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Unpacking the Potential of Tangible Technology in Education: A Systematic Literature Review*

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The main purposes of this study were (a) to analyze the research trend of educational use of tangible technology, (b) to identify tangible learning mechanisms, and potential benefits of learning with tangible technology, and (c) to provide references and future research directions. We conducted a systematic literature review to search for academic papers published in recent five years (from 2013 to 2017) in the major databases. Forty papers were coded and analyzed by the established coding framework in four dimensions: (a) basic publication information, (b) learning context, (c) learning mechanism, and (d) learning benefits. Overall, the results show that tangible technology has been used more for young learners in the kindergarten and primary school contexts mainly for science learning, to achieve both cognitive and affective learning outcomes, by coupling tangible objects with tabletops and desktop computers. From the synthesis of the review findings, this study suggests that the affordances of tangible technology useful for learning include embodied interaction, physical manipulations, and the physical-digital representational mapping. With such technical affordances, tangible technologies have the great potential in three particular areas in education: (a) learning spatial relationships, (b) making the invisible visible, and (c) reinforcing abstract concepts through the correspondence of representations. In conclusion, we suggest some areas for future research endeavors.

Keywords: Tangible Technology, Tangible User Interface, Systematic Literature Review

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Introduction

In this study, we focus on examining the current research trends of tangible technology, which has received much attention for the past decade, to unpack its potential in education. Till now, various studies have been conducted on how teaching and learning with tangible technology can affect learners (e.g., O'Malley & Fraser, 2004; Raffaele, Buhagiar, Smith, & Gemikonakli, 2017; Shaer & Hornecker, 2010). Several scholars have reported positive learning outcomes on the use of tangible technology, such as high levels of learning engagement and academic achievement (e.g., Raffaele & Smith, 2016; Wang, Young, & Jang, 2013). In addition, studies on technical development and user evaluation have been conducted with various tangible applications for teaching and learning (Lucchi, Jermann, Zufferey, & Dillenbourg, 2010).

Despite such increasing attention and research evidence, to our knowledge, there has been no attempt to synthesize the accumulated body of empirical studies on tangible technology in education. Fundamental questions such as "how and under what conditions tangible technology can be effective for teaching and learning" and "what are the key benefits and challenges of integrating tangible technology in education" warrant a systematic investigation of the current body of literature. The purposes of this research, therefore, are (a) to analyze the research trend of educational use of tangible technology, (b) to identify tangible learning mechanisms, and potential benefits of learning with tangible technology, and (c) to provide references and future research directions. To this end, we employed a systematic literature review as a methodological approach. By conducting this systematic review, we aim to better identify what the accumulated research evidences suggest about the potential and challenges underlying the use of tangible technology in education. We also hope to identify research gaps and directions for future research endeavors in this area.

Theoretical Background

What is tangible?

Tangible is the essential element of tangible technology. By the Cambridge dictionary definition, tangible means “real and able to be shown or touched”. Tangible forms are diverse, from a small physical object that people can hold with hands to a large space where people can touch and interact with. In addition, tangibles carry the meaning of both holding (active) and feeling to be held (passive) (Shin & Oh, 2016). As shown in Table 1, tangibles can be broadly classified into four types, depending on the type of tangibles that connects users to digital information: (1) object tangibles, (2) device tangibles, (3) surface tangibles, and (4) space tangibles, (Choi, 2006).

Table 1. Types of Tangibles (Choi, 2006)

Type	Characteristic
Object tangibles	· The most extensive method · Physical objects · An interface with a single object or objects in various forms · Control the media, putting digital information into a certain object
Device tangibles	· Devices that display or print out other tangibles · An interface existing to control objects
Surface tangibles	· The most direct interface between physical space and digital space
Space tangibles	· A complex of object, devices, and surface Tangibles · Various tangibles are closely connected in a certain space.

Tangible User Interface (TUI)

Historically, the field of tangible technology has emerged and been populated with the concept of Tangible User Interface (TUI) proposed by Hiroshi Ishii at the MIT

Table 2. Definitions and Characteristics of Tangible Technology

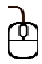
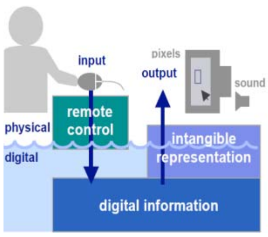
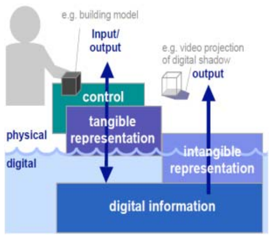
References	Definitions and key characteristics
Ishii & Ullmer (1997)	"TUIs will augment the real physical world by coupling digital information to everyday physical objects and environments." (p.2)
Manches (2010)	"Understanding the role of physically manipulating representations has gained impetus with the increasing potential to integrate digital technology into physical objects: tangible technology." (p.3)
Harfield, Tongpliew, & Choothong (2013)	"Tangible user interfaces, so called "technology you can touch", is often used in classrooms or for educational purposes." (p.184)
Strawhacker & Bers (2015)	"There is a growing interest in tangible interfaces, defined as concrete, physical manipulatives that can directly impact a digital environment." (p.293)

Tangible Media Group (Ishii, 1997). Table 2 presents various definitions and characteristics of Tangible Technology and TUI found in the literature. TUI is an attempt to expand user's various senses and expressive abilities on an interface, by converting physical objects and sensory input to digital information signals. TUI enables users to manipulate digital information through physical actions such as touching, holding and moving objects, which serves as an input mechanism that connects digital information in a virtual space to real objects on a surface. In this study, tangible technology is defined as a type of technology that directly connects digital information to physical representations and objects, enabling physical manipulations and interaction. Also, tangible technology and TUI are used interchangeably in this study.

Immersion and interaction through physical activities are two core concepts through which TUI is differentiated from the existing user interfaces. *Immersion* refers to the user's feeling as if existing in a new world, separated from reality, or experience of being in a space and time different from the physical situations of reality. *Interactivity* refers to user's physical, bodily actions to the surrounding objects in reality (Song, 2012). In the tangible technology environment, such immersion and interactivity support interaction between a user and a physical object, and an active cognitive function takes place through the interaction.

To better understand the affordances of TUI, it is useful to compare and contrast TUI and Graphical User Interface (GUI) from the input and output mechanisms for control and representations. Shaer and Hornecker (2010) suggest that most activities on a desktop computer are dependent on using external input devices such as a mouse and a keyboard, which is known as Windows, Icons, Menus, and Pointers (WIMP) interaction. GUI is an interface type of graphic representation in which users run a computational program through manipulating WIMP (Jang, Kim, & Song, 2010). Here, we present two main differences between TUI and GUI. First, the most concrete difference between TUI and GUI is on the potential of haptic (sense of touch, tactile) interaction. TUI controls digital systems through user's direct touch of digital information and allows free commands of expression and control in interaction with digital devices. Second, TUI does not have the clear separation between input and output mechanisms. On the contrary, GUI is divided into input devices that function as a controller (e.g., keyboard and mouse) and output devices that are graphic representations (e.g., monitor and head-mounted display). Since in TUI, users perceive input and output seamlessly connected, this affordance supports the expansion of user's sensory ability that

Table 3. Characteristics of GUI and TUI

	GUI	TUI
Emergence Time	1980s	2000s
Expression interface		
Input, and output mechanism		

maximizes interactive, temporal and spatial experiences.

Theoretical perspectives of tangible technology in education

Tangible technology and interfaces are not new concepts in education. More than two decades ago, Resnick et al. (1998) introduced a concept called digital manipulatives, arguing that "These new manipulatives -with computational power embedded inside- are designed to expand the range of concepts that children can explore through direct manipulation …" (p.281). Beyond the concept of traditional toys, digital manipulatives mean embedding computational and communication capabilities into physical objects to move, sense and interact with other objects. Interests toward tangible technology in education have been steadily increasing since education has become one of the main fields of applications for tangible technology (Cuendet, Zufferey, Ortoleva, & Dillenbourg, 2015). This trend has also been accelerated by the growing recognition of physical activities and interaction proven to be effective in learning processes and outcomes.

For educational integration, there are many TUI applications developed for programming, smart toys, computationally-enhanced construction kits and digital storytelling (Shaer & Hornecker, 2010). Particularly, the use of tangible technology for young children's learning has been an active field of research (O'Malley & Fraser, 2004; Pugnali, Sullivan, & Bers, 2017). Further, there has been an increasing volume of TUI studies related to learning processes, such as gestures, physical movements and embodiment that occur in physical interaction as well as the effects of learning with tangible technology.

In this section, we discuss two theoretical perspectives that ground the use of tangible technology and interfaces in education: (1) embodied cognition and (2) cognitive developmental theory. First, 'embodied cognition' refers to the perspective that "thinking is grounded in action", highlighting the interwoven nature of body, mind and knowledge. Fishkin (2004) noted that the transition from GUI through the Gesture Interface (GI) to TUI ultimately aims at an invisible interface, which is an ideal interface that would achieve high levels of embodiment where the output device is same as the input device. On a similar note, Klemmer, Hartmann, and Takayama (2006) argued that the tangible interaction paradigm with rich embodiment strengthens user experiences by providing a series of familiar metaphors (natural mapping) of the real world.

Second, from the perspective of cognitive developmental theory, many scholars (e.g., Pestalozzi, Froebel, Montessori, Piaget) have emphasized sensory learning experiences. Pestalozzi (1801) suggested the principle of intuition as a method of teaching. He argued that understanding of objects through sensory experiences is the basis of human cognition, and that learning should be developed from concrete to abstract experiences. As another scholar, Froebel developed 10 types of tangible Gabe (educational toys) and suggested that children could gain insights by playing with Gabe. Montessori also emphasized sensory learning experiences, especially the use of educational toys with tactile and muscular senses. She proposed learning environments where children use various senses every day, believing that this could lead to better cognitive development. Lastly, Piaget's developmental theory is essential to support the importance of tangible learning experiences. According to Piaget, children's cognitive development includes four stages, namely the sensorimotor stage, preoperational stage, concrete operational stage, and formal operational stage. At the concrete operational period, in particular, physical manipulations and operations are essential to children's' cognitive development (Lee et al, 2003).

The Rationale of the Present Study

Based on the existing literature aforementioned, it becomes clear that tangible technology research has been active for the past decades. However, it is still unclear what are the particular mechanisms that make the use of tangible technology effective or ineffective in teaching and learning situations. Hence, the purpose of this research is to examine the current research trends of tangible technology in education, with a particular focus on empirical evidence and technical development.

Method

Data collection and selection criteria

To this end, we conducted a systematic literature review. First, academic papers published in recent five years (from 2013 to 2017) were searched in the major databases, including ERIC, EBSCO, PsycINFO, IEEE and ACM. Articles published in the recent five years were reviewed to identify the latest trends considering that tangible technology is an emerging issue. As search terms, we used tangible technology OR tangible AND Education OR Learning, and only papers written in English were selected. The first search process identified 81 studies. Then, the inclusion and exclusion criteria as shown in Figure 1 were applied to further screen relevant studies. First, we included research studies that explicitly stated the term "tangible" in the title and/or abstract. This was to ensure that tangible is a main focus of the research, rather than a minor technical component or part of descriptions. Second, following the definition of tangible technology by Ishii & Ullmer (1997), we included research studies about tangible technology that couple digital information and physical objects. Therefore, studies that use only tangible physical objects without any input and/or output of digital information were excluded. Third, we only included empirical academic articles published in journals and conferences, excluding thesis, magazines, and other types of reports due to redundancy and research rigor. Forth, we only included empirical studies that allowed us to examine impacts of tangible technology on learning processes and outcomes. Accordingly, studies that have no educational implications and/or failed to meet any of the aforementioned criteria were excluded for the review. This process led to the identification of 47 studies: 18 from ERIC, 5 from EBSCO, 1 from PsycINFO, 14 from IEEE and 9 from ACM. After excluding 7 duplicated studies, the final set of data became 40 articles.

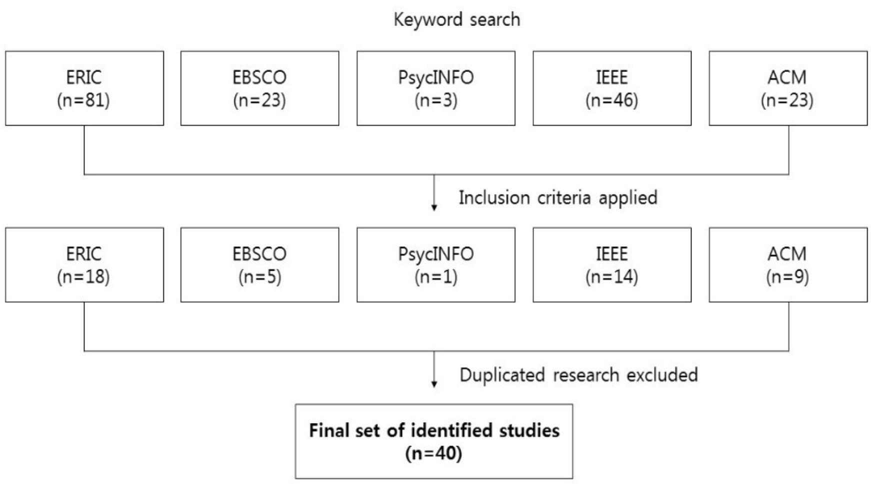


Figure 1. Inclusion & Exclusion Criteria Applied

Coding framework

The identified 40 papers were coded and analyzed by the established coding framework (Table 4) in four dimensions: (a) basic publication information, (b) learning context, (c) learning mechanism, and (d) learning benefits. We applied an inductive method to develop the coding framework, informed by Shaer and Hornecker (2010) and Cuendet et al. (2015). First, the 'publication information' category includes basic information about the country/region of publication and publication year. Second, the 'learning context' category includes four sub-categories: learner backgrounds, learning place, learning purpose and learning content. Third, the 'learning mechanism' category examines the configuration of tangible technology systems or applications and learning mode (i.e., individual vs. group/collaborative). Forth, the 'learning benefit' category examines the potential benefit of tangible learning systems in four sub-categories taken from Cuendet et al.

(2015): (a) increased usability, (b) physicality and its link with cognition, (c) multiple external representations, and (d) collaboration, co-location and simultaneous interaction.

Table 4. Coding Framework

Category	Sub-category
Publication information	▪ Country/region of publication
	▪ Publication year
Learning context	▪ Learner background: kindergarten, primary school, middle school, high school, university, post-university, all age groups
	▪ Learning places: in-school, out-of-school, both
	▪ Learning purpose: cognitive, affective, both
	▪ Learning content: subject-specific (science, language, etc.) subject-neutral
Learning mechanism	▪ Technical design configurations: tangible object only, tabletop & tangible objects, desktop & tangible objects, mobile devices (telephone or ipad) & tangible objects, tabletop only and others
	▪ Learning mode: individual, collaborative, both
Learning benefits	▪ Increased usability ▪ Physicality and its link with cognition ▪ Multiple external representations ▪ Collaboration, co-location and simultaneous interaction

Results

Basic publication information

Table 5 presents the analysis of basic publication information of 40 articles. Of 21 countries (regions) indicated in the research, 11 articles were published in the United States, followed by 3 in Canada, 3 in Taiwan, 3 in Spain, and 3 in Malta. Next, Figure 2 shows the distribution of publication years. It shows a clear upward trend from the year 2016, with 16 articles (39%) published in 2016 and 10 articles (24%) in 2017.

Table 5. Analysis of Publication Country/Region

Country/region	Frequency	Percent (%)
USA	11	27
Canada	3	7
Taiwan	3	7
Spain	3	7
Malta	3	7
India	2	5
Others	15	37

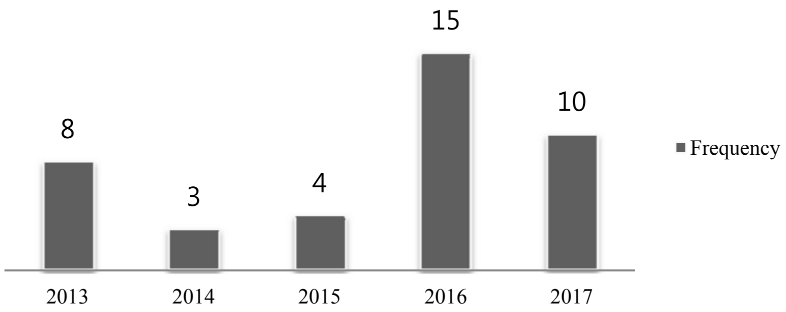


Figure 2. Publication Year

Learning context

Table 6 shows the analysis of learning context including learner backgrounds, learning place, learning purpose and learning content. First, regarding the learner background, about 30% (12 papers) examined the use of tangible technology for kindergarten learners (under 7 years old), followed by university and post-university learners (27%), primary school learners (25%), and middle/high school learners (7%). Four articles (10%) targeted various age groups of learners. It was interesting

Table 6. Analysis of Learning Context

		Frequency	Percent (%)
Learner background	Kindergarten	12	30
	Primary school	10	25
	Middle & high school	3	7
	University	8	20
	Post-university	3	7
	Various age groups	4	10
Learning place	In-school	23	57
	Out-of-school	10	25
	Both	3	7
	Not mentioned	4	10
Learning purpose	Cognitive	15	37
	Affective	4	10
	Both	20	50
	Others	1	2
Learning content	Science	17	42
	Language	7	17
	Subject neutral (skill-based)	6	15
	Social studies	3	7
	Math	3	7
	Health	2	5
	Other subject areas	2	5

to find that four papers examined the use of tangible technology for learners with special needs (i.e.., Guerreroa et al., 2016; Guía et al., 2015; Sinha & Deb, 2016; Starcic, Cotic, & Zajc, 2013). For instance, Starcic et al. (2013) conducted a study with students with low motor skills and learning difficulties. TUI enabled them to learn geometry concepts better than when they learned it based on paper-based materials. Also, collaboration between mainstream students and students with learning difficulties was facilitated through TUI.

The overall trend shows that a large portion of tangible technology research in education has focused more on young learners at kindergarten and primary school levels than adult learners. It has been reported that tangible technology can help increase young learners' playful learning experiences and make them more concentrated in learning processes (Abreu & Barbosa, 2017). For college learners, tangible technology can help them learn relatively difficult and abstract knowledge. For instance, Davenport, Silberglitt and Boxerman (2014) reported that graduate students could acquire core biological concepts when they learned with tangible models. Similarly, Schneider, Wallace, Blikstein, and Pea (2013) reported that graduate students used the tabletop to understand the visual system in neuroscience.

Second, the analysis of learning context focuses on where the research study was conducted, namely in-school, out-of-school (e.g., after school workshops, summer camps), and both contexts. About 57% of research studies were conducted in the school context, whereas 25% conducted in the outside of school context. There were three experiments conducted in both contexts, and four cases did not clearly indicate their research context. This trend shows that many studies have been conducted in the school context to promote authentic learning experiences. As an example of in-school learning context, De Abreu and Barbosa (2017) conducted the pilot experiment in a primary school in Macau in order to examine the significance of the "multimodal systems" for creative behaviors in a learning environment. As an example of out-of-school learning context, Antle (2013) worked with 132 children at a local science center and used three user interface styles (i.e., physical, mouse-based and tangible) of the jigsaw puzzle to improve children's thinking skills in spatial problem-solving.

Third, the analysis of learning purpose indicates that there are 15 studies (37%) aiming at improving cognitive learning outcomes whereas a relatively small number of research (4 articles) focused on affective learning goals. Nearly half of the studies aimed at examining the role of tangible technology to enhance both cognitive and affective learning outcomes. As an example, Tsonga, Samsudinb, Yahayac and Chong (2013) found that preschoolers who had opportunities to learn English using tangible fruits were able to improve learning performance (cognitive) and enjoyment (affective). Specifically, the learning potential related to cognitive functions can be found. Using tangible technology can be effective for educational purposes by influencing the cognitive process such as learning spatial relationships, making the invisible concept visible, and reinforcing abstract concepts through the correspondence of representations.

Lastly, we examined the learning content areas where tangible technology was applied. For the subject-specific areas, science learning took the highest proportion (42%), followed by language (17%), math (7%), health (5%) and other subject areas (5%). Six articles (15%) used the subject-neutral content. The overall trend indicates that there has been high interest of integrating tangible technology for science learning, particularly for learning relatively difficult and abstract concepts and phenomena (Johannes, Powers, Couper, Silberglitt, & Davenport, 2016).

Learning mechanism

Concerning the learning mechanism of tangible technology, we analyzed both technical and pedagogical aspects. First, Table 7 shows the analysis results of the design configurations of tangible technology systems and interfaces. Here, the technical design configurations were categorized into six types: (1) tangible object only (smart toys or robot), (2) tabletop & tangible objects, (3) desktop & tangible objects, (4) mobile devices (telephone or iPad) & tangible objects, (5) tabletop only and (6) others (e.g., combination of more than two types or 3D printer, etc.) As shown in Table 7, it appears that the combination of desktop and tangible objects (30%) is the most widely used design configuration, followed by tabletop & tangible objects (25%). Palaigeorgiou, Karakostas, and Skenteridou (2017) used the “finger trip equipment” to simulate the 3D augmented tangible map for learning geography.

Students could touch the tangible map on the tabletop to feel the height and distance. Tangible objects like toys and robots are also frequently used. As an example, RoyoBlocks, composed by wooden blocks, a plush monkey toy and supplementary educational materials, provided pre-literate learners with an opportunity to practice and hone both their reading and writing skills (Kleiman, Pope, & Blikstein, 2013). RoyoBlocks helped the children listen to a sentence prompt, attempt to form sentences, use the reading companion to check their work, and correct any errors they made.

There are also more complex configurations with multiple devices, like combining desktop and iPad with tangible objects (Guía et al., 2015; Guerreroa et al., 2016), combining tabletop and desktop with tangible objects (Sinha & Deb, 2016) and matching display screen and tangible objects (Fan, Antle & Cramer, 2016). These configurations were classified into others because they used more than two tangible objects. For example, Sullivan, Kazakoff and Bers (2013) conducted a research study on the robotics program where children had the opportunity to build robots by using Lego and art materials and then to make a robot by using a tangible and graphical computer language called CHERP with tangible blocks.

Further, there are different types of techniques used like 3D printing technology to help the exploratory construction of mechanical papercraft in a computer-aided design (CAD), which named as FoldMecha (Oh et al., 2017), and the matching equipment of smartphone and Google cardboard (Devi & Deb, 2017) or pad (Huang & Lin, 2017). While using a tabletop alone is the least used method (2%), 24% studies used tangible learning systems that integrate tabletops and tangible objects. This implies that many tangible techniques are realized by combining a tangible object and tabletop or desktop. This finding is also consistent with Shaer and Hornecker (2010) who mentioned that many tangible interfaces use computers and tabletop surfaces for enabling interaction. The combination of these various kinds of tangible technology makes the manipulation and interaction for educational purposes more effective. Based on this, technical affordance such as embodied interaction, physical manipulation and physical-digital representational mapping can be found as the educational potential of tangible technology.

For the pedagogical aspect, we examined the mode of learning with tangible technology. Almost 50% of the studies used an individual learning mode whereas 37.5% used a collaborative learning mode (see Table 7). The use of tangible technology supporting both individual and collaborative learning modes were only 3 cases, which may imply that it is still technically difficult to support multiple learning modes with tangible applications.

Table 7. Analysis of Learning Mechanism

		Frequency	Percent (%)
Technological Design configuration	Tangible object only	7	17.5
	Tabletop & tangible objects	10	25
	Desktop & tangible objects	12	30
	Mobile devices& tangible objects	3	7.5
	Tabletop only	1	2.5
	Others	7	17.5
Learning mode	Individual	19	47.5
	Collaborative	15	37.5
	Both	3	7.5
	Not mentioned	3	7.5

Learning benefits

We analyzed the benefits of tangible learning systems and applications in four areas: (a) increased usability, (b) physicality and its link with cognition, (c) multiple external representations, and (d) collaboration, co-location and simultaneous interaction.

First, 15 articles attempted to increase usability when designing tangibles to make them easy and intuitive to learners. For instance, designers considered height to allow all students, even ones not directly using the TUI system, to observe the information being projected (Raffaele et al., 2017). Studies attempted to make tangible learning systems easy, accessible and intuitive for novice users (Johannes et al., 2016; Kleiman et al., 2013; Schneider et al., 2013), to simplify the constructions process (Oh et al., 2017), and to use low-cost gaming devices to make the equipment easy to access (Sinha & Deb, 2016). Nacher et al. (2016) tested the usability of a tangible-mediated robot with children aged 2 to 6, and concluded that children over 3 could use the proposed platform. Shim, Kwon and Lee (2017) proposed the robot game environments where elementary school students could easily create a robot using a tangible programming tool.

Table 8. Analysis of Learning Benefits

Benefits	References
Increased usability	Johannes et al. (2016) Kleiman et al. (2013) Nacher et al. (2016) Oh et al. (2017) Raffaele et al. (2017) Schneider et al. (2013) Sinha & Deb (2016) Shim, Kwon, & Lee (2017)
Physicality and its link with cognition	Antle (2013) Cuendet et al. (2015) Sakr, Jewitt, & Price (2014) Skulmowski, Pradel, Kühnert, Brunnett, & Rey (2016) Starcic et al. (2013)
Multiple external representations	Sakr et al. (2014) Schneider & Blikstein (2016) Starcic et al. (2013)
Collaboration, co-location and simultaneous interaction	Guía et al. (2015) Schneider et al. (2013) Veronica, Cecilia, Patricia, & Sandra (2016)

Second, researchers found that physicality enabled by tangible technology affects users' cognition (Antle, 2013; Sakr, Jewitt & Price, 2014 Skulmowski, Pradel, Kühnert, Brunnett, & Rey 2016). In the study by Antle (2013), children could move around in the TUI environment and changed their perspective on the puzzle game. The study concluded that "ease of handling pieces, the provision for body movement around the table, and the provision of offline space for organizing of pieces all work together to facilitate exploration may facilitate the kind of exploratory actions that support successful puzzle completion" (p.951). TUI allows students with learning difficulties to move backwards and forwards easily (Starcic et al., 2013). Cuendet et al. (2015) found that TUIs are particularly adequate in vocational training as they offer learning opportunities for physical manipulations of objects.

Third, multiple external representations were used by combining physical and digital representations (Starcic et al., 2013), abstract and textual material representation (Schneider & Blikstein, 2016), or allowing representations to persist beyond the moment of their creation. Multiple external representations help students to make comparisons, to investigate the temporal dimension of activities and to invoke relevant prior knowledge (Sakr et al., 2014).

Lastly, previous studies reported the impact of tangible systems on supporting collaboration, co-location, and simultaneous interaction. Veronica, Cecilia, Patricia and Sandra (2016) presents a collaborative game based on tangible interaction, called ITCol (Tangible Interaction for Collaboration) to help adult students experience collaboration, considering characteristics such as individual responsibility and positive interdependence. Some studies positioned collaboration as their design guidelines to support students work in small collaborative learning groups (Schneider et al., 2013). Guía et al. (2015) designed a set of collaborative games in a novel multi-device environment. They found that children performed more physical and verbal interactions when they played with the system because the shared main user interface projected on the wall allowed collaboration among the children who could move around the room, and were more motivated and helped each other.

Conclusions

This study aimed to unpack the potential of tangible technology in education through the systematic literature review. Overall, this study confirms the increasing research interest toward tangible technology in education, as seen in the rise of publication in recent years. Based on the results of this study, the current trend of tangible technology in education can be stated: "tangible technology has been used more for young learners in the kindergarten and primary school contexts mainly for science learning, to achieve both cognitive and affective learning outcomes, by coupling tangible objects with tabletops and desktop computers."

From the synthesis of the review findings, this study suggests the affordances and potential of tangible technology in education as summarized in Table 9. First, we view that the affordances of tangible technology useful for learning include embodied interaction, physical manipulations, and the physical-digital representational mapping. In essence, the power of tangible technology lies in the affordance of supporting learners freely explore and express learning experiences through physical and sensory manipulation.

With such technical affordances, tangible technologies have the great potential in three particular areas in education: (a) learning spatial relationships, (b) making the invisible visible, and (c) reinforcing abstract concepts through the correspondence of representations. First, the visual mapping in tangible technology can be a powerful mechanism when students need to learn spatial relationships such as map reading skills. For instance, Cuendet et al. (2015) developed TUI called "Tapacarp" for carpenter apprentices to develop spatial skills. Similarly, Starcic et al. (2013) conducted a study on TUI-integrated geometry reasoning to visualize the abstract geometry concepts for concrete-experiential learning.

Second, tangible technology is useful when students need learn invisible concepts such as neuroscience and anatomy. For instance, Schneider et al. (2013) used the tabletop environment that allowed graduate students to better understand abstract invisible concepts in neuroscience through the association with physical objects. In Sakr et al. (2014), primary school students learned about the travel of light using an interactive tangible tabletop. Students could learn the invisible concept of light with TUI designed to explain the reflection, refraction and absorption of light depending on object's shape, material and color.

Third, tangible technology can be effective when reinforcing the learning of difficult and abstract concepts such as programming and language. It should be noted that for this type of learning, no spatial mapping exists between the concepts learned, and in many cases, TUI is used to reinforce concept learning through the coupling of visual and sound. According to Ku, Huang and Hust (2015), Chinese idioms are obscure for elementary school children to learn and comprehend. TUI makes children more excited and amused about learning Chinese idioms, improving student's motivations for learning. Programming which can be a hard concept to children was also taught by TUI called "CHERP" (Djambong & Freiman, 2016; Strawhacker & Bers, 2015; Sullivan & Bers, 2016). By CHERP tangible wooden blocks, children can understand programming algorithms, seeing how their manipulation of blocks is connected to operating the robots.

Table 9. Unpacking the Affordances and Potential of Tangible Technology in Education

Technical affordances	Educational potential
▪ Embodied interaction ▪ Physical manipulation ▪ Physical-digital representational mapping	▪ Learning spatial relationships (e.g., map reading skills) ▪ Making the invisible visible: (e.g., science, anatomy) ▪ Reinforcing abstract concepts through the correspondence of representations (e.g., learning Chinese letters through sound)

Some limitations of this study should be noted. First, while we attempted to systematically locate and screen the relevant articles, the selection was limited by the databases. It is possible that we have missed out important studies due to the selection of databases and languages. Second, in some studies, there was not sufficient information that allowed us to fully apply the coding framework. This limitation also implies the need for future research to provide thicker descriptions about the research context and the mechanism of tangible learning systems. We suggest the following areas for future research directions. First, while the most studies reviewed indicated the positive learning outcomes, we suggested the need to take more critical stances to examine the efficacy of tangible technology for teaching and learning. Second, there have been lack of research studies that examined the interaction effect of learner characteristics. Given the fact that the existing studies tend to target young learners, we suggest the need to broaden learners' age groups and to examine the effect of tangible technology for adult learners. Lastly, extending the content areas of application beyond science learning is another important area for future development.

References

*The reference of the 40 articles used in the review are marked with **

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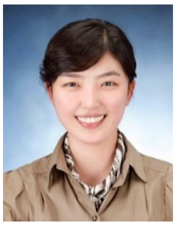

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