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The Use of Tangible User Interfaces in K12 Education Settings: A Systematic Mapping Study

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ABSTRACT Tangible User Interfaces have enriched and expanded the user experience when interacting with computers and smart devices. The monopoly of graphical user interfaces has been broken thanks to the emergence of new complementary technologies that allow for new ways of interacting with computer systems, such as tangible interaction, among others. Due to the scope and number of research articles addressing the Tangible User Interface that have been published, it can now be considered an interaction mechanism that is relatively mature and integrated within society. However, while the application of tangible interfaces in different areas is described as a success, there are only a limited number of research articles about their impact on education and learning systems. As a result, it is difficult to show the actual impact of Tangible User Interface technology in K12 education settings. This study tries to fill this gap by performing a systematic mapping study that shows the current state of research on the impact of this technology in these settings, analyzing the findings and identifying the main advances and limitations of this novel technology.

INDEX TERMS Tangible user interfaces, technology in education, systematic mapping.

I. INTRODUCTION

The evolution of interactive systems has been driven by the proliferation of new devices and interaction mechanisms. Natural user interfaces, multi-touch displays, cameras and sensor-based interaction are just some of the innovative interactive technologies users can now employ in different application domains [1]. Tangible User Interfaces (TUIs) have gained a prominent position in this wide range of new devices and interaction mechanisms.

Tangible User Interface (TUI) is a term originally proposed by Ishii and Ullmer in 1997 [2] with the aim of going beyond the traditional Graphical User Interface (GUI) and making computing truly ubiquitous and invisible, augmenting the real physical world by coupling digital information to everyday physical objects and environments. Nowadays, TUIs are being successfully applied in many different fields, such as gaming, manufacturing, and teaching, among others.

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One of the fields in which the introduction of computer technologies has been especially challenging is education. It would be impossible to summarize in this article the number of initiatives carried out in schools, universities and many similar educational institutions that have been aimed at improving the quality of education by introducing computer technologies. Digital whiteboards, tablets, computers and laptops are only a few common examples of this effort. However, this effort has not always been successful, partly because very often academic staff have been given little support and training to incorporate these innovations into their teaching [3].

Although this study shows the interest of the research community in the use and application of Tangible User Interfaces, it reveals that there are some points that have not received enough attention. For instance, it is not clear whether tangible interfaces have been successfully applied in education, especially in the K12 education stage. And when they have been successful, it is not clear which technologies best support tangible interfaces in education, or indeed whether or not it is possible to identify or measure their impact on learning processes.

Previous literature reviews of Tangible User Interfaces do not cover the main goal of this study. In [4], the authors provide a body of work on Tangible User Interfaces, which can be used as a starting point, since it was published in 2010. Elderly people's use of Tangible User Interfaces for social interactions is the main focus of the literature review in [5]. In [6], a systematic and industrial mapping of toy user interfaces is presented, with special attention to physical, tangible, toys, but it is not focused on education. A more closely related, though shorter, study can be found in [7], which evaluates children's technologies beyond the desktop computer.

Thus, the main aims of this systematic mapping study are the following:

1) Provide a summary of the state of the art of TUI-based systems applied to education.
2) Perform an analysis of the technologies employed by TUI-based systems applied in education, with a special focus on K12 education levels (Kindergarten, Primary and Secondary education).
3) Identify the opportunities for the future of TUI as research applied in education.
4) Find the trade-offs of using TUI-based systems compared with traditional approaches.

The rest of the paper is organized as follows. Section II presents background concepts and related works. Section III explains the methodology applied in this research study. Section III-A describes the first step in the methodology (definition of research questions). In section III-B, the different search strings are defined and applied to the databases. Section III-C describes the third step in the methodology, which produces the list of selected articles. Section III-D presents the results from the analysis of the selected articles. Section IV includes a discussion and final remarks on the study performed and analyzes its validity. Finally, we present a summary of the main conclusions and ideas for future works.

II. BACKGROUND AND RELATED WORKS

This section presents the related work, namely that on the use of Tangible User Interfaces in K12 education settings. Firstly, we present the definition and origin of Tangible User Interfaces, and then we outline the adoption of this technology in education.

The term Tangible User Interfaces (TUI) was firstly introduced in 1997 by Ishii and Ullmer in [2]. In that popular article, and in the subsequent references (i.e. [4], [8]–[11]), the authors stated that tangible interfaces would augment the physical world with these new interfaces. A tangible interface allows users to use their sense of touch to interact with computer systems. Thus, the user can interact with the system by touching it, grasping or manipulating real objects. An interactive system that includes Tangible User Interfaces is also known as a TUI-based system. In just a couple of decades, the interest of the research community in this kind of interfaces has increased dramatically, as is shown by the number of publications containing this keyword.

There are other previous works that try to define terms and present examples of applications related to Tangible User Interfaces. For instance, in [13], the authors provide an overview of the Tangible User Interface, discuss its functional characteristics, present some application cases, and discuss the design and application issues for TUI in education. However, a more complete work that presents definitions, application domains, frameworks and taxonomies, conceptual foundations, implementation technologies and evaluation methods is presented in [4].

Some authors try to organize terms, as in [14], where we can find a taxonomy of TUIs. This work presents a Tangible User Interface (TUI) taxonomy which uses the metaphor and embodiment metaphor as its two axes.

Our study analyzes the use of TUIs in K12 education settings. Among the previous works, we should review similar works in the field of education.

The main goal of the work in [15] is to review the state of the art of interactive technologies which can help educators, game designers and Human-Computer Interaction (HCI) experts in the area of game-based kindergarten instruction.

A preliminary report that analyzes Tangible User Interfaces for children can be found in [7]. This work presents a review of a set of Tangible User Interfaces (TUIs) for assisting children in learning. In addition, it examines how tangible technologies may be beneficial to children's learning.

Besides the field of education, there are a considerable number of fields in which Tangible User Interfaces have been applied with success. The following paragraphs review these fields and provide some examples.

The contribution in [16] includes a brief examination of recent research findings in the field of tangible robot programming and argues that the combination of tangible programming and robot construction may offer unique opportunities for educational robotics.

Tangible User Interfaces applied to children with special needs is one of the promising areas. As an example, in [17], the authors present a novel software system that applies the distributed user interface paradigm together with Tangible User Interfaces (TUIs) with the aim of improving memory and attention in children with Attention Deficit Hyperactivity Disorder (ADHD).

One of the most recent works on this topic can be found in [18], in which the authors perform a thorough systematic literature review of TUI and interactions in young children's education. In this case, the authors define a set of four Research Questions that are different from the ones addressed in this paper, and the target databases are also different, so a different set of articles is obtained. Another interesting recent review on tangible interaction for children is presented in [19], in which the authors cover the period 2015-2020 and focus on the use of TUI to improve creativity. We can

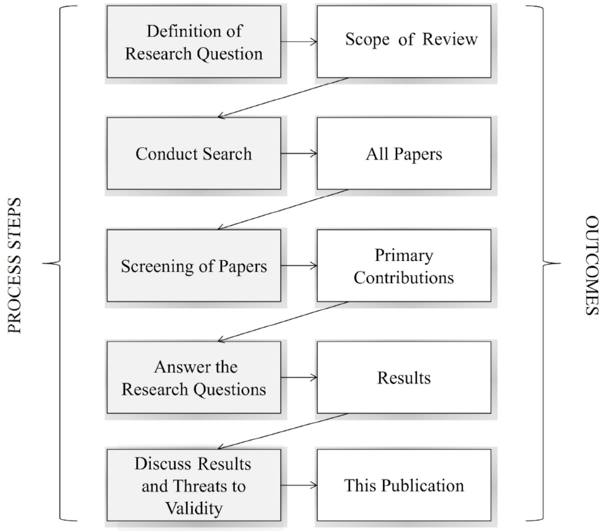

FIGURE 1. **Steps and outcomes based on the methodology adapted from [21]**

TABLE 1. **Research questions.**

ID	Research question
RQ1	What is the state of the contributions about Tangible User Interfaces applied to education published between 2010 and 2019?
RQ1.1	How many academic studies on Tangible User Interfaces were published between 2010 and 2019?
RQ1.2	What are the publication channels used to publish studies on Tangible User Interfaces?
RQ1.3	What is the definition of tangible used by researchers?
RQ1.4	What research methods have been used in studies on Tangible User Interfaces?
RQ1.5	What kinds of contributions are provided by studies on Tangible User Interfaces?
RQ1.6	What are the educational levels and subject areas of studies on Tangible User Interfaces?
RQ1.7	What is the impact of the selected contributions?
RQ2	What are the technologies applied to support TUI?
RQ3	What is the impact of the use of TUI technologies compared with traditional approaches in education?
RQ4	What are the research opportunities identified in the development of TUI-based systems in education?

conclude that these research studies are complementary to the one performed in this paper, and illustrate the interest of the research community in this topic.

The main goal of the systematic mapping study presented in this article is the analysis of the influence and impact of Tangible User Interfaces in K12 education settings. Our study shares the vision and goal of the research presented in [20], with certain differences: the study period in our case is much more recent, covering the period 2010-2019, and we focus on analyzing the impact of TUIs in the K12 educational stage.

III. RESEARCH METHODOLOGY

This section describes the systematic mapping process applied in this study, which has been inspired by, and adapted from, [21], and enriched with some steps defined in [22].

The methodology used in our systematic mapping is based on [21], and the steps and outcomes followed in our study are illustrated in Figure 1. Each of these five steps is discussed in the remainder of this section.

1) Definition of research questions (Section III-A): In the first step, the main goal of the study is subdivided into a set of complementary sub-goals, something that is best accomplished by defining research questions. The outcome of this step is the delimitation of the scope of the review.
2) Conduct search (Section III-B): Having defined the scope, the next step consists in defining the search string. In this step, we consider what databases should be considered for the search. The outcome of this step is a group of papers organized by database.
3) Screening of papers (Section III-C): In this step, the researchers carry out a thorough analysis that filters the whole set of articles, in order to generate a group of selected papers that are called primary contributions, which is the outcome of this step.
4) Answer the research questions (Section III-D): In this step the primary contributions are used to answer each research question. The outcome of this step is a set of artifacts depending on each research question.
5) Discuss results (Section IV) and threats to validity (Section VI): The last step in our methodology is to summarize the results in a general discussion. In this step the threats to validity are also discussed.

The next sections describe each step.

A. DEFINITION OF RESEARCH QUESTIONS (STEP 1)

The main objective of this research is to analyze the use and determine the impact of Tangible User Interfaces in the K12 education stage. To achieve this goal, a number of research questions (see Table 1) were defined to cover the most relevant aspects related to TUI.

B. CONDUCT SEARCH FOR PRIMARY CONTRIBUTIONS (STEP 2)

The next step is to define search strings that have to be developed on the basis of the goal of this study. However, before defining the search string, some discussion about the search terms is necessary.

As the main objective indicates, the search term is Tangible User Interfaces. Since many authors do not use the complete term (tangible user interface), we decided to accept it by using "tangible interface". The search string has to consider the term both in singular and plural.

Furthermore, we found a never-ending discussion on where the division between the terms education and learning lies. Resolving that discussion is beyond the scope of this article,

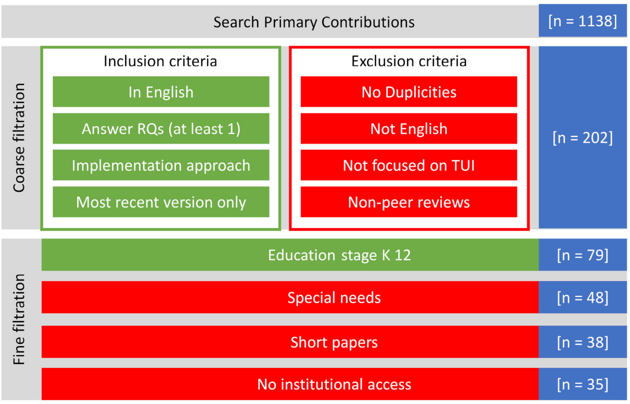

FIGURE 2. Screening process.

so we decided to use both ''education'' and ''learning'' in the search term, connected with an OR logic operator.

Therefore, the main search string in our case has the following terms: tangible AND (learning OR education). The search is limited to the period 2010-2019.

This step also includes the selection of data sources. We are interested in all results from relevant databases for all possible subject areas, not only Computer Science. Table 2 presents the search strings used on the selected databases (i.e. ACM Digital Library, IEEE Explore, ISI Web of Knowledge, Science Direct and Scopus).

Table 3 shows the number of articles found in each database. Another divergence can be found in the results from Web of Science. Depending on the web site employed, it is possible to obtain a different number of results. In this study, the results were obtained from the *apps.webofknowledge.com* site.

The information retrieved from each database was stored in different files. Each file contains the relevant information (metadata) from each article found. All the databases allow users to download files, offering useful extensions (CSV, BibTeX, etc.) with the search results.

C. SCREENING OF PAPERS FOR INCLUSION AND EXCLUSION (STEP 3)

This step allows us to exclude studies or papers that are not relevant to the answering of the research questions. Contributions were selected in the systematic mapping if they included a study on TUI usage in education, and, in accordance with the aims stated in Section I, if they were focused on K12 (kindergarten and grades 1 to 12). Systematic mapping and literature reviews are also included. This screening process is depicted in Figure 2, where we can see how the number of papers is reduced after applying the different filters.

This stage begins with 1,138 articles, and it should conclude with a list of primary contributions, which are obtained after applying a set of filters that are described in this section. The first step is to define the inclusion and exclusion criteria.

TABLE 2. Search string used on each database.

Database	Search string
ACM Digital Library	query: (Title:(("tangible interface" AND (learning OR education)) OR ("tangible interfaces" AND (learning OR education)) OR ("tangible user interface" AND (learning OR education)) OR ("tangible user interfaces" AND (learning OR education))) OR Abstract:(("tangible interface" AND (learning OR education)) OR ("tangible interfaces" AND (learning OR education)) OR ("tangible user interface" AND (learning OR education)) OR ("tangible user interfaces" AND (learning OR education))) OR Keyword:(("tangible interface" AND (learning OR education)) OR ("tangible interfaces" AND (learning OR education)) OR ("tangible user interface" AND (learning OR education)) OR ("tangible user interfaces" AND (learning OR education)))) "filter": Publication Date: (01/01/2010 TO 12/31/2019), ACM Content: DL
IEEE Xplore	((("Publication Title":"tangible interfaces" AND (education OR learning)) OR ("Abstract":"tangible interfaces" AND (education OR learning)) OR ("Author Keywords":"tangible interfaces" AND (education OR learning)) OR ("Publication Title":"tangible interface" AND (education OR learning)) OR ("Abstract":"tangible interface" AND (education OR learning)) OR ("Author Keywords":"tangible interface" AND (education OR learning)) OR ("Document Title":"tangible interfaces" AND (education OR learning)) OR ("Publication Title":"tangible user interfaces" AND (education OR learning)) OR ("Abstract":"tangible user interfaces" AND (education OR learning)) OR ("Author Keywords":"tangible user interfaces" AND (education OR learning)) OR ("Document Title":"tangible user interfaces" AND (education OR learning)) OR ("Publication Title":"tangible user interface" AND (education OR learning)) OR ("Abstract":"tangible user interface" AND (education OR learning)) OR ("Author Keywords":"tangible user interface" AND (education OR learning)) OR ("Document Title":"tangible user interface" AND (education OR learning)))) Filters Applied: 2010 - 2019
ISI Web of Science	((TI=("tangible interfaces" AND ("learning" OR "education"))) OR (TS=("tangible interfaces" AND ("learning" OR "education"))) OR (TI=("tangible interface" AND ("learning" OR "education"))) OR (TS=("tangible interface" AND ("learning" OR "education"))) OR (TI=("tangible user interface" AND ("learning" OR "education"))) OR (TS=("tangible user interface" AND ("learning" OR "education"))) OR (TI=("tangible user interfaces" AND ("learning" OR "education"))) OR (TS=("tangible user interfaces" AND ("learning" OR "education")))) AND IDIOMA: (English); Period 2010-2019
Science Direct	Title, abstract or author-specified keywords ("tangible interfaces" AND (learning OR education) OR ("tangible interface" AND (learning OR education)) OR ("tangible user interfaces" AND (learning OR education)) OR ("tangible user interface" AND (learning OR education))) Period 2010-2019)
Scopus	TITLE-ABS-KEY ("tangible interfaces" AND (learning OR education)) OR TITLE-ABS-KEY ("tangible interface" AND (learning OR education)) OR TITLE-ABS-KEY ("tangible user interfaces" AND (learning OR education)) OR TITLE-ABS-KEY ("tangible user interface" AND (learning OR education)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010)) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English"))

TABLE 3. Number of articles found in each database since 2010.

Database	Filter	Papers
ACM Digital Library	Conference papers and journal articles	294
IEEE Xplore	Conference papers and journal articles	79
ISI Web of Science	Research articles.	257
ScienceDirect	Research articles	27
Scopus	Research articles	471
	Total	1,138

TABLE 4. Filtered articles (only studies, reviews or SLR).

Database	Filter	Papers
ACM Digital Library	Conference papers and journal articles	5
IEEE Xplore	Conference papers and journal articles	25
ISI Web of Science	Research articles	82
ScienceDirect	Research articles	11
Scopus	Research articles	142
	Total	265

The inclusion criteria used were the following:

- The study should be written in English.
- The study should be published between January 2010 and December 2019.
- The study should clearly state its focus on the use of TUI in education.
- The study should describe the elements and the approach used to implement TUI-based systems in education.
- The study directly answers one or more of the research questions of this study.
- If the study has been published in more than one journal or conference, the most recent version of the study is included.

Among the exclusion criteria, we applied the following:

- Short papers.
- Duplicated articles.
- Articles not written in English.
- Articles not focused on TUI in education.
- Non-peer-reviewed articles, such as book chapters or technical reports.

Table 4 shows the number of articles (n=265) that include statements related to the goal of this research, and such statements are supported by a study. Systematic literature reviews are also included.

The five lists of selected articles are merged into a single list without duplicates. The resultant list comprises 202 preselected articles. After analyzing these 202 contributions, we identified 105 conference papers and 97 articles published in journals. In this classification we considered as conference papers those contributions published in Lecture Notes in Computer Sciences, whenever the volume was dedicated to publishing conference proceedings.

The next step of the screening phase is to apply a filter to obtain the contributions that are focused on children in K12 or grades 1 to 12, that is, students in kindergarten, primary and secondary school, which is the targeted population of this research. This filter was applied by using a semiautomatic method based on scripting that makes the first selection, followed by an audit performed by two researchers in parallel, who examined the abstract and, when necessary, the body of each contribution. At the end of this process, 79 articles were left.

The next filter applied was that of excluding articles focused on children with special needs, since the goal of the research was to discover how Tangible User Interfaces are used to improve the learning process in grades 1 to 12, in the most general sense. Among the 78 selected contributions, there were 30 articles whose focus was on children with special needs, so this filter left 48 selected articles.

One of the exclusion criteria has to do with short papers. Even these excluded articles were inspected to ensure all relevant contributions were considered regardless of the number of pages. This filter reduced the number of contributions to 38. Among the short papers included were the following: P13, P21, P31, P32.

Finally, three more papers ([23]–[25]), even though they were considered of relevance, were excluded due to the impossibility of obtaining them with our current institutional access.

At the end of the screening step, 35 primary contributions were selected. The complete list of primary contributions is presented in Appendix A.

D. ANSWER THE RESEARCH QUESTIONS (STEP 4)

This section is devoted to answering the research questions. In order to determine the extent to which the contribution answers each research question, four indicators were defined:

- Determine which term the contribution uses: Tangible User Interfaces (TUIs) or Tangible Interfaces (TIs).
- Identify the educational levels: primary, secondary, high, university, continuous.
- Identify the technology employed to support tangible interfaces.
- Determine whether or not the contribution includes a study. If so, identify the number of participants.

1) RQ1 WHAT IS THE STATE OF THE CONTRIBUTIONS ABOUT TANGIBLE USER INTERFACES APPLIED TO EDUCATION AND PUBLISHED BETWEEN 2010 AND 2019?

In this section the primary contributions are analyzed to find the publications by year (RQ1.1), the main channels such as journals or conference proceedings (RQ1.2), the definitions of TUI used by primary contributions (RQ1.3), the research methods they use (RQ1.4), the kind of contributions (RQ1.5) and, finally, to identify the quality of the primary contributions (RQ1.6).

2) RQ1.1 HOW MANY ACADEMIC STUDIES ON TANGIBLE USER INTERFACES WERE PUBLISHED BETWEEN 2010 AND 2019?

The first research question analyzes the distribution of the primary contributions over the period 2010-2019. Figure 3 shows the number of articles over the 10-year period.

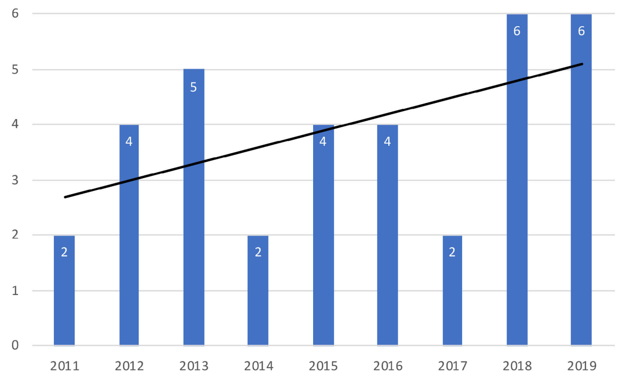

FIGURE 3. Publications per year.

In figure 3 we can see how the line formed by the number of primary contributions has a positive slope, indicating an increasing trend. The years 2018 and 2019 registered 12 published articles, which represents 34.2% of the total. The distribution of primary contributions in the 10-year period reveals the interest in Tangible User Interfaces among researchers. It should be taken into account that the primary contributions represent the papers selected from all the articles found on Tangible User Interfaces (see Section III-B).

3) RQ1.2 WHAT ARE THE PUBLICATION CHANNELS USED TO PUBLISH STUDIES ON TANGIBLE USER INTERFACES?

The aim of this research question is to collect and organize the publication channels used by primary contributions. The publications are organized into two groups: journals and conference proceedings.

Table 5 presents the number of contributions by journals (n=20) and conferences (n=15). The journals have been ordered according to their impact factor, which was taken from Clarivates (C) and Scopus (Sc), in this order. In the case of the articles published in conference proceedings we used the SJR index (Scimago Journal Ranking).

4) RQ1.3 WHAT IS THE DEFINITION OF TANGIBLE USER INTERFACES USED BY RESEARCHERS?

The goal of this research question is to analyze what the authors of the primary contributions mean when they use the term Tangible User Interface or Tangible Interface in their studies. The analysis consists of reviewing each primary contribution to look for a definition or a reference to a definition.

Table 6 shows the definitions of Tangible User Interfaces referenced by the primary contributions. Some contributions contain indirect references to a basic one, that is, the authors refer to another contribution, which contains a basic reference. For instance, contribution number P06 references [4], which references [2]. In the case of P07, the authors reference certain other works by H. Ishii [4], [8]–[11], so we can conclude that the notion they have about TUI is based on that originally given in [2].

TABLE 5. Primary contributions by journal and conference.

Title	IF	n	PC
Channel: Journal (n=20)			
Computers and Education	5.627(C)	1	P07
Transactions on Emerging Topics in Computing	4.989(C)	1	P25
Computers in Human Behavior	4.306(C)	1	P03
Transactions on Education	2.214(C)	1	P14
Journal of Supercomputing	2.157(C)	1	P15
Multimedia Tools and Applications	2.101(C)	1	P29
Personal and Ubiquitous Computing	1.735(C)	6	P01, P02 P04, P06 P09, P18
Entertainment Computing	1.297(C)	1	P15
Universal Access in the Information Society	0.920(C)	1	P19
Interacting with Computers	0.863(C)	1	P22
Journal of Internet Technology	0.715(C)	1	P34
International Journal of Child-Computer Interaction	0.489(Sc)	2	P26, P27
Journal of Emerging Technologies in Learning	0.219(Sc)	1	P28
I-Com	-	1	P35
Channel: Conference (n=15)			
Conference on Multimedia an Expo	0.33	2	P23, P24
Conference on Human Factors in Computing Systems	0.31	2	P21, P31
CHI Play	0.19	1	P13
Conference on Interaction Design and Children	0.17	4	P05, P08, P11, P17
Conference on Innovation and Technology in Computer Science Education	0.17	1	P12
MATEC Web of Conferences	0.17	1	P10
Conference on Tangible, Embedded, and Embodied Interaction	0.17	1	P30
Conference on Computer Supported Education	0.12	1	P32
IEEE Symposium on Computers Informatics	0.12	1	P33
Artificial Intelligence in Education	0.11	1	P20
Total	35		

5) RQ1.4 WHAT RESEARCH METHODS HAVE BEEN USED IN ARTICLES ON TANGIBLE USER INTERFACES?

The aim of this research question is to discover what the research methods in the primary contributions are. There are different schemes that can be applied to classify the research methods, depending on the research field. We adapted the scheme proposed in [26], which is focused on software engineering, in order to cover our field of study. In this way, we identified the following four main groups of research methods:

- Descriptive research: in this group we find literature reviews, systematic mapping and articles offering guidelines or opportunities.

TABLE 6. Tangible user interfaces in the primary contributions.

Cited Author	Definition	Primary Contribution
Tangible bits by [2]	"Tangible Bits" is an attempt to bridge the gap between cyberspace and the physical environment by making digital information (bits) tangible	P01, P02, P03, P04, P05, P06, P07, P08, P09, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19, P22, P25, P26, P28, P30, P32, P33, P34, P35
Tangible User Interfaces [9]	Tangible User Interfaces (TUIs) are built upon those skills and situate the physically-embodied digital information in physical space	P29, P32, P35
TUI based on Graspable UI by [10]	A physical handle to a virtual function where the physical handle serves as a dedicated functional manipulator	P20, P21, P27
None		P23, P24, P31

TABLE 7. Research method.

Method	Technique	PC	N
Descriptive research	Literature review	P01, P03	2
	Design implications	P02, P35	2
Experimental research	Descriptive statistics	P01, P06, P15, P17, P18, P19, P25, P26, P19	9
Quantitative evaluation	Artifact and user study	P04, P24, P27, P30, P32, P34	6
Qualitative evaluation		P04, P09, P10, P11, P12, P13, P20, P21, P22, P23, P25, P27, P31, P33	14
Usability evaluation		P05, P07, P08, P14, P29	5

- Experimental research: any article with a hypothesis test is included in this group.
- Quantitative evaluation: this group includes articles that provide quantitative studies (such as quantitative article evaluation or surveys).
- Qualitative evaluation: articles using any qualitative method (interviews, pilot studies, heuristics, etc.).

By taking into account the above scheme, we analyzed each primary contribution to determine the research method. Table 7 shows that qualitative evaluation is the most widely-used research method among the primary contributions. It should be noted that 2 primary contributions combine quantitative and qualitative evaluation.

6) RQ1.5 WHAT KIND OF CONTRIBUTIONS ARE PROVIDED BY STUDIES ON TANGIBLE USER INTERFACES?

The aim of this research question is to discover the kind of contributions provided by the primary contributions. The following list shows the different categories obtained by adapting the classification proposed in [27]:

- Empirical: Provide new knowledge by making new findings.
- Artifact: Prototypes, systems, techniques, tools, etc.
- Method: Define new ways to carry out the research.
- Theory: New concepts, models, principles or frameworks.
- Dataset: New useful corpus or repositories.
- Meta-analysis: Surveys, literature review, etc.
- Essay: A document that seeks to change minds.

Table 8 shows the kind of contribution in each primary contribution.

There are 11 primary contributions under the category Empirical. These 11 studies rely on an experimental research method, which implies using a statistical test to validate a given hypothesis. Although the intervention implies using an artifact or prototype, the primary contributions' claims are more ambitious than those in the Artifact category.

Two of the primary contributions make a descriptive contribution, and comprise a literature review (P12) and design implications (P19).

7) RQ1.6 WHAT ARE THE EDUCATION LEVEL AND SUBJECT AREA OF STUDIES ON TANGIBLE USER INTERFACES?

The aim of this research question is to determine what the academic grade or educational level are that have been the object of study in the primary contributions.

Table 9 shows the result of this analysis. Programming (robots, computational thinking and similar aspects) is the academic subject that received the attention of 10 contributions (P04, P06, P08, P11, P12, P14, P17, P21, P27, P34). This subject does not appear in the official curricula of the K12 education stage in most countries.

Figure 4 shows the number of primary contributions for each educational level. The mostly widely addressed grades were those from 1 to 6, which corresponds to children from 6 years old to 11-12 years old.

8) RQ1.7 WHAT IS THE IMPACT OF THE SELECTED CONTRIBUTIONS?

In this research question an impact criterion is defined. To do this, we assigned a relevance number, which is based on the PlumX metrics [28]. This indicator helps us to sort the list of primary contributions, and is based on the citation count, the article usage data and the caption number. To balance these metrics, we applied the following formula to obtain a single value (1).

$$\begin{aligned} relevance &= 0.60 * (cites/MAX\_CITES) + 0.20 \\ &\quad *(usage/MAX\_USAGE) + \\ &\quad +0.10 * (caption/MAX\_CAPTION) \end{aligned} \tag{1}$$

Appendix B shows the list of the primary contributions ordered by relevance. It can be observed that the citation count is the main metric, with a weight of 60%, followed

TABLE 8. Contribution, method and data collection.

PC	Contribution type	Research method	Data collection	Analysis
01	Empirical	Experimental research	Observation	Statistical analysis
02	Method	Design method	Observation	Discussion
03	Meta-analysis	Literature review	Systematic literature review	Discussion
04	Artifact	Quantitative and qualitative	Observation, Interviews	Statistical analysis
05	Artifact	Usability evaluation	Observation, Questionnaire	Statistical analysis
06	Empirical	Experimental research	Observation	Statistical analysis
07	Empirical	Experimental research	Observation, Questionnaire	Statistical analysis
08	Artifact	Usability evaluation	Observation	Statistical analysis
09	Artifact	Qualitative evaluation	Questionnaire	Statistical analysis
10	Artifact	Qualitative evaluation	Observation, Interview	Discussion
11	Artifact	User study	Interview	Discussion
12	Artifact	Qualitative evaluation	Questionnaire	Descriptive statistics
13	Artifact	User study	Questionnaire	Discussion
14	Artifact	Usability evaluation	Observation	Statistical analysis
15	Empirical	Experimental research	Interview	Statistical analysis
16	Artifact	User study	Observation	Descriptive
17	Empirical	Experimental research	Observation, Questionnaire	Statistical analysis
18	Empirical	Experimental research	Observation, Questionnaire	Statistical analysis
19	Empirical	Experimental research	Observation	Statistical analysis
20	Artifact	Qualitative evaluation	Observation, Questionnaire	Statistical analysis
21	Artifact	Qualitative evaluation	Observation	Discussion
22	Artifact	Qualitative evaluation	Observation, Questionnaire	Statistical analysis
23	Artifact	Qualitative evaluation	Observation, Questionnaire	Discussion
24	Artifact	Quantitative and qualitative	Heuristics	Discussion, Statistical analysis
25	Empirical	Experimental research	Observation	Statistical analysis
26	Empirical	Experimental research	Observation	Statistical analysis
27	Artifact	Quantitative and qualitative	Questionnaire, Observation	Statistical analysis
28	Empirical	Experimental research	Questionnaire, Observation	Statistical analysis
29	Artifact	Usability evaluation	Questionnaire, Observation	Statistical analysis
30	Artifact	Quantitative evaluation	Observation	Descriptive statistics
31	Artifact	Qualitative evaluation	Interview	Discussion
32	Artifact	Quantitative evaluation	Questionnaire	Descriptive statistics
33	Artifact	Preliminary user study	Questionnaire	Descriptive statistics
34	Artifact	Quantitative evaluation	Observation	Descriptive statistics
35	Method	Design implications	Observation	Discussion

by usage with 20%, and caption with 10%. The list of the primary contributions in Appendix B has been ordered according to this quality indicator.

9) RQ2 WHAT ARE THE TECHNOLOGIES APPLIED TO SUPPORT TUI?

The goal of this research question is to find and classify what technologies made tangible user interfaces possible for the artifacts described in the primary contributions.

Figure 5 shows the technologies used to support Tangible User Interfaces. It should be noted that a prototype might integrate more than one technology, so there are more technologies than primary contributions. The different technologies have been grouped into the following sets:

- Camera: This group includes the prototypes using a camera to detect a visual pattern, a depth camera, and position-detection. We can identify certain subgroups:
  - Visual pattern: P01 (Tern [29]), P02 (Sound Maker [30]), P09, P11, P13, P17, P28, P33, P35
  - RGBD camera: P20 (EarthShake), P24 (The book of Elli), P32
- Electronic blocks: P14 (A-Bricks), P15 and P25 (TOK),
  - A-Bricks: P14
  - TOK: P15 and P25
  - PROTEAS Kit [31]: P04, P06, and P27
  - PhonoBlocks: P26
  - Comb: P30
  - Mobeybou: P31
- RFID: P07, P12 (TanPro-Kit), P16 (StoryCube), P22 (QuizBot), and P33 (Tangilearn)
- Different sensors:
  - Pressure sensor: P23 (Learn-Pads)
  - Pitch detection: P29 (Musa)

TABLE 9. Educational level and subject area.

Educational level	Subject area	PC	N
Pre	Drawing	P09	1
	Music	P02	1
	Stage-narrative	P15	1
	Learn physics concepts	P20	1
	Programming	P21	1
	Language learning	P25, P33	2
1st grade	Music	P02, P29	2
	Programming	P06, P11, P12, P14, P17, P21, P34	6
	Storytelling	P16	1
	Learning process	P19	1
	Learn physics concepts	P20	1
2nd grade	Music	P02, P13, P29	3
	Programming	P06, P11, P12, P17, P21, P27, P34	7
	Music,	P13	1
	Storytelling	P16	1
	Learn physics concepts	P20	1
	Mathematics	P23	1
3th grade	Programming	P06, P08, P11, P12, P17, P21, P27, P34	8
	Music	P13, P29	2
	Storytelling	P16	1
	Learn physics concepts	P20	1
	Mathematics	P23	1
	Language and narrative	P30	1
4th grade	Learning process	P05	1
	Programming	P06, P08, P11, P17, P34	5
	Collaborative learning	P07, P22	2
	Music	P13, P29	2
	Geography	P28	1
	Cognitive skills	P18	1
	Mathematics	P23	1
5th grade	Music	P02, P13, P29	3
	Programming	P04, P06, P08, P17, P34	5
	Writing	P10	1
	Geography	P28	1
	Collaborative learning	P22	1
	Mathematics	P23	1
	Natural sciences	P32	1
6th grade	Programming	P04, P06, P08	3
	Music	P02, P13, P29	3
	Geography	P28	1
	Mathematics	P23	1
7th grade	Programming	P08, P27	2
	Music	P13	1
	Mathematics	P23	1
8th grade	Programming	P08, P27	2
	Music	P13	1
Young children	Museum	P01	1
Young children	Mathematics	P03 (Review), P35 (Design)	2
Young children	Music	P30	1
Primary school	Greek alphabet	P24	1

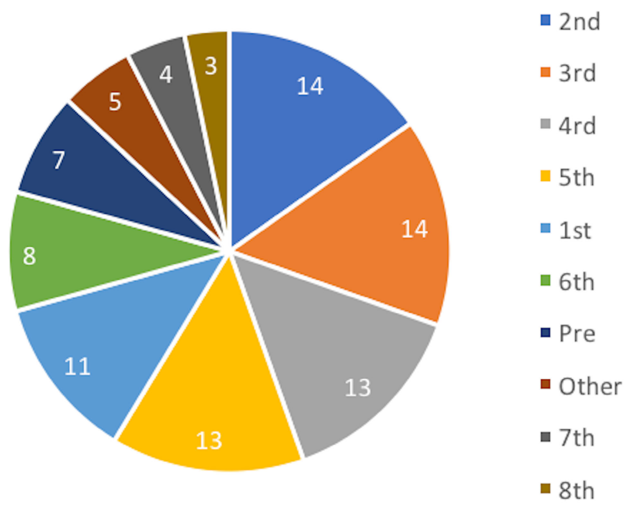

FIGURE 4. Educational levels targeted by the primary contributions.

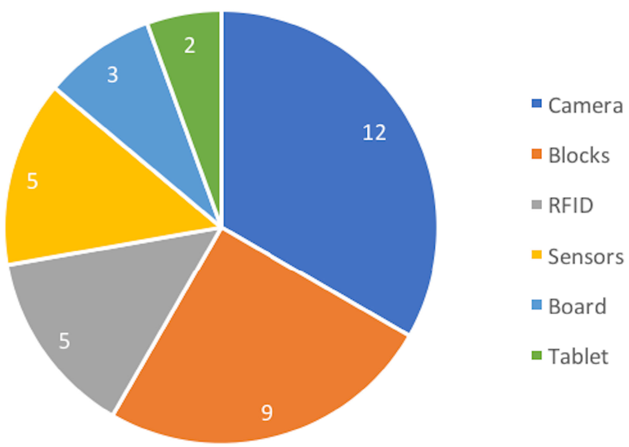

FIGURE 5. Technologies that support TUI in the primary contributions. (%)

  - Flex sensor: P08 (HandiMate)
  - Accelerometer: P16 (StoryCube)
  - Electromechanic: P05 (Teegi)
- Electronic board:
  - TagTiles: P18
  - littleBits: P21
  - e-Tuning: P34
- Tablet:
  - iPad: P19
  - Graphics tablet: P10 (BatiKids)

The camera is the most widely-used technology among the primary contributions (n=12). Visual pattern recognition uses cameras to identify physical objects that incorporate a visual pattern (a QR code or other visual pattern). Some of the prototypes also use augmented reality, adding digital information to physical elements.

The second place (n=9) is occupied by the group of primary contributions that make use of an electronic system based on blocks. In this group we can see different approaches: cubes connected by RS232, and electronic blocks using a board.

In third position (n=5) there are two groups: RFID and Sensors. NFC or RFID has been used in many TUI-based applications, for instance in [32], even before the term TUI was widely accepted. The Sensors group includes different technologies such as accelerometers, pressure sensors, electromechanical devices, flex sensors and pitch detection. This last case (P29) is considered a TUI by its authors but this could be controversial since the user does not employ the sense of touch.

10) RQ3 WHAT IS THE IMPACT OF THE USE OF TUI TECHNOLOGIES COMPARED WITH TRADITIONAL APPROACHES IN EDUCATION?

The aim of this research question is to determine whether or not Tangible User Interfaces in the primary contributions influence students' outcomes. This step can be performed by analyzing the primary contributions to look for added values (claims) and metrics:

- What are the added values of using Tangible User Interfaces?
- What are the metrics or tools employed to measure these added values? This metric is described in Table 8.
- Are the added values claimed by the authors supported by the study?

Table 10 shows a list of the main claims contained in the primary contributions (second column). The last column indicates whether or not the claim is supported by the primary contribution.

Most of the primary contributions claim that TUIs are perceived as fun, engage children in learning, promote interest and attention, inspire, and are more enjoyable, in comparison with traditional interfaces (graphical user interfaces).

A closer look at the results in Table 10, allows us to identify the list of primary contributions that have a direct impact on academic grades. A considerable number of primary contributions claim that the use of Tangible User Interfaces has a direct impact on the learning process. These studies are the following: P05, P06, P08, P11, P12, P14, P15, P16, P17, P19, P20, P21, P22, P25, P26, P28, P29, and P33, which represent 51.4%.

Collaboration is also a relevant keyword among the claims (P18, P22, P27, P28, and P31), which include expressions such as ''support collaboration'', ''appropriate for collaborative work'', etc.

It is also noteworthy that there are some primary contributions that claim TUIs improve problem solving skills (P11, P14, P19, and P22).

11) RQ4 WHAT ARE THE RESEARCH OPPORTUNITIES IDENTIFIED IN THE DEVELOPMENT OF TUI-BASED SYSTEMS APPLIED IN EDUCATION?

This research question tries to summarize the research opportunities identified that can be extracted from the primary contributions.

TABLE 10. Analyzing the impact of TUIs in education in the primary contributions.

PC	Added value or claim	Supported?
P01	It is advantageous to combine tangible interaction with more traditional interfaces.	Yes
P02	Identification of an appropriate set of embodied metaphors that children may use in their reasoning about abstract concepts related to sound parameters.	Yes
P03	TUIs offer new opportunities for training the mental number line.	Review
P04	TUIs are more attractive, especially for girls, more enjoyable and easier to use by younger children (7-8 years old). Older children (11–12 years old) did not consider TUIs as the easiest-to-use UI.	Yes
P05	Teegi affected the cognitive, affective and conative (motivation to learn) dimensions of the "learning proneness".	Yes
P06	Children produced fewer errors, and performed more effective debugging, and younger children in particular needed less time to accomplish the tasks with the TUI.	Yes
P07	QuizBot is perceived as engaging and fun. Participants enjoyed interacting with the TUI most.	Yes
P08	Through the iterative design process they enhanced their knowledge of physics-based engineering concepts.	Yes
P09	The results suggest that the physicality of the TUI has advantages over the GUI since TUIs have a stronger potential for engaging children in the activity proposed.	Yes
P10	BatiKids gives users the chance to be more explorative and expressive.	Yes
P11	T-Maze is easy to learn; children's logical thinking abilities and problem solving abilities may improve.	Yes (easy to learn)
P12	Children can use the system to complete tasks easily and gain a basic understanding of the related programming concepts.	Yes
P13	The system engages children and encourages to music composition.	Yes
P14	A-Bricks is effective in enabling students to express logical thinking abilities and to solve problems on their own.	Yes
P15	Digital manipulative enables the performance of embodied stage-narratives, promoting children's imagination and creative thinking, as well as fostering early literacy skills and metalinguistic awareness.	Yes
P16	Users find StoryCube full of playfulness, easy to learn and use, and that it somehow inspires children in storytelling activities.	Yes (preliminary study)
P17	Results revealed that graphical input could keep children focused on problem solving better than tangible input, but it was less stimulating for class discussion. Tangible output supported better schema construction and causal reasoning and promoted more active class engagement than graphical output but offered less opportunity for analogical comparison among problems.	Yes (preliminary study)
P18	TagTiles can be used to train specific skills and serve as a screening tool for these skills (IQ-scores).	Yes
P19	TUI on the iPad reduces the number of students seeking learning support as well as enhancing student engagement and collaboration in class.	Yes
P20	EarthShake produces large and significant learning gains, improvement in explanation of physics concepts, and clear signs of productive collaboration and high engagement.	Yes
P21	Engages children in play, also provide opportunities to learn CT (computational thinking) concepts, practices, and perspectives. Also, tangible technologies can be used to teach CT.	Yes
P22	The system provides evidence that collaborative problem solving skill acquisition should concentrate on collaborative games based on physical spaces in which technology based on robots is perceived by children as natural and as having motivating game elements.	Yes
P23	The system creates an atmosphere of fun among the children and engages them in learning.	Yes
P24	The system's recognition algorithms perform sufficiently well and its design is appropriate for the target user group	Yes (preliminary study)
P25	The use of TOK has a clear impact on children's lexical knowledge and phonological awareness developments.	Yes
P26	The results showed that the EFL children achieved significant learning gains relative to their baseline performance.	Yes
P27	Interaction with the tangible interface was perceived as more fun by all students and more appropriate for collaborative work by elder students and girls.	Yes
P28	The system can support interaction and collaboration among young children, as well as enriching the learning process and making it more enjoyable.	Yes
P29	Children are able to improve their knowledge of the piano keyboard.	Yes
P30	The usage of shape as a meaningful element of interaction could be a promising design strategy for interfaces aimed at children.	Yes
P31	Mobeybou motivated and inspired children to actively and collaboratively create narratives integrating elements from the different cultures.	Yes
P32	The system promotes the interest and attention of the participants.	Yes
P33	The system offers profound effects on the preschoolers' learning performance and enjoyment level.	Yes
P34	e-Tuning teaches students programming logic and trains their logical thinking abilities while increasing learning motivation.	Yes
P35	Design implications.	Yes

TABLE 11. **Identification of research opportunities in the primary contributions.**

PC	Research opportunities identified
P01	New metaphors for a tiered hybrid interface (tangible and graphical).
P02	Future work on leveraging embodied knowledge in supporting the process of learning abstract concepts.
P03	The possibilities provided by TUIs for the purpose of embodied number line training.
P04	Exploration of the advantages of tangible interfaces in relation to learning outcomes and the effects of the nature and the complexity of the tasks, size of the team and the level of previous experience among members of the same age group.
P05	Methodologies to evaluate the pedagogical potential of interactive systems in real context of use, and further facilitate their integration in classrooms.
P06	Learning and performance and possible training applications, such as with adult novices or individuals with special needs. Advanced modern programming techniques may be combined with tangibility and researched to provide additional insight into early programming.
P07	The relationship between user acceptance and collaborative performance. How tangible and tactile solutions meet the different needs posed by different learning settings and students.
P08	Gesture mapping carried out for the toys.
P09	Validation of the use of drawing as a method for evaluating technology with preschoolers.
P10	There is a multitude of applications in the general area of Ubiquitous Computing and TUI to be discovered [32].
P11	Provision of a cooperative way for children to play with T-Maze.
P12	Improvement in the design of representation of programming concepts to make it easier for children to understand and remember.
P13	Trilling of the system with schools and teachers, to explore what impact interactive installations can have on learning musical concepts in a longitudinal study.
P16	Customization of hardware; enrich character' props; support simultaneous interaction; conduct a formal user evaluation.
P18	Tap (based on TagTiles) can be a tool in the early detection of shortfalls (spatial (working) memory, spatial reasoning, selective attention and perception).
P19	Researching the quality of collaboration when using the iPad, and its correlation with students' knowledge construction. The integration of the tangible features of the iPad into instructional activities.
P20	Isolation of the effect of tangibility and collaboration in an experiment with a tightly matched screen-based game used as a control condition.
P22	Improvement of the game graphics, increasing the number of bombs and items, playtime, children participation, and robot shapes.
P23	Development of new video games for various topics. Develop a logic engine module that plays the role of a personal trainer and controls the intensity of the games based on the heart rate of the users. Enhance the system with vibrotactile actuators.
P24	User testing with young students to address system usability. Supplement the system with additional curricula.
P25	Use of a comparison group and more discriminating evaluation instruments. Integrate digital manipulatives in the pre and primary school curriculum. Develop other digital manipulatives to address different aspects of children's development.
P26	More wide-scale controlled experiments with at-risk and EFL children.
P27	Development and use of new features on the tangible objects in order to help users return to the system after a period of time.
P29	Extension to other areas of application, where it is necessary to use complex devices that, like musical instruments, require face-motor coordination.
P30	Research on long-time studies in kindergartens, the expert evaluations in studio or live situations, the adaption of pre-attentive perception concepts to TUIs, and the influence on holding function-states in working memory.
P31	Optimization including new hardware and sets for different countries. Investigate the pre and primary school potential for promoting language and narrative competences, as well as multiculturalism.
P33	Improvement of TangiLearn until a robust system is developed, and performance of a comparative study.
P35	Testing interactive prototypes with students to evaluate the benefit of the digital and tangible system.

Table 11 shows the research opportunities identified in the primary contributions. Most of the papers propose extending their study by either increasing the number of participants (P25, P26), performing longitudinal, long-term studies (P04, P30), carrying out large-scale experiments (P24), or evaluating the prototype in a school (P13).

Some contributions point out the need to define and study design aspects related to Tangible User Interfaces (P12), such as metaphors (P01), embodied knowledge (P02, P03), gestures (P08), improvements in the learning process (P27), the performance of a formal usability evaluation (P16, P23, P24), or the use of drawing (P09).

The pedagogical potential of TUIs is another research opportunity identified by the primary contributions (P05, P06, P13, P35).

The possible benefits of TUIs for people with special needs is highlighted by some contributions (P06, P18).

How TUIs promote or improve collaboration and cooperation among students is another research opportunity detected (P07, P11, P19).

Finally, some authors define research opportunities in terms of improving the proposed TUI prototype (P16, P22, P24, P32, P33). Some contributions do not define research opportunities (P14, P15, P17, P21, P28, and P34).

IV. DISCUSSION

This section discusses and analyzes the results by reviewing each research question.

The interest in Tangible User Interfaces is reflected by the number of publications in the period 2010-2019 (RQ1.1).

Table 4 shows 265 contributions that apply Tangible User Interfaces in K12 education. After eliminating duplicates we obtained 202 contributions. This number shows the interest of the community in this kind of systems. This is also confirmed by the positive slope of the line resulting from the number of publications. It is important to note the considerable number of contributions that apply Tangible User Interfaces for children with special needs.

A large number (n=20) of the primary contributions are journal articles, the rest (n=15) being conference papers (RQ1.2). Short papers are not usually included among the primary contributions in similar previous works [22], [26], [34]. However, we included some short papers for the following two reasons: (a) some of the short papers are among the most relevant contributions according to the metric used (see Eq. 1); and (b) the focus of our study is to analyze the impact of a particular interaction technique on education and there are some short contributions that include this kind of result.

There is a consensus about what the primary source of the term Tangible User Interfaces is, even though some authors prefer to use the term tangible interfaces. This is the content of RQ1.3, with [2] the most frequently referenced in the domain of tangible interfaces, which also might include the subsequent related references ([4], [8]–[11]). However, the concept of tangible user interface has to be better defined. There is a close relationship between touch and tangible interaction. The term graspable object should also be considered [4]. Following the unwritten concept of tangible interface in the primary contributions, we can conclude that a Tangible User Interfaces should be conceived as a graspable user interface. Therefore, a touch-based interaction system would only be considered tangible if the user can grasp the object.

The research method employed by each primary contribution is analyzed in RQ1.4. Only 9 contributions are experimental research with a rigorous statistical analysis based on a research hypothesis. Most of the authors base their claims on qualitative evaluation. A usability evaluation usually includes a qualitative evaluation.

All the primary contributions provide an artifact (RQ1.5), that is a tangible user interface prototype, which is used to intervene in a classroom or a group of children. The authors use observation to analyze how children react to the proposed system.

The third grade (n=15) received the most attention from the primary contributions, and the first grades (1 to 3) of primary education are the most frequently chosen for the application of the interventions (RQ1.6). While music, foreign languages, programming, mathematics and geography are the academic subjects in the primary contributions, it is perhaps surprising to see the absence of subjects such as history, natural sciences or language.

The metric used in this study to sort the primary contributions is described in RQ1.7. Other studies have analyzed the quality of the primary studies using a different method, namely a subjective analysis performed by the authors [26]. Using an independent metric instead of a subjective analysis, has the advantage of avoiding human error or any personal bias. The debate about this research question involves analyzing whether or not the number of citations is a more important indicator than usage or caption. This field of research is changing quickly, so we have considered other indicators beyond the citation count. It will not be long before the impact on social networks is included among the metrics that measure the impact of a contribution.

An interesting aspect of this study is the analysis of the technology used in the primary contributions to support Tangible User Interfaces (RQ2). Almost all the contributions propose tangible user interface prototypes based on graspable objects (P18 is an exception). Twelve contributions use cameras, either visual pattern or depth cameras, to detect physical objects. Sensor-based prototypes are diverse, with RFID (or NFC) being one the promising technologies to implement Tangible User Interfaces.

The impact in education is analyzed in RQ3, which similar previous studies, namely [20] and [4], did not include. As we mentioned in Section 10, 51.4% of the contributions (n=18) claim that Tangible User Interfaces have had a real impact on education. The analysis of these 18 contributions reveals that only a few have a real impact on the learning process of one of the daily academic subjects or courses. Most of the contributions affect motivation, engagement, interest in learning, and attention, which are also obviously important aspects of the learning process at the K12 education stage. The interest of some contributions in the collaborative or cooperative dimension of education is also relevant and promising since they are educative competences that are being included in many official curricula.

Research Question 4 presents a list of the research opportunities identified in the primary contributions, which are listed in Table 11. This study has also made it possible to identify research challenges. One of them was pointed out at the beginning of this section, namely the potential of Tangible User Interfaces when applied to improving different aspects of learning in children with special needs. Some authors note the importance of extending their studies by increasing the number of participants or the duration of the study. Long-term studies, while they are harder to implement, are key in analyzing the real impact of an intervention on the learning process. The next section includes detailed information regarding the main findings of this research together with the implications, and a list of the main gaps detected, which will require further research efforts.

V. FINDINGS AND IMPLICATIONS

This section summarizes the main findings from the analysis of the primary contributions, and a discussion of the implications of using Tangible User Interfaces in educational settings, mainly in kindergarten, primary and secondary education, is also included.

The different findings can be organized into the following categories: added educational value, classroom, academic subjects and technologies.

The first category, added educational value, enumerates a list of educational values that can be improved by using Tangible User Interfaces:

- TUIs promote children's engagement in educational activities.
- TUIs support enjoyable learning activities.
- TUIs foster collaboration among students.

The next category (classroom) collects the findings about the use of TUIs in the classroom:

- TUIs can be combined with traditional applications.
- TUIs have proved effective in the learning of Maths.

Regarding the academic subjects, we have the following findings:

- The learning of abstract concepts (such as in Maths) is one of the preferred subjects for applying TUIs.
- TUIs have proved effective in learning music.
- Programming is also an academic subject in which TUIs have been applied successfully.
- Learning physics concepts (at an early age) using TUIs is also effective.

The last category contains the technologies used in TUIs:

- The use of cameras to implement TUIs is particularly common.
- Blocks have been applied to implement ad-hoc TUI solutions.
- RFID/NFC and other sensors are also a good technology resource to implement TUIs.

In addition, we have also identified a set of limitations that require further research efforts:

- The adoption of TUIs in K12 educational environments requires qualified staff with technological skills to exploit this type of systems properly.
- The lack of technological infrastructure in educational settings to support this type of interaction limits its implementation.
- Further research is needed to facilitate the user interaction with tangible objects in order to make it a "calm technology" [35].
- The integration of TUIs with social networks and gamification techniques could provide extra motivation in educational environments.
- The definition of specific and well-defined metrics to compare the students' performance using GUI- and TUI-based learning activities.
- The performance of ergonomic studies in educational environments centered on the physical design of Tangible objects.

Among the implications, we can highlight the following:

- The adoption of IoT can contribute to a more widespread and varied use of TUI application.
- A better integration of TUIs in daily learning activities is key to their success.
- Graspable learning activities are an important subject in early education. Innovative TUI applications can contribute to this specific field.

VI. THREATS TO VALIDITY

In this section, we analyze the threats to validity, which are always present in a research study ([21], [36], [37]), and describe the strategies used to reduce their effects. To assess the validity of this study, the authors used the validity framework presented in [36], which they previously applied in another systematic mapping [38]. This study addressed: (a) construct validity; (b) external validity; (c) internal validity; and (d) conclusion validity.

The *validity of construction* is related to obtaining the correct measures for the concept that is being studied [21], [36], [37]. To reduce this threat, a data collection process was defined for a correct selection of items (for example, inclusion and exclusion), which was used in the filtration of the contributions. This threat was managed by auditing the protocol, a task that was performed by one of the authors. Whenever inconsistencies were found, the whole process was repeated. The protocol needed 4 iterations to reach the final set of primary contributions.

External validity is related to the extent to which the results of the study can be generalized [21], [36]. In order to know to what degree the results of a study can be generalized, it is extremely important to describe the context of the research [39], [40]. This threat is minimized in this study with a rigorous research methodology that adapts the guidelines of [41], and the extraction of data with respect to the methodology (data collection procedures) was carried out following the guidelines of [21] and [42].

Internal validity can be affected when causal relations between the different aspects under study are analyzed and the researchers are not aware of the connections among them. In our case the different factors under investigation are presented independently and the relationships between them are explicit.

The *validity of the conclusion* is related to the influence introduced by the researchers in the analysis of these data. This risk can not be completely eliminated, though it was reduced by taking the following measures: (a) five researchers participated in the analysis of the primary documents; (b) a complete "audit" of the process that filtered 1,148 documents to identify 35 primary documents; (c) as noted above, the 35 relevant articles were reviewed by at least two authors, and the conclusions drawn from the analysis of the 35 primary documents involved the five authors.

These four validity threats have to be considered together with the result bias, which refers to the fact that positive research results are more likely to be published than negative results [43]. In this case, its effect is minimal because the objective of the study is to present the state of the art of TUI research in the K12 education stage. However, we recognize that the publication bias could have affected our results with respect to the benefits and challenges of using TUIs.

The selected period of study (2009-2019) can also be considered a limitation because we have not included works published in 2020, which are the most recent contributions on TUIs, such as [44], which is also relevant because of the technology used to implement the tangible interface.

Publication bias can also be affected by the sources of the data in a study and their publication channel. The databases used were: ACM digital library, IEEE Xplore, ISI Web of Science, Science Direct and Scopus, since it is known that these sources return most of the publications and have been used in similar types of literature mapping exercises in software engineering ([26], [45]).

In addition, scientific studies, books, book chapters, short articles, experience reports and assimilation studies, which are not peer-reviewed, were excluded. The reason for excluding these publications is that they present studies that are preliminary or too simple, and their relevance is slight.

The search step can also be improved by including the method proposed by [34], which the authors applied in designing Systematic Literature Reviews.

VII. CONCLUSION AND FUTURE WORK

This systematic mapping study provides a structured understanding of the current state of Tangible User Interfaces in the K12 education stage. This research study has been performed by identifying 35 primary contributions out of 1,138 TUI-related articles over a ten-year period (2010–2019). The contributions identified were analyzed with respect to: (1) current state of TUIs; (1.1) the frequency of publication by year; (1.2) publication channels; (1.3) definitions of TUIs; (1.4) research method; (1.5) type of contribution; (1.6) education level and academic subject; (2) technologies to support TUIs; (3) impact on education; and (4) research opportunities. The research study concludes with a discussion highlighting the main findings and an analysis of the threats to validity. The research method used in this study is an adaptation of the one presented in [41], to which we have added some activities proposed in [26]. One of the main contributions in the research method is the use of a metric to establish the relevance of the selected primary contributions. Thus, the final list of 35 primary contributions has been ordered according to a metric defined in Section III-D8. The main result of this study is an ordered list of 35 primary contributions that apply Tangible User Interfaces in the K12 education stage. And there is a second, but no less important, level of contributions. At this second level of results we can highlight the following: (a) the list of journals and conferences of the primary contributions; (b) a review of the concept of Tangible User Interface, which should consider only graspable interaction; (c) a list of the research methods used by the primary contributions; (d) a classification of the main contributions of the primary studies; (e) the education level and the academic subject used by the primary contributions; (f) a summary of the technologies employed by the primary contributions; (g) a summary of the impact on K12 education claimed by the primary contributions; and (h) a list of research opportunities identified by the primary contributions. Future work has also been identified in the article, and there is indeed a section devoted to identifying research opportunities in the primary contributions, as shown in Table 11. In addition, in section V we have gathered a list of limitations that require further research efforts. Another source of future work emerges from the research method applied in this study. For instance, as a result of the screening of papers and the filters applied thereafter, a considerable number of contributions that apply TUIs for children with special needs were found, something which could be the focus of a similar study. Another interesting idea is to review and formalize the concept of Tangible User Interfaces, in order to prevent authors from considering TUI-based interactive techniques that are not tangible in the sense we have discovered in this study. Another source of future research can be found in the study of the relationships between the different results obtained in this study. For instance, it is possible to establish a relationship between the technology used to support TUIs (those described in Section III-D9) and the claimed impact on education (Section III-D10).

APPENDIX A
PRIMARY CONTRIBUTIONS

P01. Horn M. S., Crouser R. J. and Bers M. U. 2012. Tangible interaction and learning: the case for a hybrid approach. Personal and Ubiquitous Computing, 16(4):379-389.

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TABLE 12. Indicator of relevance of the primary contributions (data available in May 12, 2020).

PC	Captures	Citations	Usage	Relevance
P01	435	101	538	0,6836
P02	1243	71	459	0,5632
P03	196	26	2037	0,3541
P04	173	32	539	0,2527
P05	14	4	2216	0,2249
P06	173	31	133	0,2101
P07	342	11	1046	0,1873
P08	41	6	1549	0,1787
P09	105	19	626	0,1778
P10	1	5	1602	0,1744
P11	103	27	17	0,1702
P12	40	2	1549	0,1549
P13	11	1	1602	0,1514
P14	62	23	17	0,1432
P15	58	18	213	0,1308
P16	81	11	598	,1258
P17	65	3	716	0,0877
P18	60	10	232	0,0852
P19	73	2	716	0,0824
P20	14	10	232	,0815
P21	70	1	716	0,0762
P22	114	2	320	,0499
P23	26	6	93	0,0461
P24	24	6	93	0,046
P25	40	6	9	0,0397
P26	47	0	360	0,0363
P27	24	2	111	0,0238
P28	5	0	242	0,0222
P29	12	1	113	0,0171
P30	21	1	93	0,016
P31	8	1	93	0,015
P32	5	0	113	0,0106
P33	14	0	93	0,0095
P34	1	0	93	0,0085
P35	22	0	25	0,004

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APPENDIX B
RELEVANCE OF THE PRIMARY CONTRIBUTIONS

Table 12 shows an ordered list of the primary studies according to the relevance indicators (captures, citations and usage).

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