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.

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. [8]–[12]), 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 conclude that these research studies are complementary to
FIGURE 1. Steps and outcomes based on the methodology adapted from [21] 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.

| 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? |

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, 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 2 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 II, 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. The inclusion criteria used were the following:

- The study should be written in English.

| Database                  | Search string                                                                 | Filters Applied: 2010 - 2019 |
|---------------------------|-------------------------------------------------------------------------------|-------------------------------|
| ACM Digital Library       | query: (Title: (“tangible interfaces” AND ( learning OR education )) OR (“tangible interfaces” AND (learning OR education)) OR (“tangible user interfaces” AND (learning OR education))) OR Abstract: (“tangible interface” AND (learning OR education)) OR (“tangible user interfaces” AND (learning OR education)) OR (“tangible user interface” AND (learning OR education)) OR (“tangible user interfaces” AND (learning OR education))) OR Key-word: ("tangible interface" AND (learning OR education)) OR ("tangible user interfaces" AND (learning OR education))) OR ("tangible user interface" AND (learning OR education))) | Filters Applied: 2010 - 2019 |
| IEEE Xplore               | ("Publication Title": "tangible interfaces" AND (learning OR education)) OR ("Abstract": "tangible interfaces" AND (learning OR education)) OR ("Author Keywords": "tangible interfaces" AND (learning OR education)) OR ("Publication Title": "tangible interfaces" AND (education OR learning)) OR ("Author Keywords": "tangible interfaces" AND (education OR learning)) OR ("Document Title": "tangible interfaces" AND (learning OR education)) OR ("Publication Title": "tangible interfaces" AND (education OR learning)) OR ("Author Keywords": "tangible interfaces" AND (education OR learning)) OR ("Document 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 ("Document Title": "tangible interfaces" 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 | Filters Applied: 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)) | Filters Applied: 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) ) OR TITLE-ABS-KEY ("tangible user interfaces" AND (learning OR education) ) | Filters Applied: 2010 - 2019 |
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 3 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 pre-selected 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 papers those contributions published in Lecture Notes in Computer Sciences.

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.

**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).

**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
FIGURE 3. Publications per year

shows the number of articles over the 10-year period.

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).

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).

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 [8]–[12], so we can conclude that the notion they have about TUI is based on that originally given in [2].

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
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 TUI based on Graspable UI by [10] | Tangible User Interfaces (TUIs) are built upon those skills and situate the physically-embodied digital information in physical space | P29, P32, P35 |
| 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 |

reviews, systematic mapping and articles offering guidelines or opportunities.

- 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.

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).

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.

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:

\[
\text{relevance} = 0.60 \times (\text{cites/} \text{MAX\_CITES}) + 0.20 \times (\text{usage/} \text{MAX\_USAGE}) + 0.10 \times (\text{caption/} \text{MAX\_CAPTION})
\]

(1)
TABLE 8. Contribution, method and data collection

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

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 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.

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 (Tangiblelearn)
| 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|    |
|                   | Storytelling                       | P16| 1  |
|                   | Learn physics concepts             | P20| 1  |
|                   | Mathematics                        | P23| 1  |
| 3rd 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  |
Different sensors:
- Pressure sensor: P23 (Learn-Pads)
- Pitch detection: P29 (Musa)
- 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.

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).
| 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| T-Maze is easy to learn; children’s logical thinking abilities and problem solving abilities may improve.                                                                                                              | Yes (easy to learn) |
| P11| BatiKids gives users the chance to be more explorative and expressive.                                                                                                                                                 | Yes        |
| P12| It is advantageous to combine tangible interaction with more traditional interfaces.                                                                                                                                   | 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| Ontoeducative: 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        |
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 [1] 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 [2] 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 ( [8]–[12]). 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 of 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 II. 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.
- TUIs support enjoyable learning activities.
- 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 inconsistences 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-D. 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-D) and the claimed impact on education (Section III-D).

APPENDIX A. PRIMARY CONTRIBUTIONS

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P14. Kwon D.-Y., Kim H.-S., Shim J.-K., and Lee W.-G. 2012. Algorithmic Bricks: A tangible robot programming tool for elementary school students. IEEE Transactions on Education, 55(4): 474-479.

P15. Sylla C., Coutinho C., and Branco P. 2014. A digital manipulative for embodied “stage-narrative” creation. Entertainment Computing, 5(4):495-507.

P16. Wang D., He L., and Dou K. 2014. Storycube: Supporting children’s storytelling with a tangible tool. Journal of Supercomputing 70 (1): 269-283.

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P18. Verhaegh J., Fontijn W., Aarts E., and Resing W. 2013. In-game assessment and training of nonverbal cognitive skills using tagtiles. Personal and Ubiquitous Computing 17 (8): 1637-1646.

P19. Wang T., Towey D., and Jong, M.S.Y. 2016. Exploring young students’ learning experiences with the iPad: a comparative study in Hong Kong international primary schools. Universal Access in the Information Society, 15(3): 359-367.

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APPENDIX B. RELEVANCE OF THE PRIMARY CONTRIBUTIONS

Table[2] shows an ordered list of the primary studies according to the relevance indicators (captures, citations and usage).

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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 | 1620 | 0.1514 |
| P14 | 62 | 23 | 17 | 0.1432 |
| P15 | 58 | 18 | 213 | 0.1308 |
| P16 | 81 | 11 | 598 | 0.1258 |
| P17 | 65 | 3 | 716 | 0.0877 |
| P18 | 60 | 10 | 232 | 0.0852 |
| P19 | 73 | 2 | 716 | 0.0824 |
| P20 | 14 | 10 | 232 | 0.0815 |
| P21 | 70 | 1 | 716 | 0.0762 |
| P22 | 114 | 2 | 320 | 0.0499 |
| 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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