Tangible Interaction for Children's Creative Learning: A Review

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ABSTRACT

Creativity is an important part of children's education. Tangible User Interfaces (TUIs) provide new possibilities for creative learning. In this review, we gave an overview of recent studies that supported children's creative learning using TUIs. Results showed that TUIs had many advantages, such as they (1) were novice-friendly, (2) supported children's cognitive process and development, (3) promoted their initiatives, (4) enabled them to think outside the box, and (5) encouraged communication and collaboration in an authentic context. Meanwhile, we summarized previous work's three main limitations: First, most of the studies did not have a long-term experimental verification with sufficient sample size and objective evaluation; Second, some TUI designs lacked a balance of abstractness, openness, richness, and complexity; Finally, the use of TUIs had little consideration of the teacher's role. Therefore, further research should focus more on the trans-disciplinary nature of TUIs for creative learning and leverage collaboration between human-computer interaction researchers and school teachers.

KEYWORDS

tangible user interface, TUI, tangible interaction, creative learning, review, children

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1 INTRODUCTION

Digital technologies are integrated into people's daily life and children's education. Inevitably, this will have an influence, direct or indirect, on children's intellectual development, such as creativity. Creativity should not be neglected in school education [102], since it is an important skill for the 21st century [25, 38, 124]. "Creativity is seen as an essential skill that leads to knowledge creation and the construction of personal meaning" [25]. Graphical User Interfaces (GUIs), such as computer-assisted learning and Creativity Support Tools (CSTs) [71, 117], have been used to develop students' creative behaviors. However, this approach has its limits due to its monotonous and mechanized interactive means. In fact, "traditional STEM (Science, Technology, Engineering, and Mathematics) curricula and tools do not always successfully foster the open-ended imaginative, playful and creative behavior that technology education has the power to cultivate" [124]. Tangible User Interfaces (TUIs) may provide new potentials to facilitate creative learning through a natural, interactive interface [41, 119].

While TUI was first introduced in 1997 [53], studies about designing and using TUIs for children's creative learning have been conducted mainly in the past five years [16, 24, 32, 61, 93, 133]. Thus, we analyze recent publications from 2015 to 2020. We aim to provide a comprehensive picture of how TUIs support children's creativity in the field of Human-Computer Interaction (HCI), education, and psychology.

Our review will focus on three key questions: (**RQ1**) In what contexts do children use TUIs for creative learning? (**RQ2**) How have these TUIs helped or facilitated creative learning? (**RQ3**) What are the challenges for designing and using TUIs in those contexts? After a brief introduction of the background for creative learning (Sect. 2), Sect. 3 lays out the search and filter criteria and the general methodology. We outline our findings for these questions in Sect. 4.1, 4.2, and 4.3, respectively. Finally, we summarize and discuss the results in Sect. 5.

2 BACKGROUND

2.1 Tangible learning for children

Tangible learning involves gesture, motion, or full-body interaction and "emphasizes the use of the body in educational practice" [59]. TUIs use the interaction with physical manipulatives and embodied metaphors to promote understanding of abstract concepts. By embedding technology in everyday objects with natural actions like grabbing, technology becomes ubiquitous, mixing the physical and digital world [138]. Tangible interaction with digitally enhanced interfaces has been previously explored for learning in different domains, for example, tangible programming [139], tangible music composition [108], art [107], history [128], and storytelling [136].

TUIs are intuitive, easy to use, and need less cognitive effort to manipulate objects [140]. More than 100 years ago, Froebel and Montessori [36, 85] already found the potentials of manipulative materials and sensory experience for children. Perception is closely linked to cognition, and research has shown that manipulation of physical materials with haptic perception could improve the constructive learning process [81]. TUIs support learning by providing embodied interaction with physical movements, which can enhance children's thinking and learning [95]. For example, Kazanidis et al. [59] found that TUIs "can offer a natural and immediate form of interaction that is accessible to learners, allow active and hands-on engagement, allow for exploration, expression, discovery and reflection, and promote collaboration".

TUIs bring the following benefits for children's learning, which we compiled from previous research (e.g. [140, 144]): (1) **Playfulness**: Play is an important nature of children's lives and promotes their "social, emotional, physical, and cognitive development" [34]. TUIs promote playful interactions with physical objects; (2) **Trial and error**: TUIs foster exploration and experimentation in active play with trial and error. TUIs allow children to try different things and easily reverse their actions [140]; (3) **Sensory engagement**: TUIs engage multiple senses, which can aid the constructive learning process [144]; (4) **Spatial learning**: Tangible interaction improves spatial perception through physical embodied interaction, for instance, rotating objects with one's hands. Spatial skills are important for everyday tasks, such as tool use and navigation, and are also linked to better performance in STEAM (Science, Technology, Engineering, Arts and Mathematics) disciplines [9]. TUIs can also improve spatial memory [76]; (5) **Social connection**: TUIs can be used for learning in groups and enable natural group interaction and discussion [144]. Collaborative tangible learning environments could help children "get over their initial fears in the areas of mathematics and science and even begin to enjoy these subjects" [115]; (6) **Accessibility**: TUIs can make learning accessible for children with impairments, for example, visual impairments or learning disabilities [144]; (7) **Feeling of competence**: By directly manipulating objects with their hands or bodies, children can gain a sense of competence and autonomy while interacting with technology [140].

2.2 Children's development of creativity

Childhood is an important stage for creativity development [75, 130, 135]. The nature of children is to be curious and unrestrained. Barron [86] proposed the first widely accepted definition of creativity in 1955, which emphasized its novelty and public usefulness [87]. In this case, children's creative potential might be overlooked because their creative insights are only expressed in daily activities without notable contribution. Kaufman's *Four C model* [58] expanded the traditional dimensions of creativity to four models: "Big Creativity" (eminent and objective) and "Little Creativity" (commonplace and sometimes subjective), "Pro-creativity" (professional) and "Mini Creativity". According to this model, children's creativity could be categorized as "mini-c", which inherent in the learning process.

In addition, previous studies [42] found that individual creativity depended on the following five components:

Knowledge (also known as crystallized intelligence [17]): Vygotsky [135] summarized the mechanism of creative imagination: knowledge was the understanding of reality, which was gained from self-experience or learned from others' experience (e.g. historical and social experience). This knowledge provides material for an individual's imagination. Imagination, which is critical for children's creativity, could change children's perception of reality. New thoughts and concepts have to embody with materials to affect and change the real environment.

Motivation [38]: In addition to external neural stimulation that provides materials for imagination, initiative needs, motives, and desires are also critical factors for creativity [135]. Motivation and willingness to participate in creative activities determine the success and the sustainability of creative development [113]. Keller's *ARCS Model* [62] indicated that attention and satisfaction were determined factors for motivation. To promote motivation, the attraction strategy in ARCS suggested increasing concreteness and learner's curiosity and participation, and satisfaction strategy encouraged to provide natural consequence and positive feedback.

Cognitive ability (known as fluid intelligence [17]): Divergent thinking [127] and ideation [97] were regarded as crucial foundations for creativity development in many previous studies. Although divergent thinking is thought to only directly affect idea generation in the early-cycle problem-solving activity [83], a solution generated from divergent thinking still affects effective implementation in the later convergence phase indirectly. The convergence of ideas is also a skill required for the development of creativity [82].

Personality: Based on the *Five-Factor Model (FFM)* or *Big 5* [27], openness (both attitudinal and perceptual openness) and psychoticism are the most significant factors influencing individuals' creativity. Neuroticism and conscientiousness affect children's creativity in art and science, respectively [8].

Environment [33]: The environment created jointly by parents, families, educational institutions, and society has a non-negligible influence on the nurturance of children's creativity [130]. Thus, it is essential to create a supportive environment that arouses interest [4]and promotes creative performance [121].

According to Torrance's developmental curve of creative abilities [130], the overall trend of children's creativity ability is gradually rising. However, there are periodical declines at certain ages, such as five-year-old or around fourth grade [106, 130]. Urban [130] found the manifestations of young children's creativity were (1) asking questions, (2) exploring their bodies, (3) making, manipulating, and experimenting with objects, and (4) expressing their feelings. As children get older, their perceptions become more conscious, and their creative behaviors become more purposeful and social. It is an interesting research topic to explore how new technologies stimulate children's creative thinking and generate a *long-term impact* on their creativity development [79]. Studies from different perspectives have explored how to promote students' creative learning inside [31, 32, 52, 96] and outside the school [24, 77]. Specifically, as shown in Table 3, they have been conducted mainly from five perspectives: lower the knowledge threshold, support cognitive process and development, cultivate intrinsic motivation, foster openness, and create an authentic and collaborative environment.

Embodied cognition theory indicates that "thinking and acting are intertwined in nature", which means our body is not only dominated by our mind. Meanwhile, interaction with physical space and objects affects our thoughts [57]. It positively affects learning from various aspects, such as sensorimotor, cognitive, and affective experience. From HCI perspective, i.e. tangible, embedded, and embodied interaction, the meaning of TUIs is to discover and share by interacting with computational objects in the physical world and using human's body, object, and space [51]. It provides a broad umbrella term for the research, which focus on the role of physicality, including full-body interaction, motion/gesture-based interaction, and kinesthetics interaction.

3 METHODS

We mostly followed the procedure outlined by Tsafnat et al. [129] for our systematic literature review. The review was conducted in December 2020 using seven databases (see Table 1) from three main research areas (HCI, education, and psychology), considering only papers published since 2015.

The keywords used for the search were *tangible** and *creati**. Although "embodied" is used as a synonym for "tangible", we did not included it for two reasons: First, in the field of HCI, "tangible" is more related to the computer-aided physical interactive prototype; Second, in psychology or pedagogy, "embodied" has a broader meaning, which is not directly relevant to our research. Due to the different searching designs of databases, the combinations of search terms were lightly adjusted. For example, Science Direct did not support wildcards, so we used "tangible AND (creative OR creation)" as a search term instead of "tangible* AND creati*". In addition, in the Springer, the search term could only be searched in text or title, which means it was impossible to search the particular term in the abstract. When we searched with "tangible* AND creati*" in the content, it yielded 45,604 results from 2015 to 2020. To reduce it to a manageable number of results, we used the combination "title: tangible* AND text: creati* child*" instead, and got 196 results. Finally, as shown in Table 1, we retrieved 643 papers in total.

We filtered these 643 results using three steps: First, we scanned their title and abstract. Then, we used a full-text search to see whether the papers included the relevant terms, such as "creati*", "tangible", "children" or "youth". If the study did not contain these keywords or "tangible" was not related to TUIs, we excluded it. In addition, we only considered studies for the children (our target participants), who were no more than 12 years old. Finally, we filtered the results using two more inclusive criteria: (1) the study focused on the impact of TUIs on children's creative learning behavior or development; (2) the purpose of TUIs was to improve the children's creative learning. The complete list of the remaining 53 papers can be found in the Appendix.

4 FINDINGS AND DISCUSSION

4.1 Contexts and participants (RQ1)

As mentioned, we reviewed 53 papers related to TUIs for children's creative learning. However, the summary of the contexts and demographic information in this subsection is based on a subset of 22 papers, because only these papers had a complete and clear description of the case study that included user context, number and age of participants, and activity.

The most **common contexts** to use TUIs for creative learning were school (6 studies), workshop (6), and museum (3). Kindergarten and home had two studies, respectively. The other three studies had no specific contexts. As shown in Table 2, TUIs have supported eight different activities. In school, TUIs have engaged students in activities such as three-dimensional modeling [32], multi-dimensional games [31], and storytelling with musical components [52, 96]. However, most studies aimed at playful and extracurricular activities, and few integrated with the formal curriculum. In the workshop, students used technology to design and implement paper *Mechatronics* [93], compose music [30], create stories [98], and design programs to solve real-world problems [82]. In the museum, children used TUIs to learn historical and cultural knowledge through storytelling [24] and interacted with tangible tokens for bio-design [77]. In addition, for kindergarten children, results showed that interacting with robots not only promoted their abilities of computing thinking but also cultivated and enlightened them in art, music, and culture [122, 124]. Finally, it is worth mentioning the study of Le Goc et al. [72]. They integrated augmented reality and TUIs to make creative learning through remote cooperation possible.

Regarding the **age distribution**, results indicate that more studies have been conducted for older children than for younger ones. From 3 to 6 years old, the number of studies rose gradually as 3, 6, 8 and 10. From 7 to 9 years old, it was around 10. For the last three years (i.e. 10-12 years old), there were 12 or 13 studies per year. Children's age would affect how they understand and deal with rules [99, 100, 133]. Younger children (aged 4 to 6) prefer more intuitive feedback, such as visual feedback and meaningful sound. In contrast, older children (aged 10 to 12) are more inclined to combine more complex and abstract interactive methods to play their games [133]. For example, children at around 10 to 11 years old prefer more complex rules with flexible details [78]. In the study of *MagicBuns* [133], children understood different interactions and could create their own play space. In addition, children at different ages used TUIs in different ways. For instance, some comparative studies found that physical interfaces could significantly improve younger children's speed of tasks completing, compared with virtual interfaces. However, TUIs did not improve the older learner obviously, and it might because they liked to spend more time exploring the interface [111].

Except for age, children's **gender** also made a difference in their behaviors. For example, Rogers [104] found that boys were better at assembling toys and were more confident to participate in STEM activities. Combining activities familiar to both male and female students could promote gender equality. The Diorama project [25] successfully increased girls' interests by integrating programming learning with storytelling, which girls were good at. Berta's study [12] also found that TUIs for game development could increase girls' curiosity particularly. At the same time, they felt more confident and competent, and gained a new understanding of game development [38].

About the **number of participants**, 72.7% of studies were within 50. The largest one was 193 (includes 134 children), conducted in the museum [77]. Another study was conducted in a university workshop and had 130 children [30]. There were 86.4% of studies conducted as cooperative teamwork.

Table 1: Search processes and results

Search Database	Search Term	Search Place	Search Results	Review Results
ACM Digital Library	tangible* AND creati*	Abstract	183	32
IEEExplore	tangible* AND creati*	Abstract	57	6
SpringerLink	title:tangible*;text:creati* child*	Title and text	196	7
Science Direct	tangible AND creative OR creation	Title, abstract, keywords	90	3
ERIC	tangible* AND creati*	Abstract	53	5
APAPsyInfo	tangible* AND creati*	Abstract	62	0
APAPsyArticle	tangible* AND creati*	Abstract	2	0
			643	**53**

Table 2: Activities supported by TUIs in the review results

Activities	Number of studies	References
Storytelling	8	[24, 25, 39, 52] [68, 96, 98, 118]
Robot programming	3	[14, 124, 124]
Music composition	3	[21, 30]
Real-world problem solving	2	[77, 82]
Play	2	[31, 133]
3D Modeling	1	[32]
Paper Mechatronics	1	[93]
Design anti-boredom machine	1	[10]

4.2 Advantages or influences of TUIs (RQ2)

As mentioned in the background section, creativity in this review was considered from five dimensions: knowledge, cognitive ability, motivation, personality (openness), and environment. TUIs affect children's creativity indirectly through five dimensions: (1) scaffold novice with different **knowledge** and skill levels to lower their knowledge thresholds for creative activities; (2) promote intrinsic **motivation** by facilitating exploration and self-directed creation; (3) support children's **cognitive process** by reducing cognitive efforts for imagination and spatial thinking, and enabling children to have multi-dimensional perceptions and more flexibility in divergent thinking; (4) encourage children to break the boundary of disciplines and keep an **open** mind to practice their knowledge in a free creative space; (5) build a collaborative and practical **environment** where children can share space, objects, and ideas in an authentic context. Based on 53 reviewed papers, we used affinity diagramming to classify these influences into six categories, mapped to the five dimensions. This is summarized in Table 3. More details and examples will be discussed in the following six subsections.

4.2.1 Scaffold novice. TUIs help to scaffold novices. First, as we know, without prior knowledge and related experience in a field, novices would face many challenges [82]. New learners' cognitive structures are more dependent on working memory [37, 65]. It is important to scaffold children within the zone of proximal development [110] but not limit their imaginations. To achieve this goal, TUIs encapsulate complex technical details and extend cognitive bandwidth to increase technology accessibility and promote children's creativity [21, 77]. For instance, the design of construction kits facilitated storytelling [98], programming [103], and music composing [30, 126] for children who had no related knowledge or skill. *BacPack* [77] simplified the professional content and made the public understand the knowledge. We could learn from these designs that TUI designers should strive to create the feeling of easiness and let children feel like experts in hands-on workshops to arouse their intrinsic motivations [38].

Second, lacking self-confidence, self-regulation, self-efficacy, and persistence are typical characteristics of novices [101]. For these problems, TUIs are very beneficial to provide children a comfortable design space, where they are allowed to use familiar materials like cardboards [109] to create low-cost prototypes. This environment could inspire their curiosities and allow them to be immersed in creating ideas without worrying about risks [31] and failures. For instance, gestural 3D modeling, printing platform *TADCAD* [32] and, paper Mechatronics [93] are good examples to facilitate continuous deconstruct and re-configure creative ideas.

4.2.2 Support cognitive development. "TUI can help support children cognitive processes" [1, 5]. First, the affordance of TUIs extends children's cognitive bandwidth so that they could focus more on experimenting with novel elements [143]. Norman [92] found that establishing natural mappings could decrease cognitive loads. Also, a concrete prototype seemed to be vital for design because it helped children complement the cognitive process of imagination [64]. Second, good TUI designs enable multidimensional interaction and feedback. It benefits children in many ways, not only their cognitive development [26] but also their bodies (e.g., fingers, muscle and dexterity development, and hand-eye physical coordination [21, 74]). Meanwhile, multi-modality provides more flexibility and possibilities for children to allocate meaning [24]. "Learning arises in the interplay between bodily experience and conceptual insight" [91]. Unlike pragmatic behavior, children often perform exploratory actions, namely epistemic actions, to uncover the world through offload internal cognitive resources into the external world [80]. Thus, an increase in epistemic actions benefits children's cognitive processes and is associated with creative design [63]. Furthermore, intuitive tangible interaction enhances children's spatial cognition and creative cognition [80, 109]. Spatial thinking, including spatial awareness and reasoning, is important for mathematics and science

Table 3: Advantages or Influences of TUIs on children's creative learning

Creativity Dimensions	Advantages or Influences of TUIs	Examples of Design Concept in the reviewed papers
Knowledge	Scaffold novice	Accessibility [21], affordance [143], "low floors" [98, 103], feel of easiness [38], familiar [38, 82], low-cost [57, 93, 109], no worry to failure [93], risk-taking [31, 82], iterative [61, 93, 125], flexible tinkering [61]
Cognitive ability	Support cognitive development	Free cognitive bandwidth [44], reduce cognitive burden [21], complement cognitive process [142], hand-eye coordination [54], give/assign/make meaning [24], epistemic actions [80], spatial cognition [80, 118], creative cognition [80]
Motivation	Promote initiative creation	Sensory engagement [60], exploration [24, 31, 38], self-expression/ physical expression [31, 61, 98, 102], arouse scientific curiosity [102], co-design/ co-designer[16, 61], self-directed/ self-driven [101], sense of agency/ control [10], active imagination/ development [10, 38], enhance confidence/ confidence to cultivate interest [38, 93]
Personality (openness)	Think beyond boundaries	Open/ open-end development/ play/ inquiry/ problem solving [31, 38, 77, 101, 102, 133], free/ freedom [31, 77, 101, 102], think outside box [31], explore beyond instruction [31], original [31], unintended interpretations [24]
Environment	Engage communication and collaboration	Joint engagement/ joint collaborative activity [39, 120], social interaction [39], shared working space/ space for spatial interaction [141], common ground [72], insight/ exchange expertise/ share ideas [93], co-creating [39], inspiration [24]
	Return to reality, beyond reality	Meaningful [77, 98], reality/ real world context/ problem/ application [38, 77, 98], authentic context [38], practical issue[142], intuitive [30, 77], overcoming time and size scales [77]

learning and real life [89]. Therefore, many TUIs are designed to promote the formation of mental models in three-dimensional space. For instance, *CyberPLAYce* [118] scaffolded students to analyze and organize data logically in physical space for problem-solving.

4.2.3 Promote initiatives. Motivation has a significant impact on children's creative development activities [113]. TUIs have promoted children's sensory engagement [60], active participation, exploration, and self-expression. In the following, exploration and Maker culture would be elaborated to explain how TUIs promote children's initiatives. **Exploration** was crucial to children's creative development activities [38]. Exploring in an open and inquiry-based learning environment with diverse new interactions and physical flexibility, children could effectively develop their characters and ideas. Because when various attempts and combinations are possible, children are more motivated to do creative exploration and expression [7, 31, 38, 102]. For example, a project named *MakerWear* [61] enabled children to design a wearable object and as a stylist to create a unique appearance to express and show their personality fully. Moreover, children could even come up with ideas to express their emotional states through Tangible Computational Media (TCM) [98], where TUIs empowered children to explore different possibilities of expression during story-making and extended their creative potentials in profound ways. In children's daily life, tangible interactive objects could stimulate their imaginations and against boredom. Usually, children become bored because they lack control or lose their senses of agency [10], especially when there are too many external stimuli leading to passive imagination [134]. TUIs draw children's attention from mind-wandering daydreaming to targeted and active imagination to create new games or tell stories [10]. Giving children more decision-making power and a sense of control, tangible creating helps children achieve a transition from boredom into opportunities for creativity.

Except encouraging exploration, TUIs have also set off a "**Maker trend**". Children no longer only passively accept digital information but also become active creators who use digital fabrication technologies as imaginary play tools to change the world. In Maker education, children could create objects that react to their actions, physiological signals, and environments [61]. It also helped to build their own learning tools [32] and make ideas for TUI designs as co-designers [16, 30]. For instance, students came up with creative suggestions for the application scenarios of *micro:bit* [116], such as for modern languages or physical education. As Catala et al. summarized, in the TUI development process, "children can be user, testers, informants, design partners, or protagonists" [16]. In this case, children would have sufficient space for self-directed learning and decision making to show their motivations, subjective initiatives, and creative confidences [21, 30, 98], which are often missing but required in STEAM (Science, Technology, Engineering, Art, and Mathematics) education [57].

4.2.4 Think beyond boundaries. Comparing with step-by-step traditional school education, TUI creates a more open and free creative space for students to think beyond boundaries [77]. In many studies, children were found to explore beyond the instruction, which resulted in many original or unintended ideas, interpretations, designs, and solutions about the problems [24, 31]. The research about *Mapping Place* [24] showed that providing young children with background knowledge helped them understand the concepts and focus on the task well. However, children, who were immersed directly in the tangible learning environment without prior knowledge, treated visual components more like literal symbols, not abstractions of specific meaning. In addition, TUIs help to create multi-modal perception and interdisciplinary creative learning environments. For example, the Diorama Project [25] combined four disciplines (i.e., language, art, programming, and electronics) and tried to use a tangible education tool to help children acquire knowledge and skills effectively and actively. Furthermore, in *Mapping Place* [24] as cultural heritage, tangible objects were used to imply culture's logic and structure.

4.2.5 Encourage communication and collaboration. TUIs facilitate both communication and collaboration for children. For communication, tangible interaction encourages children's active participation, joint engagement, and social interaction in the real world [39, 120]. Both verbal and non-verbal communication (with the help of gesture sketching or physical object) contribute to a successful collaboration [72]. TUIs create a shared workspace, where physical objects visualize ideas, experiences, and insights that are difficult for children to express in words. For the collaboration, when a child needed partners to help hand over items from a distance in a shared physical space, the cooperation between team members would naturally increase [77]. Moreover, TUIs promoted creativity for the sharing process enabled children to gain inspiration and new perspectives from other people's ideas or feedback. Furthermore, children were satisfied and proud of the completed work and accomplishment [116] and gained a sense of creative confidence because their ideas have inspired others [93].

4.2.6 Return to reality, beyond reality. The invention process is inherently object-driven in nature [18]. Both authentic tasks and physical materials in the real world enable children to concrete their imagination and creative ideas into solid form and finally change reality. For example, providing meaningful themes, like enhance living and smart homes, tangible creative activities made it possible for children to gain a better understanding of concepts in the authentic context and implement the knowledge they have learned into daily life [102]. Moreover, the potential of children's creativity is triggered by different materials [2, 46, 90], especially by familiar materials in an unexpected situation [25]. However, it is worth noting that the more is not always the better. The increasing diversity of resources can inspire ideas, while limited choices can help students focus on the creation at hand [142]. Therefore, too much or too complicated computational-enriched medium should be avoided to prevent children with limited skills from frustration in implementation [142]. TUI could shorten the distance between interaction input and output and allow children to manipulate and create things with more unconscious and intuitive actions [30, 79]. More importantly, TUI could also increase children's perception of space and time by presenting the invisible micro-world and showing long-term slow changes in a fast-forward manner within a limited time. For example, *BacPack* [77] exhibited in a museum could display the microscopic long-term biological development process. At the same time, it enabled children to do bio-designs through spatially arranging or comparing different combinations of objects.

4.3 Challenges to design and use TUIs (RQ3)

From the review results, we found that to improve research in TUI for children's creative learning, researchers, TUI designers, and teachers need to work together. As shown in Fig. 1, first, TUI designers should balance abstractness, openness, richness, and complexity for tangible interaction, and make a smooth experience; Second, teachers' experience and effects should be highly valued: helping

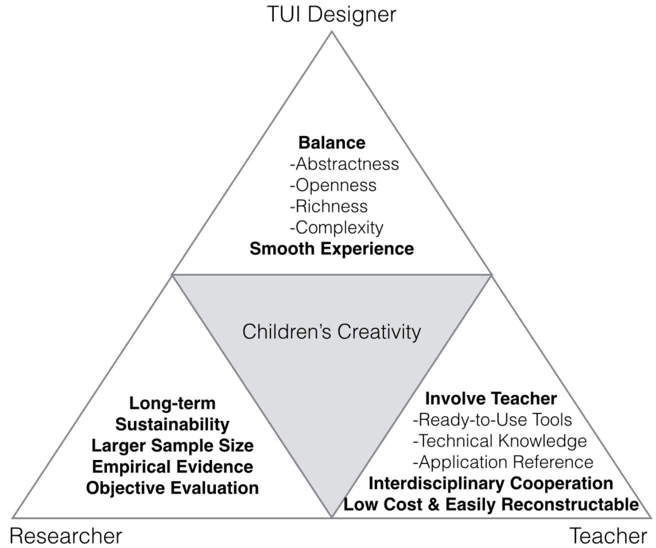

Figure 1: Future research directions for researchers, designers and teachers to improve TUIs for children's creative learning

them understand the purposes and functions of TUIs, and collaborating with them to conduct the research; Finally, researchers should consider conducting longer-term experiments with more participants, using more objective evaluations to verify the effects of TUI on children's creative learning, and making it feasible and sustainable daily learning activities rather than only one-time research projects.

4.3.1 Important TUI design factors. Four key factors of TUI design for children's creative learning were achieved and summarized from review results: abstractness, openness, richness and complexity, and smooth experience. The following explanations show different perspectives from children, teachers, and researchers.

Abstractness: Lack of prior knowledge makes children do not understand the learning contexts [24]. Thus, teachers used to design explicit instruction for children to understand the tasks well [101]. For example, Kurland and Pea [69] found that "certain concepts needed to be explicitly taught rather than expecting children to discover them on their own". In contrast, TUI designers considered more about scaffolding creative and divergent thinking and ideation [82]. One study showed that children who had no course introduction and directly started exploring and creating showed more collaborative behaviors [24]. Therefore, the abstractness of the learning process is important [57]. Ontological ambiguity "enables students to move between actual affair states and imagined possibilities", similar to the connections that children would establish with objects in the creative process [40, 105]. Thus, TUI researchers would like to use abstractness and ambiguity of the physical object to promote children's imagination. It also encourages children to flexibly use knowledge and problem-solving skills in a new and uncertain environment to become a good creative maker [93, 101]. Furthermore, in order to abstract learning feedback, it is important to consider both the ambiguity and affordance when exploiting physical objects [61, 80]. To match children's actual learning levels, a well-designed TUI should: (1) start from a child's perspective, (2) make the TUI functions simple to understand, (3) make the learning progress easy to recognize. In such a situation, children would be more confident and engaged to take risks and reconstruct from mistakes [82]. In other words, when children of different ages play and learn together, the TUI should be understandable for younger children while having enough capabilities for older children to explore [133]. For instance, *MagicBuns* [133] was designed with a low-level behavioral abstraction like an LED module for young children. Meanwhile, it had an accelerometer-based motion module for older children to do higher-level abstractions.

Openness: Teachers and researchers had different situations for learning openness [101]. In the real learning environment, the theoretically impressive constructive approach could only be applied to a limited extent, mainly due to limited resources (time, space, equipment). Thus, to help children learn better, teachers often design a simplified problem, a determined purpose, and well-structured instruction [43, 45, 55]. There are mainly three reasons: First, "insufficient scaffolding hampered some of the students to contribute their group's problem-solving processes on one's own initiative" [101]; Second, if children follow pre-structured instruction, they would have enough time for creative thinking and reflection, even though lacking experience or have unreasonable time management [101]; Finally, younger children need more guidance, because their comprehensive abilities are still developing and hard to find solutions for complex problems. A good example is the *ImproviSchool* project [96]: children not only perceived creativity during improvisation but also had a high satisfaction of creative efforts and learning results. Therefore, it might be reasonable for teachers to value the learning scaffolding to meet children's abilities and provide opportunities for their self-evaluations and reflections [101]. However, scaffolding might also hinder children's creativity because they have limited freedom to choose their interests [102]. Lack of control causes children to feel bored in school [13, 70], negatively impacts their meta-cognitive developments, and even leads to declines in academic performance, absenteeism, and dropout [29]. Thus, it is also reasonable to create a complex, inquiry-based, and self-directed TUI learning environment for children. They are given the freedom to pursue their interests, make choices, and plan their work independently [73, 102]. If tangible objects were equipped with the capacities to unfold indefinitely [19], children could develop ideas without restrictions [102]. As a result, children could develop an intrinsic motivation for creativity and active imagination and turn boredom into innovation [10]. The content could have an unclear goal and insufficient information to design, construct creatively, and solve open-ended problems from the real world, such as energy-saving and improve living [43, 88, 101].

Richness and complexity: Another issue is how to consider both the richness and complexity of TUI learning environments. As we know, too simple designs are hard to inspire children's creativity. However, too many interactive objects and physical manipulation might overwhelm them. Sometimes, researchers design very complex interfaces and ignore the mental developments of their target users of different ages and their limited knowledge, experience, and skills [101]. Unconstrained physical interaction could be "detrimental to learning", since "physicality is not important" rather "their manipulability and meaningfulness make them manipulative educationally effective" [112]. For example, a pilot workshop about TUIs for children [61] showed that overwhelming children with too many contents could confuse and frustrate them. Especially younger children need more time to figure out the function of each TUI module. One solution was to take children's age into consideration, remove the complicated modules, and gradually introduce new functions [61]. Another solution was to scaffold children when they encountered too complex and abstract learning contents [3]. However, this scaffold should meet children's level and be adjusted from the feedback of interactive behaviors, which means it supports them but not deprives them of challenges [3, 28]. Moreover, scaffolding is not only design through simplification to support students' ideation or construction. More importantly, it enables them to overcome their difficulties independently. Therefore, TUI designs should provide children with opportunities for sense-making, searching, selecting relevant information, arguing their decisions, and reflecting on their creative learning [101].

Smooth experience: According to Resnick and Rosenbaum's design guidelines [49], fluid experimentation and immediate feedback are critical factors for TUI designs. Previous studies [61, 82] have shown that TUIs with "glitchy" hardware devices or software systems would have a negative effect on children's interaction experience and learning effectiveness. There are two reasons: (1) it affects children's understanding and makes them confused and frustrated [61]; (2) the malfunction of TUIs hinders children's creative design and makes them feel hesitant and stressed. In other words, the incomprehensibility and unreliability of TUIs would make children become cautious and refuse to take risks [114], and even lose their courage to learn from failures and mistakes, which consequently limit their creativity [61, 82]. Therefore, before inviting children to play with TUIs, it is necessary to conduct a comprehensive and thoughtful test to fix those "glitches". In addition, no timely feedback or no clear state signs also affects the smooth experience. It makes children frustrated and confused because they worry about failure [21]. For instance, in Abreu and Barbosa's study [31], children stopped using the screen because it did not respond to their behaviors in time. Similarly, when the output is different from what the children expected, they would feel disappointed and reduce their game playing time [21].

4.3.2 Consider teachers in the TUI design. If the teacher's role is not considered, TUI-supported creative learning might not work. In the past five years, most related studies are conducted by HCI researchers and not teachers [101]. It caused **three problems** [124]: (1) TUIs might not support their teaching methods, their original teaching strategies might have to be changed for TUIs; (2) high learning costs to use it in the class; (3) poor user experience from their teaching perspectives. Therefore, tangible creative learning was normally used in after-school activities rather than in the real class. Because "without teachers, you don't really get it as a part of the school culture" [101]. **Three possible solutions** for the above problems are [124]: (1) involving teachers as stakeholders and refining TUI designs based on their feedback; (2) providing some training programs to help teachers understand the design purposes and functions; (3) TUI researchers cooperate with teachers to understand actual school contexts and the children's characteristics. In this way, a tangible interactive environment makes teachers themselves become practitioners for creative thinking, indirectly influencing children's behaviors [75]. From the requirements of actual school education, TUI designs could be avoided to use too professional or expensive equipment instead keeping low cost and easily reconstructable TUI tools, which increases the TUI affordability and accessibility [57, 109].

In addition, if teachers learn from successful TUI examples, they could rethink and improve their teaching methods [101]. It is important to integrate TUIs into school education and see the evidence of good performance [96, 116]. For TUI application, the most important thing is to provide ready-to-use educational tools to support teaching [25], where teachers could integrate TUIs in educational activities easily and actively [101]. In other words, teachers could design a tangible interactive environment to "define learning outcomes, and facilitate the activities", and finally achieve the teaching goal [56, 101]. For example, *WeMake* [57] proposed a framework for students, teachers, and interdisciplinary researchers to design embodied learning environments collaboratively. To benefit teachers, TUIs could be designed to track children's behaviors during the activities. Thus, it can be easier to understand children's mental status, "to find opportunities to provoke their interest, challenge their thinking and support independent or collaborative problem solving" [75]. Finally, as children know how to do, teachers can "fade their visible support" [48]. It can also remind teachers to notice and respond to children in time, especially when they meet difficulties in more complex tasks [3].

4.3.3 Problems to evaluate TUIs. In the review results, three issues about how to design a TUI and evaluate its effect were summarized. First, previous TUI designs put more effort into developing prototypes and their interaction ways, rather than the content, effect, cognitive and motivational factors of learning [14, 50, 57, 79]. A meaningful comparative study showed GUIs to be more beneficial for concept learning, while TUIs encouraged children's exploration and increased their participation and cooperation [122]. However, the number of comparative studies was very limited [109], especially for preschool children [124]. Second, previous studies lack empirical evidence or experimental confirmation to support the effectiveness of TUIs [23, 35]. There were two problems [93, 98, 101]: (1) the number of participants in these experiments was very small; (2) the experiment time might not be enough to get actual feedback. Long-term research was better to have children reflect on their interaction [25]; however, most studies were conducted within a short time, such as a one-day workshop. Finally, it is hard to evaluate the actual effects of TUIs on children's creative learning, especially for design-related studies [102]. According to Cherry and Latulipe's Creativity Support Index [22], creative behaviors were measured from exploration, collaboration, engagement, effort/reward tradeoff, tool transparency, and expressiveness. Children's perception and feedback with survey or questionnaire [61, 90] and comments were other means. However, they were insufficient [79] for its subjective methods. For instance, *ImproviSchool* researchers used a self-reporting tool to evaluate but proposed a more objective way was needed [96]. A quantitative analysis of the effect of tangible interaction on creativity might be better [79], such as based on Gero's Function-Behavior-Structure (FBS) coding scheme [98] and Amabile's Consensual Assessment Technique (CAT). Actually, for the unclear definition and measure difficulties of creativity, it is still a challenge to do an objective evaluation on Creativity Support Tools (CSTs) [71, 117].

5 CONCLUSION

Childhood is an important period for creativity development. In this review study, 53 papers published between 2015 and 2020 were reviewed, and 22 of them were used for basic information analysis (RQ1). The result showed most common contexts to use TUI for children's creative learning were school, workshop, and museum. More studies were designed for older children than younger ones. Corresponding to five dimensions of creativity, i.e., knowledge, cognitive ability, motivation, personality (openness), and environment, TUIs benefited children's creative learning by providing novice-friendly interaction, supporting the cognitive process, promoting their initiatives, encouraging them to think outside the box, and facilitating communication and collaboration in an authentic context (RQ2). There are three main challenges to design and use TUI for children's creative learning: (1) finding the balance of abstractness, openness, and complexity in TUI design and creating a smooth experience for young children; (2) cooperating with teachers in TUI design so that the tangible interactive learning could be integrated into school education; (3) increasing the number of sample size and long-term experiments and providing more objective evaluation.

We have contributed to providing an overall picture of the participant characteristics, user contexts, and TUI effects on children's creative learning and insight that current TUI concepts for children was essentially conducted by HCI researchers and designers rather than teachers with substantial experience. We argued that the importance of teachers should not be neglected and discussed how researchers, designers, and teachers need to be included to improve the future studies. However, four limitations still existed: (1) Although studies from education and psychology were searched, this literature review preset readers were mainly from HCI. Thus, findings and discussion might more benefit HCI researchers. Also, there was an objective reason: limited papers on education and psychology were obtained. It might because they used different keywords such as "embodied" and "physical computing" to describe tangible interaction. Therefore, if a future review study wants to explore the differences or compare studies among HCI, psychology, and education, search terms should be carefully chosen. (2) Only studies between 2015 and 2020 with keywords "tangible", and "creati*" were reviewed, which might lose some important findings that were published earlier or deal implicitly with creativity. In fact, adolescence is also a critical state for creative development. Future studies can investigate a longer span to understand how creativity is developed from childhood to adolescence and the different designs of their TUIs; (3) Results of TUI effects were not clear or sufficient in some studies. For example, some studies aimed to improve children's creativity, but TUI was only one part of the experimental design; (4) Few findings of using TUIs in the class were obtained. As we already mentioned in the findings, most TUI studies were conducted as after-school activities, which might not be helpful for teachers understanding the usefulness and advantages of TUIs for children's creative learning.

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A APPENDIX: IMPORTANCE RANKING OF REVIEW RESULTS

Ref.	Title	Database	Year	Importance*
[10]	"It's just too much": Exploring Children's Views of Boredom and Strategies to Manage Feelings of Boredom	ACM	2020	5
[82]	"... and we are the creators!" Technologies as Creative Material	ACM	2020	5
[101]	Supporting Fab Lab facilitators to develop pedagogical practices to improve learning in digital fabrication activities	ACM	2019	5
[38]	From Players to Makers: An Empirical Examination of Factors that Affect Creative Game Development	Science Direct	2018	5
[96]	Orchestrating tangible music interfaces for in-classroom music learning through a fairy tale: The case of ImproviSchool	ERIC	2018	5
[16]	Rethinking children's co-creation processes beyond the design of TUIs	ACM	2018	5
[93]	Paper Mechatronics: Present and Future	ACM	2018	5
[80]	Characterizing Tangible Interaction During a Creative Combination Task	Springer	2017	5
[98]	Constructing Meaning: Designing Powerful Story-Making Explorations for Children to Express with Tangible Computational Media	ACM	2017	5
[14]	Active Learning Environments with Robotic Tangibles: Children's Physical and Virtual Spatial Programming Experiences	IEEE	2017	5
[61]	MakerWear: A Tangible Approach to Interactive Wearable Creation for Children	ACM	2017	5
[31]	Creative Engagement: Multimodal digital games in children's learning environment in Macau S.A.R.	ACM	2017	5
[57]	WeMake: A Framework for Letting Students Create Tangible, Embedded and Embodied Environments for Their Own STEAM Learning	Springer	2017	5
[133]	Tangible Play Objects: Influence of Different Combinations of Feedback Modalities	ACM	2016	5
[132]	Make and play: card games as tangible and playable knowledge representation boundary objects	IEEE	2015	5
[32]	TADCAD: A tangible and gestural 3D modeling & printing platform for building creativity	ACM	2015	5
[24]	Mapping Place: Supporting Cultural Learning through a Lukasa-inspired Tangible Tabletop Museum Exhibit	ACM	2015	5
[66]	StoryBlocks: A Tangible Programming Game to Create Accessible Audio Stories	ACM	2019	4
[52]	Computational Thinking as Play: Experiences of Children who are Blind or Low Vision in India	ACM	2019	4
[21]	The Humming Box: AI-powered Tangible Music Toy for Children	ACM	2019	4
[142]	The roles of material prototyping in collaborative design process at an elementary school	ERIC	2019	4
[102]	The Nature of Physical Computing in Schools: Findings from Three Years of Practical Experience	ACM	2017	4
[30]	Supporting Creative Confidence in a Musical Composition Workshop: Sound of Colour	ACM	2017	4
[25]	The Diorama Project: Development of a Tangible Medium to Foster STEAM Education Using Storytelling and Electronics	Springer	2017	4
[39]	Bear Abouts: sharing stories across the physical and digital	ACM	2017	4
[77]	BacPack: Exploring the Role of Tangibles in a Museum Exhibit for Bio-Design	ACM	2017	4
[118]	A Tangible, Story-Construction Process Employing Spatial, Computational-Thinking	ACM	2016	4
[79]	Measuring the Effect of Tangible Interaction on Design Cognition	Springer	2016	4
[44]	The Kitsch-Instrument : Hackable Robotic Music	ACM	2015	4
[68]	Hi Robot: Evaluating RoboTale	ACM	2015	4
[72]	Investigating Active Tangibles and Augmented Reality for Creativity Support in Remote Collaboration	Springer	2020	3
[20]	Dialogue and materiality/embodiment in science|arts creative pedagogy: Their role and manifestation	Science Direct	2019	3

Ref.	Title	Database	Year	Importance*
[54]	TanCreator: A Tangible Tool for Children to Create Augmented Reality Games	ACM	2018	3
[60]	Dynamic interactive number lines for fraction learning in a mixed reality environment	IEEE	2018	3
[124]	Dancing robots: integrating art, music, and robotics in Singapore's early childhood centers	ERIC	2017	3
[122]	"I want my robot to look for food": Comparing Kindergartner's programming comprehension using tangible, graphic, and hybrid user interfaces	ERIC	2015	3
[123]	Designing with Genes in Early Childhood: An exploratory user study of the tangible CRISPEE technology	Science Direct	2020	2
[15]	Engage Your Students via Physical Computing	IEEE	2019	2
[94]	SynFlo: A Tangible Museum Exhibit for Exploring Bio-Design	ACM	2016	2
[131]	4th Graders Creating Robots with Sensors	IEEE	2015	2
[32]	Creating Unique Technology for Everyone	ACM	2015	2
[90]	Situated Tangible Gamification of Heritage for Supporting Collaborative Learning of Young Museum Visitors	ACM	2020	1
[11]	Tangible Digital Play in Australian and U.S. Preschools	ERIC	2019	1
[47]	Perceptions of computer science among children after a hands-on activity: A pilot study	IEEE	2018	1
[109]	Code Notes: Designing A Low-Cost Tangible Coding Tool For/With Children	ACM	2018	1
[137]	Towards a Tangible Storytelling Kit for Exploring Emotions with Children	ACM	2017	1
[67]	Iyagi: An Immersive Storytelling Tool for Healthy Bedtime Routine	ACM	2017	1
[73]	Demo: Use of Tangible Learning in STEM Education	ACM	2016	1
[126]	MuSme: A Tangible Skin Suit for Music Creation	ACM	2016	1
[12]	A Tangible Serious Game Approach to Science, Technology, Engineering, and Mathematics (STEM) Education	Springer	2016	1
[141]	Sandtime: A Tangible Interaction Featured Gaming Installation to Encourage Social Interaction Among Children, and Mathematics (STEM) Education	Springer	2016	1
[84]	Introducing Computer Programming to Children through Robotic and Wearable Devices	ACM	2015	1
[6]	The role of materiality in tangibles for young children's digital art drawings	ACM	2015	1

* Importance scales from 1-5, 5 means the most important.