges, and best applications with good examples. For the *definition*, developers paid more attention to tangible properties and interactive modalities. Teachers considered learning requirements and interactive naturalness more. For example, developers understood it as "Learning with tangible objects, which can use movement, touch or gestures, and have haptic feedback." Teachers considered it was "Emphasise the reality of the subject and the human interaction with the object, interaction should be familiar and makes sense for the task in a human sense." Participants thought it was "Students and teachers interact with their physical environment or with each other in physical ways (e.g., proximity, co-location)."

For the *advantages*, developers proposed some popular topics for TUIs, e.g., playfulness and natural interaction. Teachers thought it was empathy, engagement, emotion and meaning. Participants' opinions were comprehensive and included perspectives of engagement, interaction, teacher, and environment. For instance, developers proposed natural interaction, remote group collaboration, playfulness, reduced cognitive overload. Teachers deemed it: maximised empathy and engagement for students who are bored or disabled, especially during formal learning situations; Left an emotional impact while participating in bodily activities for collaborative learning situations; Allowed for multiple meanings to emerge when learning an open concept with a learning community. Participants' opinions were: (1) More human-native and social forms of engagement, (2) More team interactions, (3) Help teachers know activity progress, (4) Multi-modal learning through embodied interaction, spatial cognition, and social-emotional factors, (5) Immediate visibility to all participants and shared discourse.

For the *challenges*: Developers were worried about the system, interaction and cost. Teachers were about suitability and purpose. Participants were about abstraction, representation and good application. More specifically, developers accounted for cost and effort, design intuitive interaction, and technical reliability. Teachers held the opinions of ambiguity of meaning and purpose of a learning activity might lead to disengagement; Efficiency and accuracy of knowledge transmission; Learning outcome is hard to assess; Not suitable for all learning situations; Drive to make "cool" tech, ignore the abstraction; and shoehorning technology into space/situation where that technology is not helpful or needed. Participants reputed it was hard to bring abstraction, represent complex situations, build a prototype and think about good applications, and it had costs and installation time, physical-digital interface remained elusive.

For the *Best Application*, the developer felt it was to support group works and tangible learning for children. Teachers reputed educational games for K12 and personalised learning for those with disabilities. Participants thought about basic cognitive operations (age 4 8), manual professions, and vocational training. For example, *TinkerLamp* [33], *BeeSim* [103], *Ambient Wood* [113], *Embedded Phenomena* [93], and *EvoRoom* [77].

5 DISCUSSION

In the following, we will discuss the findings gained from our literature review and survey to shed light on the current state of TUIs in learning.

5.1 Was TUI Really Effective or More Effective than Other Interfaces?

From the findings of participant data, we know more than 75% had participant numbers below 50. For all the reviewed publications, around 65% of studies have conducted user studies, but around 80% implemented only one experiment with a study duration from 10 minutes to 3 hours. In other words, most of the results came from a small sample and short experiment time. Therefore, we should look at the effectiveness of TUIs with a rational and critical mind. Some comments from domain participants could help us understand the issues better. For example, teachers were concerned: researchers were "*Drive to make 'cool' tech, ignore the abstraction*", "*Shoehorning technology into space/situation where that technology is not helpful or needed*", and "*Learning outcome is hard to assess.*"

As a result, we should be aware: First, compared with "old" technology, e.g., computer, tablet or interactive whiteboard, TUI is a new approach for learning. However, "new" does not mean "better." One reason is that some students could be distracted by TUIs for their novelty effect [4]. Besides completely focusing on interacting

Table 8: Comparative studies of different interfaces in the review results.

Ref.	Year	Compared Interfaces				Tasks
		Physical	GUI (mouse)	GUI (touch)	TUI	
[146]	2008	✓		✓	✓	Jigsaw puzzle game
[85]	2010	✓	✓			Balance beam task
[22]	2012	✓			✓	Problem solving (creating *Rube-Goldberg* machines)
[7]	2013			✓	✓	Spatial problem solving (jigsaw puzzle)
[34]	2013		✓	✓	✓	Abstract problem solving (modified board game - Mastermind)
[40]	2013		✓	✓	✓	Problem solving (customised game of *Four-in-Arrow*)
[75]	2017			✓	✓	Bio-design activity
[105]	2018			✓	✓	Tasks in archaeology class

with tangibles, they might overlook or skip over other useful information, e.g., text introduction or dialogue displayed on screen [76]. Kaspersen et al. [67] found even though TUIs made the machine learning concept less abstract, participants still struggled to understand the model artefact's representation and functionality. They found was a challenge to connect the machine learning process with real-life applications. Second, not well designed TUIs could affect understanding. For example, Dünser and Hornecker [37] found it was hard for children to navigate from one page to the next when combining paper and onscreen elements. They were also spatially confused by the mirror view of their actions on the screen. In addition, "swapping between literal and symbolic mappings with the same kind of objects proved to be problematic for children." Finally, TUIs might have no or even negative effects on learning. For example, sometimes, even though the positive interactive effects for adults has been proven, it was not optimised for kids [76]. Hyunjoo Oh et al. [96] developed *Tabletop Puzzle Blocks* to allow children to create scenarios while playing with the puzzle blocks. In this case, children's focus and concentration were increased. However, compared to older children, the younger had shorter attention spans.

We summarised three advantages of TUI compared with other interfaces, such as TUI brought motor-cognitive benefits in spatial problem-solving tasks. However, we should be careful to make a conclusion, as: (1) the summary was from only 8 studies; (2) a number of studies found no difference when using TUIs. Thus, while literature presented a number of studies where TUIs have been effective, our analysis showed that this might not be universally the case. Further research is needed to show the effectiveness on a wider content range, a larger sample size, and over a longer time period to make a more reliably conclusion on the effectiveness of TUIs.

5.2 Did TUIs Really Have a Tangible Interaction?

Markova et al. [83] mentioned that there was an issue to clarify whether a system was a TUI or an interface with some tangible aspects. A similar dilemma happened in the review results, where some studies designed interactions with a physical object, but it might be not counted as a tangible interaction. As we know from tangible interaction findings, tangible inputs (see Figure 1) came from: interacting with one or several physical objects, using physical objects with an additional GUI, moving tokens on a surface, assembling or structuring objects, interacting with gestures, body, and movement. The chosen modality in the review results depended on study context variables and had specific advantages. For example, *moving tokens on a surface* could give learners feelings of augmented reality; At the same time, it made the extension of learning content easy and flexible. However, it had an obvious discrete input modality design, which limited the interactive experience.

The output was mainly haptic, visuospatial and audial information. There was a physical-digital integration, which has three types [139]: (1) Discrete: A physical input and digital output are positioned vertically on a surface; (2) Collocated: physical input and digital output are positioned and displayed on a surface; (3) Embedded: the system is embedded within a physical object. Embeddedness is a unique characteristic of TUIs. As Ullmer and Ishii [138] explained: "when viewed from the perspective of HCI, the abacus is not an input device. The abacus makes no distinction between 'input' and 'output.' Instead, the abacus beads, rods, and frame serve as manipulable physical representations of numerical values and operations." In other words, TUIs integrate *interactive control* and *physical and digital representation* with physical objects. At the same time, the interactive control should have a metaphor, which was one of the criteria for TUIs [83]. However, we found in the review results, some studies emphasised embodied interaction too much and ignored its mapping and meaning.

In addition, the influence of materials on tangible interaction was overlooked. A number of studies (15), e.g., [48, 69, 140] focused on the size and shape of the TUI and the functions it provided, ignoring the used material or only using one sentence to describe it in the implementation section. Moreover, in some cases, we could only recognise its materials from the prototype pictures [28, 56], only very few discussed the impacts of materials [23, 42, 76, 101, 104]. For instance, to give users the feeling of using a real baseball bat, Chacon et al. [82] tried to use the tangible bat model with similar shape and size, but its material and texture were not considered.

To have a better understanding of TUIs' meaning and advantages, it is beneficial to analyse them from a HCI perspective. First, humans (H), which refers to the users, might have no evident changes over time. However, the human-centred idea (the second wave of HCI [16]) requires us to consider how to design an HCI to be more intuitive and natural for human interaction. Tangible interaction research provides a good direction for us to envision this possibility.

Therefore, one of the core ideas of tangible interaction should be natural and intuitive for humans. Second, computer (C), which is beyond a traditional computer (e.g., laptop and tablet), can be tiny and ubiquitous. Its size changes how users give and receive feedback, which is as Ullmer and Ishii [138] said: "TUI had no distinction between input and output." When we think about how to design a TUI for learning, its applications could go beyond learning tools to integrating into the learning environment. Representation [106] could increase the representational capacity and functionality of the environment. Finally, interaction (I), which emphasises tangible and embodied interactive experience, should have a figurative meaning. It is the bridge between physical and digital presentation, not just having a physical object to interact with.

We conclude that while a large number of prototypes fulfil the criteria for a TUI. On the other hand, not all the prototypes fulfil the criteria for a TUI. However, researchers aimed to build a TUI. Thus, for the future, it is important to focus on all the details when designing a TUI, especially the currently underrated aspects such as material and texture.

5.3 How Can TUIs Evolve in the Future?

As shown by earlier reviews [53, 84, 112, 147, 149], we confirmed that children and collaboration were two popular areas for tangible learning. Therefore, it might become harder and harder to make an innovation or new contribution if we concentrate on them. In order to enrich the community of tangible learning, researchers should try to avoid this cluster and disperse to find other good topics. For example, in order to take advantage of embodied interaction, we could consider some groups who have visual or communicative problems (e.g., elderly [18], visual-impaired [116], autism [38] and depressed people). In addition, TUI is also good for learning abstract knowledge, which could be embedded into tangible objects to reveal by interaction.

As we could see from survey results about the opinions of TUI advantages and best applications, we recommend the future work could be: First, designing TUIs for the teacher to understand students' behaviours and do their learning analysis. TUIs make it possible to track and record individual behavioural, which is ideal for the teacher to diagnose each student's problems. Second, making TUIs have a social and emotional impact on students. Emotional [9], social learning [150] and academic achievement are highly related. Therefore, researchers could think about how to leave an emotional and social impact on students while they participate in physical activities. Finally, further developing the meaning and metaphor of tangible interaction. As we know, tangible interaction does not only mean having a physical object to interact with. The metaphor between physical and digital representation is essential, as it improves the learning by endowing an inner relationship into the interactive processes.

As a result, while we argue that it will be important to focus on the good quality of the prototypes, we found that the current direction of tangible learning is very much focused on children. Thus, future work should explore new research avenues such as elderly and cognitive impaired people.

6 LIMITATIONS

As a review for tangible learning was long overdue, we focus specifically on the TEI conference to capture the latest trends on tangible technology. In detail, we provide a whole picture of tangible learning from all TEI conference proceedings (2007–2021). In doing so, we keep our investigation focused, which allows us to specifically provide support for researchers and educators, providing them with a better understanding of tangible learning. However, this means that we have not covered all perspectives from all other conferences, such as Conference on Human Factors in Computing Systems (CHI), Interaction Design and Children (IDC), Designing Interactive Systems (DIS), and Creativity & Cognition (C & C). While this limits the point of view on tangible learning only to cover the TEI perspective, we argue that our investigation is a great starting point for future investigations and will help other communities better understand the TEI perspective.

Additionally, we set our main audience to be researchers and technology developers. Thus, the tone we used is very scientific and suggestive towards future trends. Finally, we have an emphasis on collaborative learning and the impacts of TUIs on learning. However, it will be also beneficial to compare them with some other specific review studies.

7 CONCLUSION

In recent years, tangible learning research has received increasing attention. With this review, we analysed the tangible learning studies published in the TEI conference proceedings and provided a comprehensive overview; and thus, providing an updated overview. We reviewed 92 publications from 2007 to the present and provided characteristics of previous studies, such as the study purpose and types of tangible interaction. We categorised three common topics from all the publications: collaborative learning, TUIs' impacts on learning, and comparative studies between TUI and other interfaces. We provide detailed explanations of each topic, especially about how TUI have influenced learning. Additionally, we investigated feedback and insights from 14 domain participants, which provided a more practice-oriented view.

We got three important findings: First, TUI has an impact on learning is because it can scaffold learning (e.g., facilitate concept understanding, reduce cognitive load and increase the learning activity), change learning behaviour (e.g., increase the attention, control and expression) and improve learning emotion (e.g., make it more engaged, immersive and enjoyable). Second, we should see the effectiveness of TUIs with a rational and critical mind. There are many reasons, for example, most of the previous studies were conducted with a small sample and a short experiment time; Students could be distracted by TUIs for its novelty effect; if it is not well designed, TUIs could affect understanding and have no or even negative effects on learning. Finally, some studies emphasised too much on embodied interaction and ignored its mapping and meaning. However, the interactive control should have a metaphor, which was one of the criteria for TUIs. For future work, we suggest avoiding an intensive cluster on collaborative learning and children education. Some other valuable research areas, such as TUI for teachers, TUIs' social and emotional impacts on students, develop the meaning and metaphor of tangible interaction.

ACKNOWLEDGMENTS

This research is funded by the Elite Network of Bavaria (K-GS-2012-209).

REFERENCES

[1] Zeynep Ahmet, Martin Jonsson, Saiful Islam Sumon, and Lars Erik Holmquist. 2010. Supporting Embodied Exploration of Physical Concepts in Mixed Digital and Physical Interactive Settings. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 109–116. https://doi.org/10.1145/1935701.1935723

[2] Abel Allison, Sean Follmer, and Hayes Raffle. 2010. TessalTable: Tile-Based Creation of Patterns and Images. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 203–204. https://doi.org/10.1145/1709886.1709923

[3] Miguel Bruns Alonso, Jelle Stienstra, and Rob Dijkstra. 2014. Brush and Learn: Transforming Tooth Brushing Behavior through Interactive Materiality, a Design Exploration. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 113–120. https://doi.org/10.1145/2540930.2540981

[4] Pengcheng An, Saskia Bakker, Sara Ordanovski, Ruurd Taconis, and Berry Eggen. 2018. ClassBeacons: Designing Distributed Visualization of Teachers' Physical Proximity in the Classroom. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 357–367. https://doi.org/10.1145/3173225.3173243

[5] Alissa N. Antle, Allen Bevans, Theresa Jean Tanenbaum, Katie Seaborn, and Sijie Wang. 2010. 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* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 93–100. https://doi.org/10.1145/1935701.1935721

[6] Alissa N. Antle, Min Fan, and Emily S. Cramer. 2015. PhonoBlocks: A Tangible System for Supporting Dyslexic Children Learning to Read. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 533–538. https://doi.org/10.1145/2677199.2687897

[7] Alissa N. Antle and Sijie Wang. 2013. Comparing Motor-Cognitive Strategies for Spatial Problem Solving with Tangible and Multi-Touch Interfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 65–72. https://doi.org/10.1145/2460625.2460635

[8] Alissa N. Antle and Alyssa F. Wise. 2013. Getting Down to Details: Using Theories of Cognition and Learning to Inform Tangible User Interface Design. *Interacting with Computers* 25, 1 (01 2013), 1–20. https://doi.org/10.1093/iwc/iws007

[9] Elena P. Antonacopoulou and Yiannis Gabriel. 2001. Emotion, learning and organizational change. *Journal of Organizational Change Management* 14, 5 (01 Jan 2001), 435–451. https://doi.org/10.1108/EUM0000000005874

[10] Saskia Bakker, Elise van den Hoven, and Alissa N. Antle. 2010. MoSo Tangibles: Evaluating Embodied Learning. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 85–92. https://doi.org/10.1145/1935701.1935720

[11] Saskia Bakker, Elise van den Hoven, and Berry Eggen. 2013. FireFlies: Physical Peripheral Interaction Design for the Everyday Routine of Primary School Teachers. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 57–64. https://doi.org/10.1145/2460625.2460634

[12] Saskia Bakker, Elise van den Hoven, Berry Eggen, and Kees Overbeeke. 2012. Exploring Peripheral Interaction Design for Primary School Teachers. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 245–252. https://doi.org/10.1145/2148131.2148184

[13] Amartya Banerjee and Michael S. Horn. 2014. Ghost Hunter: Parents and Children Playing Together to Learn about Energy Consumption. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 267–274. https://doi.org/10.1145/2540930.2540964

[14] Gökçe Elif Baykal, I Veryeri Alaca, Asim Evren Yantaç, and Tilbe Göksun. 2018. A review on complementary natures of tangible user interfaces (TUIs) and early spatial learning. *International Journal of Child-Computer Interaction* 16 (2018), 104–113. https://doi.org/10.1016/j.ijcci.2018.01.003

[15] Gökçe Elif Baykal, Maarten Van Mechelen, and Eva Eriksson. 2020. Collaborative Technologies for Children with Special Needs: A Systematic Literature Review. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376291

[16] Susanne Bødker. 2006. When Second Wave HCI Meets Third Wave Challenges. In *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles* (Oslo, Norway) *(NordiCHI '06)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/1182475.1182476

[17] Andrea Bonani, Vincenzo Del Fatto, and Rosella Gennari. 2018. The Evolving Design of Tangibles for Graph Algorithmic Thinking. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 65–72. https://doi.org/10.1145/3173225.3173270

[18] Way Kiat Bong, Weiqin Chen, and Astrid Bergland. 2018. Tangible User Interface for Social Interactions for the Elderly: A Review of Literature. *Advances in Human-Computer Interaction* 2018 (02 May 2018), 7249378. https://doi.org/10.1155/2018/7249378

[19] Quentin Bonnard, Patrick Jermann, Amanda Legge, Frédéric Kaplan, and Pierre Dillenbourg. 2012. Tangible Paper Interfaces: Interpreting Pupils' Manipulations. In *Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces* (Cambridge, Massachusetts, USA) *(ITS '12)*. Association for Computing Machinery, New York, NY, USA, 133–142. https://doi.org/10.1145/2396636.2396658

[20] Dirk Börner, Bernardo Tabuenca, Jeroen Storm, Sven Happe, and Marcus Specht. 2015. Tangible Interactive Ambient Display Prototypes to Support Learning Scenarios. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 721–726. https://doi.org/10.1145/2677199.2687908

[21] Marleny Luque Carbajal and M. Cecília C. Baranauskas. 2020. Analyzing the Socioenactive Dimensions of Creative Learning Environments with Preschool Children. In *Proceedings of the 19th Brazilian Symposium on Human Factors in Computing Systems* (Diamantina, Brazil) *(IHC '20)*. Association for Computing Machinery, New York, NY, USA, Article 6, 10 pages. https://doi.org/10.1145/3424953.3426510

[22] Alejandro Catala, Javier Jaen, Betsy van Dijk, and Sergi Jordà. 2012. Exploring Tabletops as an Effective Tool to Foster Creativity Traits. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 143–150. https://doi.org/10.1145/2148131.2148163

[23] D. Antony Chacon, Eduardo Velloso, Thuong Hoang, and Katrin Wolf. 2019. SpinalLog: Visuo-Haptic Feedback in Musculoskeletal Manipulation Training. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 5–14. https://doi.org/10.1145/3294109.3295626

[24] Jack Shen-Kuen Chang. 2017. The Design and Evaluation of Embodied Interfaces for Supporting Spatial Ability. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 681–684. https://doi.org/10.1145/3024969.3025033

[25] Rui Chen, Po-Jui (Ray) Chen, Rui Feng, Yilin (Elaine) Liu, Andy Wu, and Ali Mazalek. 2014. SciSketch: A Tabletop Collaborative Sketching System. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 247–250. https://doi.org/10.1145/2540930.2540973

[26] Jaewon Cho, Junwoo Yoo, Ju-young Shin, Jun-dong Cho, and Andrea Bianchi. 2017. Quantifying Children's Engagement with Educational Tangible Blocks. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 389–395. https://doi.org/10.1145/3024969.3025062

[27] Jean Ho Chu, Paul Clifton, Daniel Harley, Jordanne Pavao, and Ali Mazalek. 2015. Mapping Place: Supporting Cultural Learning through a Lukasa-Inspired Tangible Tabletop Museum Exhibit. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 261–268. https://doi.org/10.1145/2677199.2680559

[28] Paul Clifton. 2014. Designing Embodied Interfaces to Support Spatial Ability. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 309–312. https://doi.org/10.1145/2540930.2558151

[29] Margaret Cook, Jinsil Hwaryoung Seo, Michelle Pine, and Annie Sungkajun. 2018. Paper Circuitry and Projection Mapping: An Interactive Textbook Approach to Veterinary Education. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden)

(TEI '18). Association for Computing Machinery, New York, NY, USA, 131–135. https://doi.org/10.1145/3173225.3173290

[30] Emily S. Cramer and Alissa N. Antle. 2015. Button Matrix: How Tangible Interfaces Can Structure Physical Experiences for Learning. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 301–304. https://doi.org/10.1145/2677199.2680566

[31] Vinicius Kruger da Costa, Ana Priscila Valerão de Vasconcellos, Natalia Toralles Darley, and Tatiana Aires Tavares. 2018. Methodologies and Evaluation Tools Used in Tangible User Interfaces: A Systematic Literature Review. In *Proceedings of the 17th Brazilian Symposium on Human Factors in Computing Systems* (Belém, Brazil) *(IHC 2018)*. Association for Computing Machinery, New York, NY, USA, Article 31, 9 pages. https://doi.org/10.1145/3274192.3274223

[32] Raffaele Di Fuccio and Sara Mastroberti. 2018. Tangible user interfaces for multisensory storytelling at school: A study of acceptability. *Qwerty-Open and Interdisciplinary Journal of Technology, Culture and Education* 13 (2018), 62–75.

[33] Son Do-Lenh, Patrick Jermann, Amanda Legge, Guillaume Zufferey, and Pierre Dillenbourg. 2012. TinkerLamp 2.0: designing and evaluating orchestration technologies for the classroom. In *European Conference on Technology Enhanced Learning*. Springer, 65–78. https://doi.org/10.1007/978-3-642-33263-0_6

[34] Thomas J. Donahue, G. Michael Poor, Martez E. Mott, Laura Marie Leventhal, Guy Zimmerman, and Dale Klopfer. 2013. On Interface Closeness and Problem Solving. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 139–146. https://doi.org/10.1145/2460625.2460647

[35] Tanja Döring and Steffi Beckhaus. 2007. The Card Box at Hand: Exploring the Potentials of a Paper-Based Tangible Interface for Education and Research in Art History. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 87–90. https://doi.org/10.1145/1226969.1226986

[36] Marina C. Drazba, Alice Yan-Richards, and Suzanne Wilkinson. 2018. Landslide Hazards in Fiji, managing the risk and not the disaster, a literature review. *Procedia Engineering* 212 (2018), 1334–1338. https://doi.org/10.1016/j.proeng.2018.01.172 7th International Conference on Building Resilience: Using scientific knowledge to inform policy and practice in disaster risk reduction.

[37] Andreas Dünser and Eva Hornecker. 2007. Lessons from an AR Book Study. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 179–182. https://doi.org/10.1145/1226969.1227006

[38] Lizbeth Escobedo, Catalina Ibarra, Jehu Hernandez, Mariana Alvelais, and Monica Tentori. 2014. Smart Objects to Support the Discrimination Training of Children with Autism. *Personal Ubiquitous Comput.* 18, 6 (Aug. 2014), 1485–1497. https://doi.org/10.1007/s00779-013-0750-3

[39] Augusto Esteves, Michelle Scott, and Ian Oakley. 2013. Supporting Offline Activities on Interactive Surfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 147–154. https://doi.org/10.1145/2460625.2460648

[40] Augusto Esteves, Elise van den Hoven, and Ian Oakley. 2013. 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* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 167–174. https://doi.org/10.1145/2460625.2460651

[41] Taciana Pontual Falcão. 2012. Fostering Exploratory Learning in Students with Intellectual Disabilities: How Can Tangibles Help?. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 397–398. https://doi.org/10.1145/2148131.2148232

[42] Min Fan and Alissa N. Antle. 2015. Tactile Letters: A Tangible Tabletop with Texture Cues Supporting Alphabetic Learning for Dyslexic Children. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 673–678. https://doi.org/10.1145/2677199.2688806

[43] Min Fan, Alissa N. Antle, and Emily S. Cramer. 2016. Exploring the Design Space of Tangible Systems Supported for Early Reading Acquisition in Children with Dyslexia. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 689–692. https://doi.org/10.1145/2839462.2854104

[44] Trisha Garcia, Shannon Brown, and Siona Dev. 2018. TUIst: A Collaborative and Computationally Enhanced Game Board. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 337–342. https://doi.org/10.1145/3173225.3173282

[45] Fernando Garcia-Sanjuan, Javier Jaen, Vicente Nacher, and Alejandro Catala. 2015. Design and Evaluation of a Tangible-Mediated Robot for Kindergarten Instruction. In *Proceedings of the 12th International Conference on Advances in Computer Entertainment Technology* (Iskandar, Malaysia) *(ACE '15)*. Association for Computing Machinery, New York, NY, USA, Article 3, 11 pages. https://doi.org/10.1145/2832932.2832952

[46] Rosella Gennari, Alessandra Melonio, and Mehdi Rizvi. 2018. Evolving Tangibles for Children's Social Learning through Conversations: Beyond TurnTalk. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 368–375. https://doi.org/10.1145/3173225.3173248

[47] Victor Girotto, Cecil Lozano, Kasia Muldner, Winslow Burleson, and Erin Walker. 2016. Lessons Learned from In-School Use of RTAG: A Robo-Tangible Learning Environment. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 919–930. https://doi.org/10.1145/2858036.2858454

[48] Audrey Girouard, Erin Treacy Solovey, Leanne M. Hirshfield, Stacey Ecott, Orit Shaer, and Robert J. K. Jacob. 2007. Smart Blocks: A Tangible Mathematical Manipulative. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 183–186. https://doi.org/10.1145/1226969.1227007

[49] Thomas Gläser, Jens Franke, Götz Wintergerst, and Ron Jagodzinski. 2009. Chemieraum: Tangible Chemistry in Exhibition Space. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction* (Cambridge, United Kingdom) *(TEI '09)*. Association for Computing Machinery, New York, NY, USA, 285–288. https://doi.org/10.1145/1517664.1517723

[50] Alessandro Gnoli, Anthony Perritano, Paulo Guerra, Brenda Lopez, Joel Brown, and Tom Moher. 2014. Back to the Future: Embodied Classroom Simulations of Animal Foraging. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 275–282. https://doi.org/10.1145/2540930.2540972

[51] Kristian Gohlke, Michael Hlatky, and Bram de Jong. 2015. Physical Construction Toys for Rapid Sketching of Tangible User Interfaces. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 643–648. https://doi.org/10.1145/2677199.2687900

[52] Taisa G. Gonçalves, Christophe Kolski, Káthia M. de Oliveira, Guilherme H. Travassos, and Emmanuelle Grislin-Le Strugeon. 2019. A Systematic Literature Review on Intelligent User Interfaces: Preliminary Results. In *Proceedings of the 31st Conference on l'Interaction Homme-Machine: Adjunct* (Grenoble, France) *(IHM '19)*. Association for Computing Machinery, New York, NY, USA, Article 5, 8 pages. https://doi.org/10.1145/3366551.3370344

[53] Carina S. González-González, María D. Guzmán-Franco, and Alfonso Infante-Moro. 2019. Tangible Technologies for Childhood Education: A Systematic Review. *Sustainability* 11, 10 (2019). https://doi.org/10.3390/su11102910

[54] Sidhant Goyal, Rohan S. Vijay, Charu Monga, and Pratul Kalita. 2016. Code Bits: An Inexpensive Tangible Computational Thinking Toolkit For K-12 Curriculum. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 441–447. https://doi.org/10.1145/2839462.2856541

[55] Bart Hengeveld, Caroline Hummels, Kees Overbeeke, Riny Voort, Hans van Balkom, and Jan de Moor. 2009. Tangibles for Toddlers Learning Language. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction* (Cambridge, United Kingdom) *(TEI '09)*. Association for Computing Machinery, New York, NY, USA, 161–168. https://doi.org/10.1145/1517664.1517702

[56] Bart Hengeveld, Caroline Hummels, Hans van Balkom, Riny Voort, and Jan de Moor. 2013. Wrapping up LinguaBytes, for Now. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 237–244. https://doi.org/10.1145/2460625.2460664

[57] Bart Hengeveld, Riny Voort, Hans van Balkom, Caroline Hummels, and Jan de Moor. 2007. Designing for Diversity: Developing Complex Adaptive Tangible Products. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 155–158. https://doi.org/10.1145/1226969.1227002

[58] Michael S. Horn, R. Jordan Crouser, and Marina U. Bers. 2012. Tangible interaction and learning: the case for a hybrid approach. *Personal and Ubiquitous Computing* 16, 4 (01 Apr 2012), 379–389. https://doi.org/10.1007/s00779-011-0404-2

[59] Michael S. Horn and Robert J. K. Jacob. 2007. Designing Tangible Programming Languages for Classroom Use. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana)

(TEI '07). Association for Computing Machinery, New York, NY, USA, 159–162. https://doi.org/10.1145/1226969.1227003

[60] Eva Hornecker. 2010. Interactions around a Contextually Embedded System. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 169–176. https://doi.org/10.1145/1709886.1709916

[61] Eva Hornecker and Jacob Buur. 2006. 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* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 437–446. https://doi.org/10.1145/1124772.1124838

[62] Mokter Hossain, Seppo Leminen, and Mika Westerlund. 2019. A systematic review of living lab literature. *Journal of Cleaner Production* 213 (2019), 976–988. https://doi.org/10.1016/j.jclepro.2018.12.257

[63] Chuan-Che Huang, Yu-Jen Lin, Xinda Zeng, Mark Newman, and Sile O'Modhrain. 2015. Olegoru: A Soundscape Composition Tool to Enhance Imaginative Storytelling with Tangible Objects. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 709–714. https://doi.org/10.1145/2677199.2687895

[64] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '97)*. Association for Computing Machinery, New York, NY, USA, 234–241. https://doi.org/10.1145/258549.258715

[65] Azusa Kadomura, Koji Tsukada, Tetsuaki Baba, and Kumiko Kushiyama. 2012. Hangul Gangul: Interactive Toy for Hangul Learning. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 323–324. https://doi.org/10.1145/2148131.2148203

[66] Azmina Karimi, Beth Liang, Andrew Nip, Saba Nowroozi, and Celeste Pang. 2012. Time-Me: Helping Children Understand Time. In *Proceedings of the 11th International Conference on Interaction Design and Children* (Bremen, Germany) *(IDC '12)*. Association for Computing Machinery, New York, NY, USA, 268–271. https://doi.org/10.1145/2307096.2307142

[67] Magnus Høholt Kaspersen, Karl-Emil Kjær Bilstrup, and Marianne Graves Petersen. 2021. 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* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 19, 12 pages. https://doi.org/10.1145/3430524.3440638

[68] Ioannis Kazanidis, George Palaigeorgiou, and Christos Bazinas. 2018. 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, 1–5. https://doi.org/10.23919/SEEDA-CECNSM.2018.8544927

[69] Madhur Khandelwal and Ali Mazalek. 2007. Teaching Table: A Tangible Mentor for Pre-k Math Education. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 191–194. https://doi.org/10.1145/1226969.1227009

[70] David Kirsh. 2009. Projection, problem space and anchoring. In *Proceedings of the 31st annual conference of the cognitive science society*.

[71] Kian Teck Lee. 2016. Use of Tangible Learning in Stem Education. In *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications* (Macau) *(SA '16)*. Association for Computing Machinery, New York, NY, USA, Article 23, 2 pages. https://doi.org/10.1145/2999508.3008582

[72] Seung Ah Lee, Alice M. Chung, Nate Cira, and Ingmar H. Riedel-Kruse. 2015. Tangible Interactive Microbiology for Informal Science Education. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 273–280. https://doi.org/10.1145/2677199.2680561

[73] Zeina Atrash Leong and Michael S. Horn. 2011. Representing Equality: A Tangible Balance Beam for Early Algebra Education. In *Proceedings of the 10th International Conference on Interaction Design and Children* (Ann Arbor, Michigan) *(IDC '11)*. Association for Computing Machinery, New York, NY, USA, 173–176. https://doi.org/10.1145/1999030.1999054

[74] Dixon Lo and Austin Lee. 2016. Click: Using Smart Devices For Physical Collaborative Coding Education. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 500–505. https://doi.org/10.1145/2839462.2856522

[75] Anna Loparev, Lauren Westendorf, Margaret Flemings, Jennifer Cho, Romie Littrell, Anja Scholze, and Orit Shaer. 2017. BacPack: Exploring the Role of Tangibles in a Museum Exhibit for Bio-Design. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 111–120. https://doi.org/10.1145/3024969.3025000

[76] Qi Lu, Shao-en Ma, Jiayin Li, Haipeng Mi, and Yingqing Xu. 2019. IRelics: Designing a Tangible Interaction Platform for the Popularization of Field Archaeology. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 45–54. https://doi.org/10.1145/3294109.3295647

[77] Michelle Lui and James D. Slotta. 2014. Immersive simulations for smart classrooms: exploring evolutionary concepts in secondary science. *Technology, Pedagogy and Education* 23, 1 (2014), 57–80. https://doi.org/10.1080/1475939X.2013.838452 arXiv:https://doi.org/10.1080/1475939X.2013.838452

[78] Leilah Lyons, Brian Slattery, Priscilla Jimenez, Brenda Lopez, and Tom Moher. 2012. Don't Forget about the Sweat: Effortful Embodied Interaction in Support of Learning. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 77–84. https://doi.org/10.1145/2148131.2148149

[79] Laura Malinverni and Narcis Pares. 2014. Learning of Abstract Concepts through Full-Body Interaction: A Systematic Review. *Journal of Educational Technology & Society* 17, 4 (2014), 100–116. http://www.jstor.org/stable/jeductechsoci.17.4.100

[80] Andrew Manches, Claire O'Malley, and Steve Benford. 2009. Physical Manipulation: Evaluating the Potential for Tangible Designs. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction* (Cambridge, United Kingdom) *(TEI '09)*. Association for Computing Machinery, New York, NY, USA, 77–84. https://doi.org/10.1145/1517664.1517688

[81] Valérie Maquil, Christian Moll, Lou Schwartz, and Johannes Hermen. 2018. Kniwwelino: A Lightweight and WiFi Enabled Prototyping Platform for Children. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 94–100. https://doi.org/10.1145/3173225.3173275

[82] Milena S. Markova. 2014. How Does the Tangible Object Affect Motor Skill Learning?. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 305–308. https://doi.org/10.1145/2540930.2558150

[83] Milena S. Markova, Stephanie Wilson, and Simone Stumpf. 2012. Tangible user interfaces for learning. *International Journal of Technology Enhanced Learning* 4, 3-4 (2012), 139–155. https://doi.org/10.1504/IJTEL.2012.051578

[84] Paul Marshall. 2007. Do Tangible Interfaces Enhance Learning?. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 163–170. https://doi.org/10.1145/1226969.1227004

[85] Paul Marshall, Peter C.-H. Cheng, and Rosemary Luckin. 2010. Tangibles in the Balance: A Discovery Learning Task with Physical or Graphical Materials. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 153–160. https://doi.org/10.1145/1709886.1709914

[86] Christopher Martinez, Randy Kemp, David Birchfield, Ellen Campana, Todd Ingalls, and Gkisedtanamoogk. 2010. Culturally Sensible Digital Place-Making: Design of the Mediated Xicanindio Resolana. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 161–168. https://doi.org/10.1145/1709886.1709915

[87] Sarah Matthews, Stephen Viller, and Marie A. Boden. 2020. "... And We Are the Creators!" Technologies as Creative Material. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 511–518. https://doi.org/10.1145/3374920.3374980

[88] Aditya Mehrotra, Christian Giang, Noé Duruz, Julien Dedelley, Andrea Mussati, Melissa Skweres, and Francesco Mondada. 2020. Introducing a Paper-Based Programming Language for Computing Education in Classrooms. In *Proceedings of the 2020 ACM Conference on Innovation and Technology in Computer Science Education* (Trondheim, Norway) *(ITiCSE '20)*. Association for Computing Machinery, New York, NY, USA, 180–186. https://doi.org/10.1145/3341525.3387402

[89] Jason Mickelson and Wendy Ju. 2010. Math Propulsion: Engaging Math Learners through Embodied Performance & Visualization. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 101–108. https://doi.org/10.1145/1935701.1935722

[90] Andrea Miller, Claire Rosenbaum, and Paulo Blikstein. 2012. MagneTracks: A Tangible Constructionist Toolkit for Newtonian Physics. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 253–256. https://doi.org/10.1145/2148131.2148185

[91] Svetlana Mironcika, Antoine de Schipper, Annette Brons, Huub Toussaint, Ben Kröse, and Ben Schouten. 2018. 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* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 349–356. https://doi.org/10.1145/3173225.3173256

[92] David Moher, Alessandro Liberati, Jennifer Tetzlaff, Douglas G. Altman, and The PRISMA Group. 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine* 6, 7 (07 2009), 1–6. https://doi.org/10.1371/journal.pmed.1000097

[93] Tom Moher. 2006. Embedded Phenomena: Supporting Science Learning with Classroom-Sized Distributed Simulations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 691–700. https://doi.org/10.1145/1124772.1124875

[94] Martin Murer, Verena Fuchsberger, and Manfred Tscheligi. 2017. Un-crafting: De-constructive engagements with interactive artifacts. In *Proceedings of the Eleventh International Conference on tangible, embedded, and embodied interaction*. 67–77.

[95] Rebecca Nicholson, David Kirk, and Tom Bartindale. 2021. Tangible Lighting Proxies: Brokering the Transition from Classroom to Stage. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 40, 13 pages. https://doi.org/10.1145/3430524.3440659

[96] Hyunjoo Oh, Anisha Deshmane, Feiran Li, Ji Yeon Han, Matt Stewart, Michael Tsai, Xing Xu, and Ian Oakley. 2013. The Digital Dream Lab: Tabletop Puzzle Blocks for Exploring Programmatic Concepts. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 51–56. https://doi.org/10.1145/2460625.2460633

[97] Hyunjoo Oh and Mark D. Gross. 2015. Cube-in: A Learning Kit for Physical Computing Basics. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 383–386. https://doi.org/10.1145/2677199.2680597

[98] Johanna Okerlund, Evan Segreto, Casey Grote, Lauren Westendorf, Anja Scholze, Romie Littrell, and Orit Shaer. 2016. SynFlo: A Tangible Museum Exhibit for Exploring Bio-Design. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 141–149. https://doi.org/10.1145/2839462.2839488

[99] Claire O'Malley and Danae Stanton Fraser. 2004. Literature review in learning with tangible technologies. (2004).

[100] Leonhard Oschuetz, Daniel Wessolek, and Wolfgang Sattler. 2010. Constructing with Movement: Kinematics. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 257–260. https://doi.org/10.1145/1709886.1709938

[101] Roma Patel, Holger Schnädelbach, and Boriana Koleva. 2018. Come and Play: Interactive Theatre For Early Years. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 376–385. https://doi.org/10.1145/3173225.3173251

[102] Huaishu Peng. 2012. Algo.Rhythm: Computational Thinking through Tangible Music Device. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 401–402. https://doi.org/10.1145/2148131.2148234

[103] Kylie Peppler, Joshua Danish, Benjamin Zaitlen, Diane Glosson, Alexander Jacobs, and David Phelps. 2010. BeeSim: Leveraging Wearable Computers in Participatory Simulations with Young Children. In *Proceedings of the 9th International Conference on Interaction Design and Children* (Barcelona, Spain) *(IDC '10)*. Association for Computing Machinery, New York, NY, USA, 246–249. https://doi.org/10.1145/1810543.1810582

[104] Ingrid Maria Pohl and Lian Loke. 2014. Touch Toolkit: A Method to Convey Touch-Based Design Knowledge and Skills. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 251–258. https://doi.org/10.1145/2540930.2540957

[105] Christina Pollalis, Elizabeth Joanna Minor, Lauren Westendorf, Whitney Fahnbulleh, Isabella Virgilio, Andrew L. Kun, and Orit Shaer. 2018. Evaluating Learning with Tangible and Virtual Representations of Archaeological Artifacts. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 626–637. https://doi.org/10.1145/3173225.3173260

[106] Sara Price. 2008. A Representation Approach to Conceptualizing Tangible Learning Environments. In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction* (Bonn, Germany) *(TEI '08)*. Association for Computing Machinery, New York, NY, USA, 151–158. https://doi.org/10.1145/1347390.1347425

[107] Sara Price, Taciana Pontual Falcão, Jennifer G. Sheridan, and George Roussos. 2009. The Effect of Representation Location on Interaction in a Tangible Learning Environment. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction* (Cambridge, United Kingdom) *(TEI '09)*. Association for Computing Machinery, New York, NY, USA, 85–92. https://doi.org/10.1145/1517664.1517689

[108] Sara Price and Carey Jewitt. 2013. A Multimodal Approach to Examining 'embodiment' in Tangible Learning Environments. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 43–50. https://doi.org/10.1145/2460625.2460632

[109] Sara Price, Jennifer G. Sheridan, and Taciana Pontual Falcão. 2010. Action and Representation in Tangible Systems: Implications for Design of Learning Interactions. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction* (Cambridge, Massachusetts, USA) *(TEI '10)*. Association for Computing Machinery, New York, NY, USA, 145–152. https://doi.org/10.1145/1709886.1709913

[110] Pedro Ribeiro, Anna Michel, Ido Iurgel, Christian Ressel, Cristina Sylla, and Wolfgang Müller. 2018. Designing a Smart Reading Environment with and for Children. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 88–93. https://doi.org/10.1145/3173225.3173274

[111] Jessica Roberts. 2015. Exploring Effects of Full-Body Control in Perspective-Based Learning in an Interactive Museum Data Display. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 445–448. https://doi.org/10.1145/2677199.2691606

[112] Lea Dujić Rodić and Andrina Granić. 2021. Tangible interfaces in early years' education: a systematic review. *Personal and Ubiquitous Computing* (23 May 2021). https://doi.org/10.1007/s00779-021-01556-x

[113] Yvonne Rogers, Sara Price, Geraldine Fitzpatrick, Rowanne Fleck, Eric Harris, Hilary Smith, Cliff Randell, Henk Muller, Claire O'Malley, Danae Stanton, Mark K Thompson, and Mark J Weal. 2004. Ambient Wood: Designing New Forms of Digital Augmentation for Learning Outdoors. In *Proceedings of the 2004 Conference on Interaction Design and Children: Building a Community* (Maryland) *(IDC '04)*. Association for Computing Machinery, New York, NY, USA, 3–10. https://doi.org/10.1145/1017833.1017834

[114] Beat Rossmy and Alexander Wiethoff. 2019. COMB – Shape as a Meaningful Element of Interaction. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 287–295. https://doi.org/10.1145/3294109.3295646

[115] Calvin Rubens, Sean Braley, Julie Torpegaard, Nicklas Lind, Roel Vertegaal, and Timothy Merritt. 2020. Flying LEGO Bricks: Observations of Children Constructing and Playing with Programmable Matter. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 193–205. https://doi.org/10.1145/3374920.3374948

[116] Lisa M. Rühmann, Nuno Otero, and Ian Oakley. 2016. A Tangible Tool for Visual Impaired Users to Learn Geometry. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 577–583. https://doi.org/10.1145/2839462.2856536

[117] Alpay Sabuncuoglu. 2020. Tangible Music Programming Blocks for Visually Impaired Children. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 423–429. https://doi.org/10.1145/3374920.3374939

[118] Alpay Sabuncuoğlu and Metin Sezgin. 2020. Kart-ON: Affordable Early Programming Education with Shared Smartphones and Easy-to-Find Materials. In *Proceedings of the 25th International Conference on Intelligent User Interfaces Companion* (Cagliari, Italy) *(IUI '20)*. Association for Computing Machinery, New York, NY, USA, 116–117. https://doi.org/10.1145/3379336.3381472

[119] Michael Saenz, Joshua Strunk, Sharon Lynn Chu, and Jinsil Hwaryoung Seo. 2015. Touch Wire: Interactive Tangible Electricty Game for Kids. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 655–659. https://doi.org/10.1145/2677199.2687912

[120] Shima Salehi, Jain Kim, Colin Meltzer, and Paulo Blikstein. 2012. Process Pad: A Low-Cost Multi-Touch Platform to Facilitate Multimodal Documentation of Complex Learning. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 257–262. https://doi.org/10.1145/2148131.2148186

[121] Mahnaz Samadbeik, Farhad Fatehi, Mark Braunstein, Ben Barry, Marzieh Saremian, Fatemeh Kalhor, and Sisira Edirippulige. 2020. Education and Training on Electronic Medical Records (EMRs) for health care professionals and students: A Scoping Review. *International Journal of Medical Informatics* 142 (2020), 104238. https://doi.org/10.1016/j.ijmedinf.2020.104238

[122] Joseph T. Samosky, Douglas A. Nelson, Bo Wang, Russell Bregman, Andrew Hosmer, Brandon Mikulis, and Robert Weaver. 2012. BodyExplorerAR: Enhancing a Mannequin Medical Simulator with Sensing and Projective Augmented Reality for Exploring Dynamic Anatomy and Physiology. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (Kingston, Ontario, Canada) *(TEI '12)*. Association for Computing Machinery, New York, NY, USA, 263–270. https://doi.org/10.1145/2148131.2148187

[123] Theodosios Sapounidis and Stavros Demetriadis. 2017. Educational Robots Driven by Tangible Programming Languages: A Review on the Field. In *Educational Robotics in the Makers Era*, Dimitris Alimisis, Michele Moro, and Emanuele Menegatti (Eds.). Springer International Publishing, Cham, 205–214.

[124] Bertrand Schneider and Paulo Blikstein. 2016. Flipping the Flipped Classroom: A Study of the Effectiveness of Video Lectures Versus Constructivist Exploration Using Tangible User Interfaces. *IEEE Transactions on Learning Technologies* 9, 1 (2016), 5–17. https://doi.org/10.1109/TLT.2015.2448093

[125] Eric Schweikardt, Nwanua Elumeze, Mike Eisenberg, and Mark D Gross. 2009. A Tangible Construction Kit for Exploring Graph Theory. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction* (Cambridge, United Kingdom) *(TEI '09)*. Association for Computing Machinery, New York, NY, USA, 373–376. https://doi.org/10.1145/1517664.1517739

[126] Orit Shaer and Eva Hornecker. 2010. *Tangible user interfaces: past, present, and future directions.* Now Publishers Inc.

[127] Orit Shaer, Ali Mazalek, Brygg Ullmer, and Miriam Konkel. 2013. From Big Data to Insights: Opportunities and Challenges for TEI in Genomics. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 109–116. https://doi.org/10.1145/2460625.2460642

[128] Shahrokh Shahrivar, Shaban Elahi, Alireza Hassanzadeh, and Gholamali Montazer. 2018. A business model for commercial open source software: A systematic literature review. *Information and Software Technology* 103 (2018), 202–214. https://doi.org/10.1016/j.infsof.2018.06.018

[129] Takahiro Shichinohe, Tetsuo Yamabe, Takahiro Iwata, and Tatsuo Nakajima. 2010. Augmented Calligraphy: Experimental Feedback Design for Writing Skill Development. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 301–302. https://doi.org/10.1145/1935701.1935769

[130] Richard Shusterman. 2008. *Body consciousness: A philosophy of mindfulness and somaesthetics.* Cambridge University Press.

[131] Katta Spiel. 2021. The Bodies of TEI – Investigating Norms and Assumptions in the Design of Embodied Interaction. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 32, 19 pages. https://doi.org/10.1145/3430524.3440651

[132] A Istenič Starčič, Žiga Turk, and Matej Zajc. 2015. Transforming Pedagogical Approaches Using Tangible User Interface Enabled Computer Assisted Learning. *International Journal of Emerging Technologies in Learning* 10, 6 (2015), 42–52.

[133] Amanda Strawhacker and Marina U Bers. 2015. "I want my robot to look for food": Comparing Kindergartner's programming comprehension using tangible, graphic, and hybrid user interfaces. *International Journal of Technology and Design Education* 25, 3 (2015), 293–319. https://doi.org/10.1007/s10798-014-9287-7

[134] Anne Sullivan and Emily K. Johnson. 2019. BeadED Adventures: Crafting STEM Learning. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 351–358. https://doi.org/10.1145/3294109.3300997

[135] Cristina Sylla. 2013. Designing a Long Term Study Evaluating a Physical Interface for Preschoolers. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 363–364. https://doi.org/10.1145/2460625.2460695

[136] Cristina Sylla. 2013. Designing a Tangible Interface for Collaborative Storytelling to Access 'embodiment' and Meaning Making. In *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, New York, USA) *(IDC '13)*. Association for Computing Machinery, New York, NY, USA, 651–654. https://doi.org/10.1145/2485760.2485881

[137] Rana Tamim, Robert Bernard, Eugene Borokhovski, Philip Abrami, and Richard Schmid. 2011. What Forty Years of Research Says About the Impact of Technology on Learning A Second-Order Meta-Analysis and Validation Study. *Review of Educational Research* 81 (03 2011), 4–28. https://doi.org/10.3102/0034654310393361

[138] Brygg Ullmer and Hiroshi Ishii. 2000. Emerging frameworks for tangible user interfaces. *IBM Systems Journal* 39, 3.4 (2000), 915–931. https://doi.org/10.1147/sj.393.0915

[139] Elise Van Den Hoven, Evelien Van De Garde-Perik, Serge Offermans, Koen Van Boerdonk, and Kars-Michiel H Lenssen. 2013. Moving Tangible Interaction Systems to the Next Level. *Computer* 46, 08 (aug 2013), 70–76. https://doi.org/10.1109/MC.2012.360

[140] Janneke Verhaegh, Willem Fontijn, and Jettie Hoonhout. 2007. TagTiles: Optimal Challenge in Educational Electronics. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (Baton Rouge, Louisiana) *(TEI '07)*. Association for Computing Machinery, New York, NY, USA, 187–190. https://doi.org/10.1145/1226969.1227008

[141] Clarissa Verish, Amanda Strawhacker, Marina Bers, and Orit Shaer. 2018. CRISPEE: A Tangible Gene Editing Platform for Early Childhood. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. Association for Computing Machinery, New York, NY, USA, 101–107. https://doi.org/10.1145/3173225.3173277

[142] Danli Wang, Lan Zhang, Chao Xu, Haichen Hu, and Yunfeng Qi. 2016. A Tangible Embedded Programming System to Convey Event-Handling Concept. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 133–140. https://doi.org/10.1145/2839462.2839491

[143] Mark Weiser. 1999. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (July 1999), 3–11. https://doi.org/10.1145/329124.329126

[144] Margaret Wilson. 2002. Six views of embodied cognition. *Psychonomic Bulletin & Review* 9, 4 (01 Dec 2002), 625–636. https://doi.org/10.3758/BF03196322

[145] Xiao Xiao and Hiroshi Ishii. 2010. MirrorFugue: Communicating Hand Gesture in Remote Piano Collaboration. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 13–20. https://doi.org/10.1145/1935701.1935705

[146] Lesley Xie, Alissa N. Antle, and Nima Motamedi. 2008. Are Tangibles More Fun? Comparing Children's Enjoyment and Engagement Using Physical, Graphical and Tangible User Interfaces. In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction* (Bonn, Germany) *(TEI '08)*. Association for Computing Machinery, New York, NY, USA, 191–198. https://doi.org/10.1145/1347390.1347433

[147] Diana Xu. 2005. Tangible user interface for children-an overview. In *Proc. of the UCLAN Department of Computing Conference.* Citeseer.

[148] Junnan Yu, Clement Zheng, Mariana Aki Tamashiro, Christopher Gonzalez-millan, and Ricarose Roque. 2020. CodeAttach: Engaging Children in Computational Thinking Through Physical Play Activities. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 453–459. https://doi.org/10.1145/3374920.3374972

[149] Bieke Zaman, Vero Vanden Abeele, Panos Markopoulos, and Paul Marshall. 2012. Editorial: the evolving field of tangible interaction for children: the challenge of empirical validation. *Personal and Ubiquitous Computing* 16, 4 (01 Apr 2012), 367–378. https://doi.org/10.1007/s00779-011-0409-x

[150] Joseph E. Zins and Maurice J. Elias. 2007. Social and Emotional Learning: Promoting the Development of All Students. *Journal of Educational and Psychological Consultation* 17, 2-3 (2007), 233–255. https://doi.org/10.1080/10474410701413152

8 APPENDIX

Table 9: Overview of the papers included in our litterateur review. *Note*: Col. = Collaborative learning; RA = Research Article, WIP = Work In Progress, C = Child aged 1-12, A = Adolescent aged 12-18, + = Adult older than 18, T = Teacher, N = Not specific.

Ref.	Title	Year	Type	Col.	Age Group
[67]	The Machine Learning Machine: A Tangible User Interface for Teaching Machine Learning	2021	RA	✓	A, +
[95]	Tangible Lighting Proxies: Brokering the Transition from Classroom to Stage	2021	RA		C, A
[115]	Flying LEGO Bricks: Observations of Children Constructing and Playing with Programmable Matter	2020	RA		C
[117]	Tangible Music Programming Blocks for Visually Impaired Children	2020	WIP		C, A
[148]	CodeAttach: Engaging Young Children in Computational Thinking Through Physical Play Activities	2020	WIP	✓	C
[87]	"...and we are the creators!" Technologies as Creative Material	2020	WIP	✓	C
[76]	IRelics: Designing a Tangible Interaction Platform for the Popularization of Field Archaeology	2019	RA		
[114]	COMB – Shape as a Meaningful Element of Interaction	2019	RA		C, A, +
[23]	SpinalLog: Visuo-Haptic Feedback in Musculoskeletal Manipulation Training	2019	RA		+
[134]	BeadED Adventures: Crafting STEM Learning	2019	WIP		C, A
[17]	The Evolving Design of Tangibles for Graph Algorithmic Thinking	2018	WIP		C, A
[110]	Designing a Smart Reading Environment with and for Children	2018	WIP		C
[81]	Kniwwelino: A Lightweight and WiFi Enabled Prototyping Platform for Children	2018	WIP	✓	C
[141]	CRISPEE: A Tangible Gene Editing Platform for Early Childhood	2018	WIP		C
[29]	Paper Circuitry and Projection Mapping: An Interactive Textbook Approach to Veterinary Education	2018	WIP		+
[91]	Smart Toys Design Opportunities for Measuring Children's Fine Motor Skills Development	2018	RA	✓	C
[4]	ClassBeacons: Designing Distributed Visualization of Teachers' Physical Proximity in the Classroom	2018	RA		A, T
[46]	Evolving Tangibles for Children's Social Learning through Conversations: Beyond TurnTalk	2018	RA	✓	C
[101]	Come and Play: Interactive Theatre for Early Years	2018	RA		C
[105]	Evaluating Learning with Tangible and Virtual Representations of Archaeological Artifacts	2018	RA		+
[24]	The Design and Evaluation of Embodied Interfaces for Supporting Spatial Ability	2017	RA		+
[75]	BacPack: Exploring the Role of Tangibles in a Museum Exhibit for Bio-Design	2017	RA	✓	C, A, +
[26]	Quantifying Children's Engagement with Educational Tangible Blocks	2017	WIP		C
[142]	A Tangible Embedded Programming System to Convey Event-Handling Concept	2016	RA		C
[98]	SynFlo: A Tangible Museum Exhibit for Exploring Bio-Design	2016	RA	✓	C
[54]	Code Bits: An Inexpensive Tangible Computational Thinking Toolkit For K-12 Curriculum	2016	WIP	✓	C
[74]	Click: Using Smart Devices For Physical Collaborative Coding Education	2016	WIP	✓	C
[116]	A Tangible Tool for Visual Impaired Users to Learn Geometry	2016	WIP		+
[43]	Exploring the Design Space of Tangible Systems Supported for Early Reading Acquisition in Children with Dyslexia	2016	WIP		C
[27]	Mapping Place: Supporting Cultural Learning through a Lukasa-Inspired Tangible Tabletop Museum Exhibit	2015	RA		C, A
[72]	Tangible Interactive Microbiology for Informal Science Education	2015	RA		C, A, +
[30]	Button Matrix: how Tangible Interfaces can Structure Physical Experiences for Learning	2015	RA		C
[97]	Cube-in: A Learning Kit for Physical Computing Basics	2015	RA		N
[6]	PhonoBlocks: A Tangible System for Supporting Dyslexic Children Learning to Read	2015	WIP		C
[51]	Physical Construction Toys for Rapid Sketching of Tangible User Interfaces	2015	WIP		N
[119]	Touch Wire: Interactive Tangible Electricty Game for Kids	2015	WIP		C
[63]	Olegoru: A Soundscape Composition Tool to Enhance Imaginative Storytelling with Tangible Objects	2015	WIP		C
[20]	Tangible Interactive Ambient Display Prototypes to Support Learning Scenarios	2015	WIP		N
[42]	Tactile Letters: A Tangible Tabletop with Texture Cues Supporting Alphabetic Learning for Dyslexic Children	2015	WIP		C
[111]	Exploring Effects of Full-Body Control in Perspective-Based Learning in an Interactive Museum Data Display	2015	RA		N
[3]	Brush and Learn: Transforming Tooth Brushing Behavior through Interactive Materiality, a Design Exploration	2014	RA		+
[25]	SciSketch: A Tabletop Collaborative Sketching System	2014	RA	✓	+
[104]	Touch Toolkit: A Method to Convey Touch-Based Design Knowledge and Skills	2014	RA		+
[13]	Ghost Hunter: Parents and Children Playing Together to Learn about Energy Consumption	2014	RA		C
[50]	Back to the Future: Embodied Classroom Simulations of Animal Foraging	2014	RA		C
[82]	How Does the Tangible Object Affect Motor Skill Learning?	2014	WIP		N
[28]	Designing Embodied Interfaces to Support Spatial Ability	2014	WIP		N
[108]	A multimodal approach to examining 'embodiment' in tangible learning environments	2013	RA	✓	C
[96]	The digital dream lab: tabletop puzzle blocks for exploring programmatic concepts	2013	RA		C
[11]	FireFlies: physical peripheral interaction design for the everyday routine of primary school teachers	2013	RA	✓	C
[7]	Comparing Motor-Cognitive Strategies for Spatial Problem Solving with Tangible and Multi-Touch Interfaces	2013	RA		+
[127]	From big data to insights: opportunities and challenges for TEI in genomics	2013	RA		+
[34]	On interface closeness and problem solving	2013	RA		+
[39]	Supporting offline activities on interactive surfaces	2013	RA		+
[40]	Physical Games or Digital Games? Comparing Support for Mental Projection in Tangible and Virtual Representations of a Problem-Solving Task	2013	RA	✓	A, +
[56]	Wrapping up LinguaBytes, for now	2013	RA	✓	C
[78]	Do not Forget about the Sweat: Effortful Embodied Interaction in Support of Learning	2012	RA		N
[22]	Exploring Tabletops as an Effective Tool to Foster Creativity Traits	2012	RA	✓	A
[12]	Exploring Peripheral Interaction Design for Primary School Teachers	2012	RA		C, T
[90]	MagneTracks: A Tangible Constructionist Toolkit for Newtonian Physics	2012	RA		C, A
[120]	Process Pad: A Low-Cost Multi-Touch Platform to Facilitate Multimodal Documentation of Complex Learning	2012	RA		C
[122]	BodyExplorerAR: Enhancing a Mannequin Medical Simulator with Sensing and Projective Augmented Reality for Exploring Dynamic Anatomy and Physiology	2012	RA		N
[65]	Hangul Gangul: Interactive toy for Hangul Learning	2012	WIP	✓	C, +
[102]	Algo.Rhythm: Computational Thinking through Tangible Music Device	2012	WIP		N
[41]	Fostering Exploratory Learning in Students with Intellectual Disabilities: How Can Tangibles Help?	2012	WIP		N
[10]	MoSo Tangibles: Evaluating Embodied Learning	2011	RA		C
[5]	Futura: Design for Collaborative Learning and Game Play on a Multi-Touch Digital Tabletop	2011	RA	✓	C, A, +
[89]	Math Propulsion: Engaging Math Learners through Embodied Performance Visualization	2011	RA		A
[1]	Supporting Embodied Exploration of Physical Concepts in Mixed Digital and Physical Interactive Settings	2011	RA	✓	C
[129]	Augmented Calligraphy: Experimental Feedback Design for Writing Skill Development	2011	WIP		N
[145]	MirrorFugue: Communicating Hand Gesture in Remote Piano Collaboration	2011	RA		+
[109]	Action and Representation in Tangible Systems: Implications for Design of Learning Interactions	2010	RA		A
[85]	Tangibles in the Balance: A Discovery Learning Task with Physical or Graphical Materials	2010	RA		+
[86]	Culturally Sensible Digital Place-Making: Design of the Mediated Xicanindio Resolana	2010	RA	✓	N
[60]	Interactions Around a Contextually Embedded System	2010	RA		C, A, +
[100]	Constructing with Movement: Kinematics	2010	WIP		C, A
[2]	TessalTable: Tile-Based Creation of Patterns and Images	2010	WIP		C
[107]	The effect of representation location on interaction in a tangible learning environment	2009	RA	✓	C
[55]	Tangibles for Toddlers Learning Language	2009	RA		C
[49]	Chemieraum: Tangible Chemistry in Exhibition Space	2009	RA		C, A
[125]	A Tangible Construction Kit for Exploring Graph Theory	2009	RA		C
[80]	Physical Manipulation: Evaluating the Potential for Tangible Designs	2009	RA		C
[106]	A representation approach to conceptualizing tangible learning environments	2008	RA		N
[146]	Are Tangibles More Fun? Comparing Children's Enjoyment and Engagement Using Physical, Graphical and Tangible User Interfaces	2008	RA	✓	C
[35]	The Card Box at Hand: Exploring the Potentials of a Paper-Based Tangible Interface for Education and Research in Art History	2007	RA		N
[57]	Designing for Diversity: developing Complex Adaptive Tangible Products	2007	RA		C
[59]	Designing Tangible Programming Languages for Classroom Use	2007	RA		C
[84]	Do tangible interfaces enhance learning?	2007	RA		C
[37]	Lessons from an AR Book Study	2007	RA		C
[48]	Smart Blocks: A Tangible Mathematical Manipulative	2007	RA	✓	C
[140]	TagTiles: optimal challenge in educational electronics	2007	RA	✓	C
[69]	Teaching Table: A tangible mentor for pre-K math education	2007	RA		C