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Estudios e Investigaciones

E-textiles for STEAM education in primary and middle school: a systematic review

E-textiles para la educación STEAM en educación primaria: una revisión sistemática

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Abstract

The growing interest in implementing maker education has highlighted the potential of electronic textiles (e-textiles) in the field of education. This article employs a systematic review methodology to characterize the scientific literature related to the educational use of e-textiles in primary education, focusing on their role in activities that stimulate diverse knowledge, abilities, and skills within the framework of Science, Technology, Engineering, Art, and Mathematics (STEAM) competencies. The review covers the period from 2006 to 2021, adhering to the PRISMA standards. Four prestigious international databases (Scopus, ERIC, WoS, and ACM) were consulted, resulting in the identification of 483 articles. After screening, 35 articles that met the predefined eligibility criteria were selected for analysis. The results and discussions elucidate that the majority of studies were conducted in non-formal educational settings, predominantly utilizing the LilyPad kit as the primary tool. The findings provide data supporting the effectiveness of e-textiles in facilitating learning related to computing, circuits and computational thinking. Numerous studies suggest that the use of e-textiles contributes to equity in STEAM competency acquisition, particularly notable due to the prevalence of female authorship in this field. In conclusion, our study demonstrates that the integration of e-textiles into educational activities for students aged 6 to 13 promotes STEAM skills across all domains. This impact extends to both formal and non-formal contexts, with methodologies designed to encourage student participation and competency-based learning.

Keywords: e-textiles, STEAM, *maker* culture, primary and middle school, systematic review.

Resumen

El creciente interés por implementar la educación *maker* ha puesto de relieve que los textiles electrónicos (e-textiles) ofrecen numerosas posibilidades en el ámbito educativo. El artículo se basa en la metodología de revisión sistemática con el objetivo de caracterizar la producción científica relacionada con el uso educativo de los e-textiles en educación primaria[1] como elemento de acción en actividades que buscan despertar diversos conocimientos, habilidades y destrezas en el aprendizaje competencial de Ciencia, Tecnología, Ingeniería, Arte y Matemáticas (STEAM). La revisión se realiza entre los años 2006 al 2021 siguiendo los estándares PRISMA. Se consultaron cuatro bases de datos de reconocido prestigio internacional (Scopus, ERIC, WoS y ACM), encontrando, tras el cribado, 483 artículos, de los cuales se seleccionaron los 35 que cumplían con los criterios de elegibilidad

establecidos. Los resultados y discusión arrojan que la mayoría de los estudios se desarrollan en la educación no formal, siendo el kit LilyPad la herramienta de uso predominante. Se evidencian datos de la eficacia del uso de e-textiles para el aprendizaje de computación, circuitos, el pensamiento computacional. Existen numerosos estudios que determinan que los e-textiles promueven el fomento de la equidad y el aprendizaje competencial STEAM, siendo un campo dominado por la autoría femenina. Nuestro estudio concluye que el uso de los e-textiles en actividades educativas para estudiantes de 6 a 13 años, promueve habilidades en todas las áreas STEAM, en contextos formales y no formales, utilizando metodologías que fomentan la participación entre el alumnado y el aprendizaje competencial.

Palabras clave: e-textiles, STEAM, cultura *maker*, educación primaria, revisión sistemática de literatura.

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INTRODUCTION

STEAM (Science, Technology, Engineering, Arts and Maths) education is a new educational competency model that emphasises the theorisation and integration of the arts in learning in the fields of science, technology, engineering, and mathematics, often grouped under the acronym STEM (Aguilera & Ortiz-Revilla, 2021). This model stands out because it is committed to teaching and learning processes through transdisciplinarity (White & Delaney, 2021). As it is closely rooted in maker education (Jia et al., 2021), it seeks to guarantee the acquisition of transversal knowledge, in which the contents of each of these fields are not worked on in isolation, but in an interdisciplinary way in order to ensure competent, functional, contextualised, and meaningful learning. The commitment to this approach has resulted in the incorporation of new teaching resources such as e-textiles, which, similarly to educational robotics due to their multidisciplinary nature, are effective in preparing teachers to integrate computer science and computational thinking into the curriculum (Fields et al., 2019). For this reason, we consider it essential to incorporate maker skills in initial and continuous teacher training (Valente & Blikstein, 2019). As demonstrated in the E-STITCH program, e-textiles are put forward as one of the key factors for STEAM subjects to operate at the same level (Tofel-Grehl et al., 2021; Tofel-Grehl et al., 2022). This program, led by US teachers Colby Tofel-Grehl and Kristin Searle (2023), who are leaders in the field of e-textiles applied to university education, is an example of a growing trend of incorporating this methodology in university classrooms.

E-textiles are textiles that have embedded digital and electronic components (Buechley et al., 2008). Researchers such as Buechley et al. (2013) and Jayathirtha and Kafai (2020) point out that carrying out e-textile projects is an effective way of educating in STEAM and developing skills from an early age. In the results of their meta-synthesis of 64 papers over a decade of e-textiles, 8 of which are included in our study, Jayathirtha and Kafai state that e-textiles constitute an exciting and promising field for equitable participation and broadening access to computer science education. They conclude that it is necessary to advocate for more in-depth research to determine the opportunities they provide for students to access the field of computer science. Buechley et al. (2013) provide empirical evidence of the benefits of using e-textiles in education and how e-textile construction kits are reshaping technology education.

At this time of expansion of maker education, it is of interest to examine the effectiveness of e-textiles in arousing curiosity for scientific and technological subjects at an early age. In this paper, a systematic literature review is provided, examining the use of e-textiles as an educational resource to support STEAM learning in students aged 6 to 13. In order to meet this goal, the following research questions were made:

- Which STEAM areas are worked on through e-textiles, and using which technologies?
- What methodological approaches are used to integrate e-textiles in primary education?
- In what contexts is e-textile learning addressed for students aged 6-13?

BACKGROUND

E-textiles in the context of the maker movement

Electronic textiles or e-textiles are "fabric artefacts that include embedded computers and other electronic devices" (Peppler, 2013, p. 38). The creation of these artefacts is associated with the field of wearable technologies, which has traditionally been reserved for scientists, textile engineers, health professionals, and pioneers in the arts and fashion design (Ryan, 2014). This multidisciplinary field stems from 1990s research in the field of interaction design applied to wearables, and it is characterised by the use of new flexible, conductive, and smart materials, by means of which highly visual and aesthetic results can be achieved (Berzowska, 2005; Orth et al., 1998). The creation of these artefacts brings together engineering and computing to create computers that are "soft, colourful, accessible, and beautiful" (Buechley et al., 2013, p.1), allowing for the possibility of combining art and creative expression

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with engineering, delving into knowledge domains such as programming, manual work, and electronics (Kafai et al., 2019).

This field was complex and inaccessible until the late 1990s, but around 2006 the emergence of the maker movement and the Do it Yourself (DIY) philosophy made its democratisation possible (Posch & Fitzpatrick, 2021; Perner-Wilson & Buechley, 2013). Maker culture emerged in the United States and became popular globally through Maker Faires (Dougherty, 2013). Makers (Hatch, 2014) carry out activities that consist of creating objects in both physical and digital collaborative learning spaces, and their projects are associated with the use of 3D printers, robotics or e-textiles, among others (Anderson, 2012). Maker education advocates making (or creating/building) as a way of learning (Peppler & Bender, 2013) and stands out for contributing to the so-called 21st-century skills (González-Pérez & Ramírez-Montoya, 2022). The roots of this movement are associated with Papert's constructionist theory (1980), and in turn, with constructivist learning theories (from classics such as Piaget, Vygotsky, and Dewey).

When developing and constructing e-textiles, electronic artefacts are created that can be wearable or that include programmable circuits or computers, which promotes learning, as a personally meaningful artefact is created (Papert & Harel, 1991). In recent years, creating digital media and learning electronics have become accessible to all audiences (Spina & Lane, 2020), making e-textiles applied to education an interesting teaching resource for STEAM education.

STEAM education with e-textiles

STEM education is based on an inclusive model that facilitates experiential learning and responds to the demands of the new millennium (Tytler, 2020; Sanders, 2009). Art was gradually integrated, in order to add a more creative and innovative perspective, thus giving rise to the term STEAM (Perignat & Katz-Buonincontro, 2019; Maeda, 2013; Yakman 2008). Among the various initiatives proposed on the basis of this educational approach, project-based learning in the context of e-textiles stands out. When considering the constructionist approach in the field of STEAM, e-textiles promise to be an important teaching resource that offers numerous possibilities for education focused on these areas (Kara & Cagiltay, 2023; Hughes & Morrison, 2018). In this regard, among other aspects, several authors have shown that the creation of e-textile artefacts benefits the development of creative and critical thinking (Lui et al., 2019; Peppler & Wohlwend, 2018) and encourages students to learn about electrical circuit concepts in a new way (Tofel-Grehl et al., 2017). Given their characteristics, various authors argue that they represent an opportunity for the expansion of computer science learning (Jayathirtha & Kafai, 2019), including elements of circuits, design thinking, and the arts, thus blurring the traditional boundaries between disciplines (Kafai et al., 2014). This field and its applications to education are identified as a key factor for working on STEAM subjects (Fields & Kafai, 2023; Peppler, 2013) and fostering computational thinking (Wing, 2006). In particular, because the incorporation of iterative design (Fields et al., 2019) provides the learning scenario for students to acquire risk-taking skills resulting in a critical-thinking basis for computational thinking.

Following Papert (1980), the fields of learning sciences and educational technology have focused on students learning by manipulating and creating digital objects. This is reflected in the use of platforms such as, for example, TurtleStitch, which allows you to embroider what you program and create projects in textiles. The projects carried out by the community represented, among others, by Margaret Low, have demonstrated their potential for students to acquire skills in design, mathematics, art, and composition (Klimczak & Solomon, 2022). Many e-textile construction kits have emerged, offering different approaches to getting started in programming, electronics. and STEAM. The use of these kits in the classroom offers greater transparency when learning than robotics construction kits (Kafai et al., 2014). Buechley (2006) designed the LilyPad kit with the aim of broadening participation in computer science.

The LilyPad kit was designed in a similar way to the LEGO Mindstorms kit (Resnick et al., 1988) and includes a low-cost, open-source, Arduino-based programmable motherboard (Banzi, 2008), conductive thread and different sensors and actuators adapted to be easily sewable to the textile, allowing users to

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design and create their own e-textiles (Buechley et al., 2008). There are other similar kits such as Flora, LilyTiny or EduWear which, like LilyPad, emphasise the act of sewing the circuits and making them visible in order to give the user an understanding of programming, electronics, and circuits (Lovell et al., 2023; Schelhowe et al., 2013; Stern & Cooper, 2015). Other prefabricated kits such as i*CATch and Make Wear offer plug-and-play and are more user-friendly (Kazemitabaar et al., 2017; Ngai et al., 2013). Quilt Snaps and TeeBoard (Buechley et al., 2005; Ngai et al., 2009b) are mainly aimed at deepening the computational experience for learners. All these construction kits offer an interesting new range of tools and materials for both teachers and learners. As their educational value has been demonstrated, e-textiles have become an increasingly important competence practice, a potentially emerging field of educational research, the development of curriculum materials similar to those of educational robotics (Fields & Kafai, 2023; Hébert & Jenson, 2020) and the emergence of books with activities adapted to the American Next Generation Science Standards (NGSS), designed for teachers to bring e-textiles into the classroom (Peppler, Gresalfi et al., 2014; Peppler, Salen Tekinbas et al., 2014). Following the recent implementation of the STEAM model in the classroom and in order to improve student learning, the use of e-textiles has been gradually integrated into educational contexts through the creation of learning spaces (Peppler, 2022; Martinez & Stager, 2013). As Halverson and Sheridan point out, "the great promise of the maker movement in education is to democratise access to power discourses, so that users can produce their own artefacts, especially if these artefacts are built with 21st-century technologies" (2014, p. 502). For all these reasons, and considering the benefits that this educational resource represents in terms of scientific and technological training at an early age, it is necessary to do research into its use in education with students aged 6 to 13.

METHOD

In order to answer the research questions, a systematic literature review (SLR) of specific scientific literature (Newman & Gough, 2020) on e-textiles applied to education in the STEAM field was carried out. We used databases specific to social science research, focusing on education (Scopus, ERIC, WoS) and one specialised in computer science (ACM Digital Library), as it is of great interest as one of the reference sources for studies at the intersection of Computer Science and the Social Sciences and Humanities. The guidelines set by the PRISMA (Preferred Reporting Items for Systematic review and Meta-Analysis protocols) statement have been followed (Page et al., 2021).

Systematic literature review

The search strategy began with the selection of keywords in the three conceptual axes that make up the SLR carried out (Table 1).

Table 1
Databases, search equations, and results

Database	Search equations	Number of items found
Scopus	TITLE-ABS-KEY (("e-textiles" OR "electronic textiles" OR lilypad OR wearable*) AND (steam OR stem OR math OR science* OR technolog* OR engineering OR art*) AND ("middle school" OR "K-12" OR "primary education" OR "primary school" OR "elementary school" OR "elementary education" OR "compulsory education")))	139
WoS	TS=(("e-textiles" OR "electronic textiles" OR wearable* OR LilyPad) AND (STEAM OR STEM OR math* OR science* OR technolog* OR engineering OR art*) AND ("K-12" OR "elementary school" OR "elementary education" OR "middle school" OR "primary school" OR "primary education" OR "compulsory education")))	86
ERIC	("e-textiles" OR "electronic textiles" OR lilypad OR wearable*) AND (steam OR stem OR math* OR science* OR technolog* OR engineering OR art*) AND ("middle school" OR "K-12" OR "primary education" OR "primary school" OR "elementary school" OR "elementary education" OR "compulsory education")	36
ACM Digital Library	AND [[All: "e-textiles"] OR [All: "electronic textiles"] OR [All: wearabl*] OR [All: lilypad]]] AND [[All: steam] OR [All: stem] OR [All: math*] OR [All: science*] OR [All: technolog*] OR [All: engineering] OR [All: art*]]] AND [[All: "compulsory education"] OR [All: "middle school"] OR [All: "primary school"] OR [All: "elementary school"]]]	448

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We used reputable databases which host impact publications in order to ensure that the studies meet the standards of the scientific community, focusing on publications with full-text availability. We considered 2006 as the starting year for the systematic review due to the publication of the paper by Buechley et al. (2006) which refers to the potential of e-textiles in education. The languages of publication included were English and Spanish, two of the majority languages in the Academy.

The bibliographic records resulting from the searches of each database were exported to an Excel document. The list of articles was managed on this software, with a tab for the record of each of the databases and a tab with the global list of publications, where duplicates were manually eliminated, resulting in a total of 641 records. The selection process was based on a review of the titles and abstracts of the registered documents. According to the eligibility criteria (Table 2), research in English addressing the use of e-textiles for STEAM learning in our study range was included; articles published outside the established period (2006-2021) were excluded. The full text was then checked for accessibility. At this point 17 papers were excluded (Figure 1).

Table 2

SLR inclusion/exclusion criteria

INCLUSION CRITERIA: (a) Published between 2006-2021 (b) Full text available. (c) Papers published in Scopus, WoS, ERIC and ACM databases. (d) Journal paper, conference, or book chapter.	**EXCLUSION CRITERIA**: (a) Publications in which the term "e-textiles" or "wearable" is mentioned as command and control devices for user monitoring, not as learning media or contexts. (b) Used in vocational training or continuing professional development (e.g. teacher training). (c) Languages other than English or Spanish. (d) Research that does not include 6 to 13 year-olds. (e) Studies where the term "wearable" refers to hard devices. (f) Studies in the field of Computer Science (CS) - HCI - that do not focus on "e-textiles" or "wearables". (g) Studies on computeror maker educationthat do not focus on "e-textiles" or "wearables".

The papers selected on the basis of the eligibility criteria were screened in the second screening stage, which removed publications where e-textiles are used as command and control technologies (e.g. smart watches, brain readers etc.), research focused on professional development and those related to e-textiles that do not focus on e-textiles. Papers that did not address e-textiles in the learning of students in the stated age range were excluded. In this stage 453 papers were excluded, resulting in 30 publications that meet the previously defined inclusion/exclusion criteria. To these, 5 papers included in a book-compilation of references in the field of e-textiles (Buechley et al., 2013) were incorporated as grey literature, resulting in 35 papers selected for content analysis (Figure 1). The papers found were reviewed by two researchers: the first author reviewed all the results, while the rest of the authors independently reviewed one third of the papers each, subsequently pooling all the assessments of each member of the research team. For those documents that raised doubts among the researchers, the analysis process was repeated.

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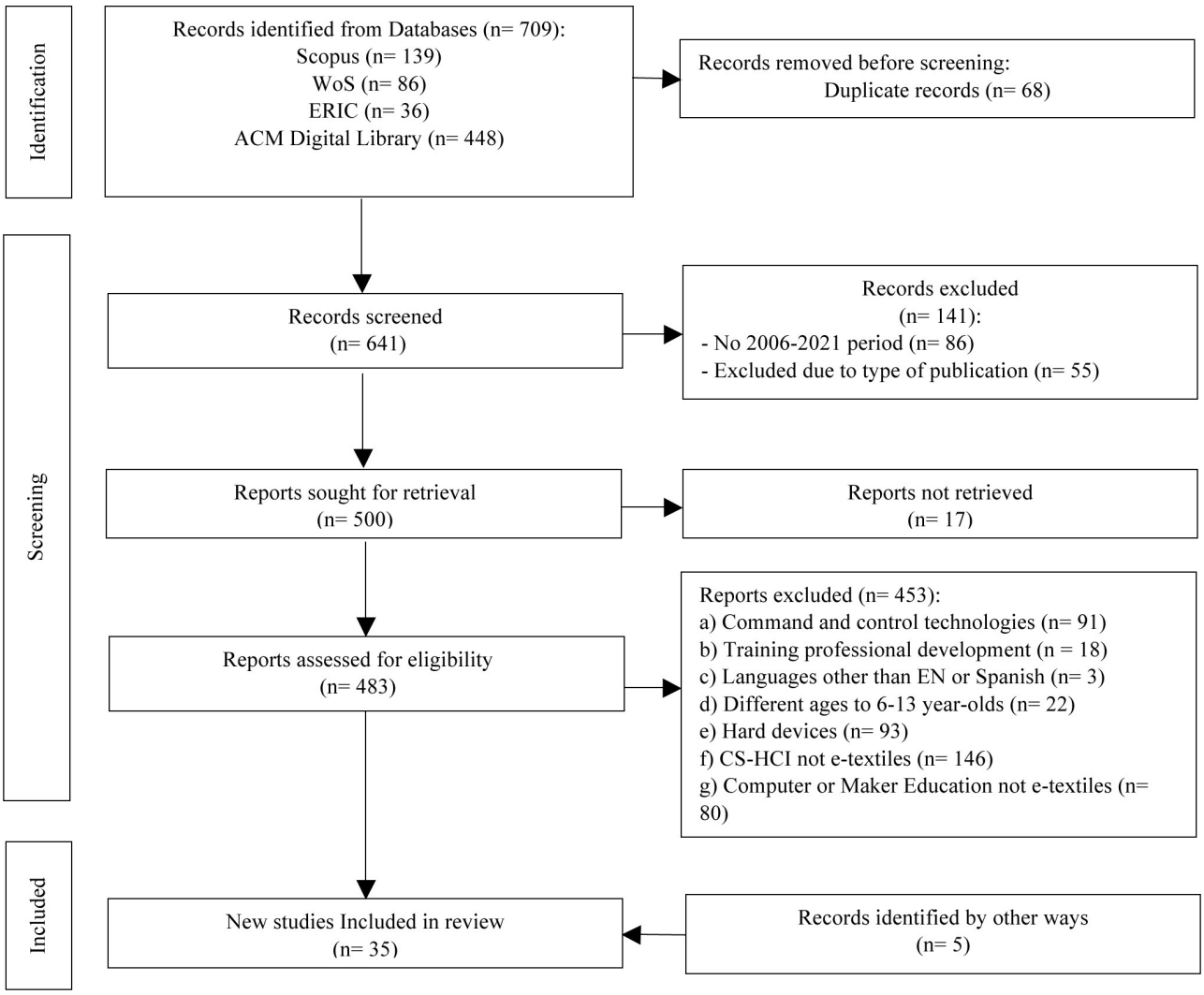


Figure 1
PRISMA 2020 Flowchart (Haddaway et al., 2022)

Data mining and content analysis

The selected documents were analysed according to the three axes of the study: digital technology (e-textiles as a resource), methodological approach, and educational context, using the critical content analysis method (Newman & Gough, 2020). Firstly, a bibliometric analysis of the scientific production included in the SLR was carried out. This analysis shows the list of authors, their geographical distribution, their year of publication, and the characteristics of research in the field of e-textiles for learning in primary education. In a second stage, the research questions generated a series of categories of analysis, including information on the hardware, software, methodology, project, educational context, and ages involved. Two individual researchers hand-coded all studies in accordance with the categories of analysis. In case of discrepancies between the researchers, coding was established through double analysis by the other researchers.

RESULTS

This section presents the results obtained from the in-depth analysis of the 35 documents included in the SLR, organised in terms of the research questions proposed.

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Bibliometric analysis

The 35 scientific texts that constitute the sample of studies in the systematic review show that the year 2013 was the time when literature on e-textiles in the field of education first emerged (Figure 2a). The first paper dates from 2009, but it is from 2013 onwards that there is evidence of more regular annual publication on this topic. The data show that the United States is the country with the highest production (Figure 2b), with Kafai, Searle and Ngai being the authors with the highest production (Figure 2c). In terms of authorship, women dominate (55.1%): in 29 of the 35 papers, the main author is a woman, which shows that the subject is an area of growth in which the studies are made up of teams led by women.

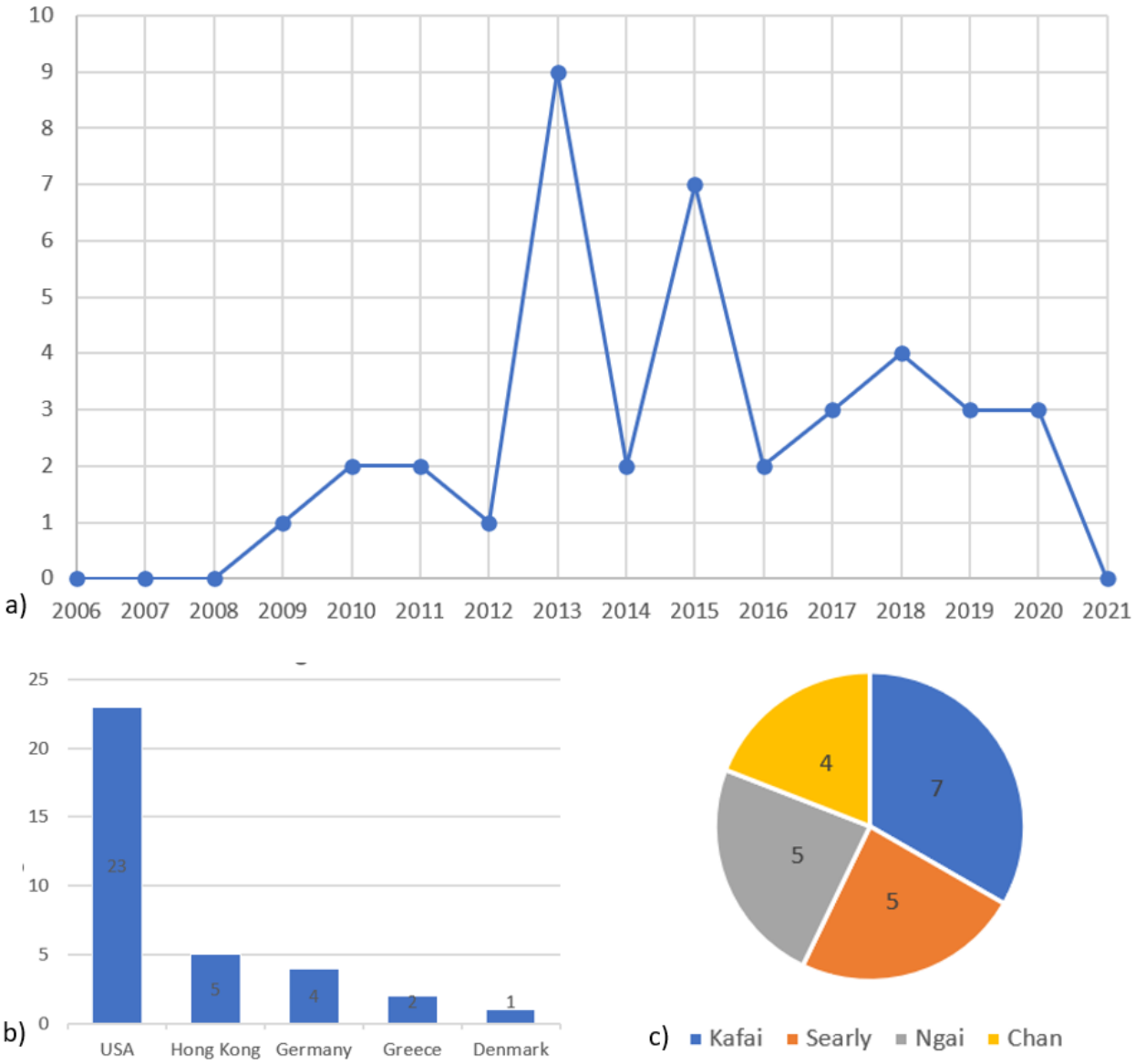


Figure 2

a) Years of publication. b) Countries of reference of the educational projects with e-textiles. c) Main authors

In terms of methodological design, research on e-textiles in education is mainly approached through qualitative designs (61.8%), predominantly through case studies (Figure 3). It is worth noting the high number of experiences shared at conferences.

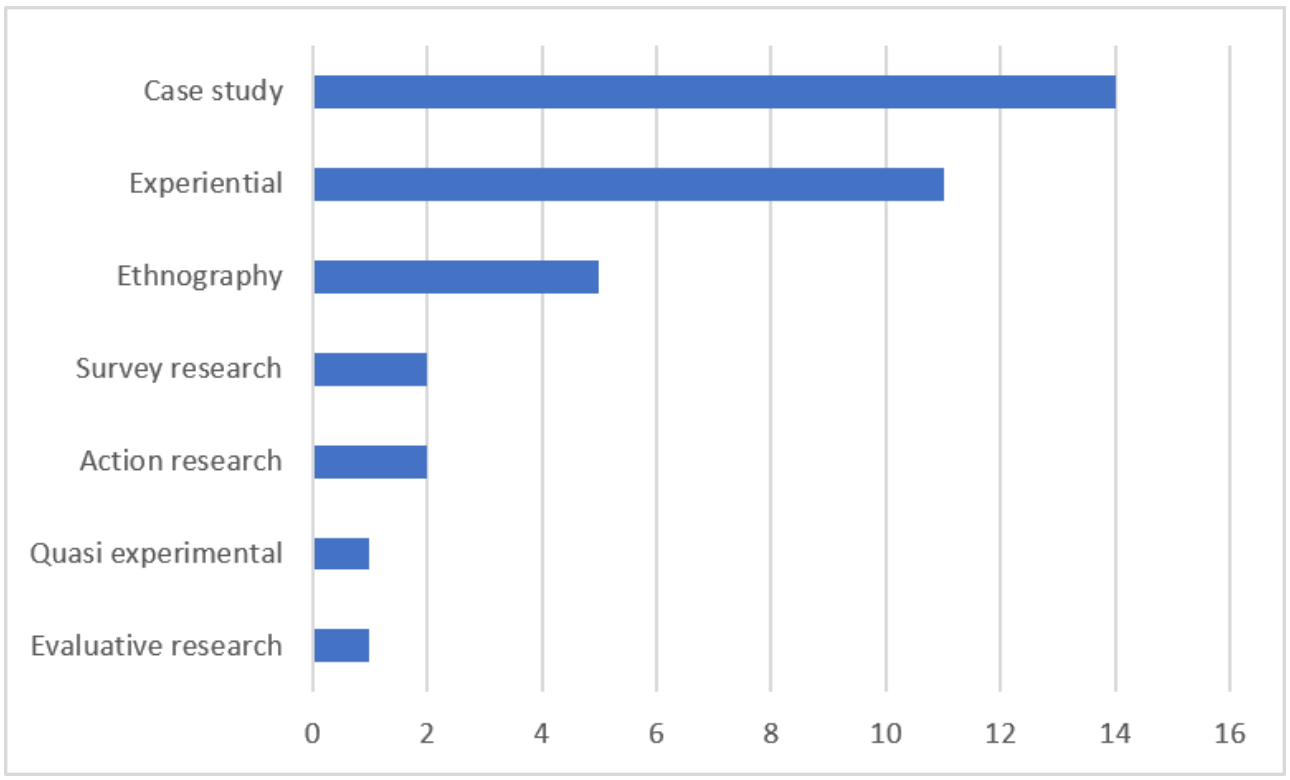


Figure 3
Methodological design of research production research on e-textiles for learning

STEAM areas and technologies for working with e-textiles in primary education

The SLR shows that 75% of the projects discussed in the publications reviewed were created with an e-textile kit using a programmable board (Table 3). Of these, the LilyPad kit is the preferred kit for experiences in this field (77.8%). Drawing on the cross-referenced data derived from the meta-synthesis, such a kit is presented as an alternative to teaching educational robotics and breaks down gender or ethnic stereotypes around tools and the design of digital artefacts (Jayathirtha & Kafai, 2020). A number of the studies reviewed conclude that it helps to close the gender gap (Buechley 2010; Buechley et al., 2013; Erete et al., 2016; Keshwani et al., 2016; Lau et al., 2009; Nugent et al., 2019; Rigden et al., 2019; Kafai et al., 2014; Searle & Kafai, 2015b; Weibert et al., 2014) and to increase minority representation (Richard et al., 2018; Searle & Kafai, 2015a) in science and technology fields. The studies show that work with e-textiles in primary education favours block programming language, which is present in two thirds of the publications reviewed, especially in the last levels of primary education, mostly involving pupils aged 11 to 13 (Table 3). This result coincides with the majority of the studies reviewed in the meta-synthesis (87%) involving students aged 11 to 18.

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Table 3
Ratio of technology used, e-resources and age group

Authors and year of publication	Board	Software	Language	Materials and componentselectronics	Ages
Ananthanarayan and Boll (2020)	Calliope	calliope.cc	blocks	Actuators and battery	8-9
Ball et al. (2017)	LilyPad	Arduino	blocks	Copper tape, conductive thread, battery, sensors, and actuators	11-18
Buechley (2010)	LilyPad	Arduino	blocks	Conductive thread, battery, sensors, and actuators	11-18
Buechley (2013)	LilyPad	Arduino	blocks	Conductive thread, battery, sensors, and actuators	10-19
Del Valle-Morales et al. (2020)	-	-	-	Conductive fabric and thread, conductive play dough, battery, actuators	10-13
Erete et al. (2016)	-	-	-	Paper prototypes (circuit design)	11-13
Guler and Rule (2013)	-	-	-	Conductor thread, actuators, battery, thermochromic textile, glow-in-the-dark tape	10-13
Kafai et al. (2011)	LilyPad	Arduino	blocks	Fabric and conductive thread, battery, sensors, and actuators	12 & 14
Kafai et al. (2014)	LilyPad	Modkit	blocks	Conductor thread, battery, sensors, and actuators	12-15
Kafai and Vasudevan (2015)	Makey Makey	Scratch	blocks	Conductive fabric and crocodile clips	11-14

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Keshwani et al. (2016)	LilyPad	Arduino	blocks	Conductive thread, battery, sensors, and actuators	9-12
Koushik et al. (2017)	LilyPad	Arduino	code	Conductive thread, battery, sensors, and actuators	11-13
Kuznetsov et al. (2011)	LilyPad	Arduino	code	Conductive thread, battery, sensors, and actuators	10-12
Lau et al., (2009)	LilyPad (Teaboard)	Bricklayer	blocks	Conductive fabric, battery, sensors, and actuators	11-16
Lo et al. (2013)	-	i*Chameleon	blocks	Actuators	10
Markvicka et al. (2018)	Arduino Leonardo	Arduino	code	Conductive tape and fabric	12-15
Merkouris et al. (2017)	LilyPad	Modkit	blocks	Conductive thread and battery	11-12
Ngai et al. (2009a)	LilyPad (Teeboard)	Bricklayer	blocks	Conductive fabric, battery, sensors, and actuators	10-16
Ngai, Chan, Leong et al. (2013)	Arduino (i*CATch)	i*CATch	blocks and code	Battery, sensors, and actuators	11-16
Ngai, Chan and Ng (2013)	Arduino (i*CATch)	i*CATch	blocks and code	Battery, sensors, and actuators	6-16
Norooz et al. (2015)	LilyPad (Body Vis)	-	-	Interactive T-shirt	4-11
Nugent et al. (2019)	LilyPad/ LilyTiny	Arduino	code	Conductor thread, battery, sensors, and actuators	9-12
Palaigeorgiou et al. (2019)	-	Arduino		El-wires	11-12

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Pedersen et al. (2020)	CPX	Make Code	blocks	Conductive thread, battery, sensors, and actuators	10-12
Peppler and Glosson (2013)	LilyPad	Arduino	code	Conductive thread, battery, and actuators	7-12
Peppler and Danish (2013)	LilyPad (BeeSim)	-	-	Interactive pet	6-8
Richard et al. (2018)	LilyPad and Makey Makey	Modkit and Scratch	blocks	Conductive thread, battery, sensors, and actuators	10-13
Rigden et al. (2019)	Flora	Arduino	code	Conductive thread, battery, sensors, and actuators	11-17
Rode et al. (2015)	LilyPad	Ardublock	blocks	Conductive thread, battery, sensors, and actuators	8-10
Searle and Kafai (2015a)	LilyPad	Arduino and Modkit	blocks and code	Conductive thread and fabric, battery, sensors, and actuators	12-14
Searle and Kafai (2015b)	LilyPad	Arduino and Modkit	blocks and code	Conductive thread, battery, sensors, and actuators	12-14
Schelhowe et al. (2013)	LilyPad (Eduwear)	Amici	blocks	Conductive thread, battery, sensors, and actuators	9-15
Trappe (2012)	Arduino	GUI-prototype	blocks	Battery, actuators, and sensors	9-10
Vasudevan et al. (2015)	Makey Makey	Scratch	blocks	Conductive fabric and crocodile clips	11-13
Weibert et al. (2014)	LilyPad	Arduino	blocks	Conductive fabric and thread, battery, actuators, and sensors	8-12

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Several studies discuss the potential of other platforms, both commercial and non-commercial, for the creation of e-textiles. Guler and Rule (2013) explore the potential of the Invent-abling kit to build analogue circuits to address gender inequality in STEM learning tools. Ananthanarayan and Boll (2020) conclude that the use of Calliope enables the creation of learning situations that foster the creative process as well as initiation into programming environments. In addition, different authors explore the educational use of plug-and-play kits that do not require sewing. These kits are designed for rapid prototyping of e-textiles and encourage iterative and exploratory learning. Koushik et al. (2017) explore the educational potential of the Snappable Sensors kit that allows for an approach to arithmetic and data analysis. Ngai et al. (2009a) design the i*CATch kit with the aim of enabling students to explore computational concepts in less time and concludes that this kit can be used at a wide range of academic levels. Schelhowe et al. (2013) present the EduWear e-textile construction kit, which proved to enable students to become more confident in dealing with technology as they were able to connect their own creations to the technologies in their environment.

The use of kits that allow the incorporation of flexible and conductive materials with the aim of designing video games and wearable controllers is also highlighted. Kafai and Vasudevan (2015) and Vasudevan et al. (2015) investigate the use of the Makey Makey kit, concluding that it offers new opportunities for learning about computational concepts and develops creative and self-expression skills. Markvicka et al. (2018) examine a low-cost kit created from commercial materials and conclude that it allows students to get started in the field of e-textiles, while offering the opportunity to use their artistic creativity within a technical context. Along these lines, we would also like to highlight the research by Lo et al. (2013), who examine the use of the educational software I*Chameleon as a multimodal interface to create e-textile projects, something that is especially interesting for the age range contemplated in this SLR. E-textiles are also used to create new learning resources - educational resources with which students can interact to promote understanding of complex concepts (Norooz et al., 2015; Peppler & Danish, 2013).

To conclude this section, we consider it necessary to look at the challenges of the 21st century, which are connected to the challenges that students in our age range will face. The studies analysed show that working with e-textiles using block programming language, applying principles of engineering, circuits, and design, enhances the skills aspects of learning. STEAM subjects facilitate commitment between situations of equity, critical and responsible use of digital culture, and the appreciation of cultural diversity through the creative processes inherent in e-textiles.

Methodological approaches to integrating e-textiles in primary education

The studies reviewed show three approaches to the educational methodology used in the teaching and learning process with e-textiles (Table 4). Firstly, there are publications describing innovative experiences that awaken students' interests in scientific and technological subjects or workshops focused on following the step-by-step instructions or guides typical of *Do it Yourself* learning, where the result is projects that are all the same or similar because they are customised by the members of these courses (44%). This is the majority trend.

In some cases, worksheet templates are encouraged (Searle & Kafai, 2015a, 2015b) to motivate and initiate students and get them interested in carrying out personally relevant projects. Then there are options that use active methodologies (36%). Finally, there are works at an intermediate point of the continuum, which use a mixed methodology. In these, there is a first stage of an activity, with step-by-step instructions, prototypes, models, tutorials, and templates that guide the process. In some cases, even prefabricated modules are provided (Ngai et al, 2009a; Ngai, Chan, Leong et al., 2013; Ngai, Chan & Ng, 2013). Then, in a second training stage, they offer spaces for the free creation and customisation of artefacts.

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Table 4
Methodological approaches to projects involving e-textiles

Educational methodology		Publications
Guided learning	Instructions. Exercises	Ball et al. (2017); Nugent et al. (2019); Richard et al. (2018); Rode et al. (2015); Weibert et al. (2014)
	Step-by-step guide	Del Valle-Morales et al. (2020); Erete et al. (2016); Markvicka et al. (2018); Pedersen et al. (2020); Peppler and Glosson (2013); Searle and Kafai (2015a); Searle and Kafai (2015b)
Mixed	Instructions and own creation	Guler and Rule (2013); Kuznetsov et al. (2011); Lau et al. (2009); Ngai et al. (2009a); Ngai et al. (2009b); Ngai, Chan, Leong et al. (2013); Ngai, Chan and Ng (2013)
Active methodologies	Design-Based Learning	Buechley et al. (2013); Buechley (2010); Schelhowe et al. (2013); Kafai et al. (2011); Kafai et al. (2014); Kafai and Vasudevann (2015); Vasudevan et al. (2015)
	Discovery learning	Ananthanarayan and Boll (2020); Lo et al. (2013); Trappe (2012)

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Looking at the artefacts built by the students in terms of the methodological approach, most of the creations based on guided projects focused on luminous bracelets (Ball et al., 2017; Del Valle-Morales et al., 2020; Erete et al., 2016; Nugent et al., 2019; Peppler & Glosson, 2013) and interactive soft toys (Kuznetsov et al., 2011; Pedersen et al., 2020; Rode et al., 2015; Weibert et al., 2014). By contrast, projects based on active methodologies were more diverse, including mainly textile video game controllers (Kafai & Vasudevan, 2015; Lo et al., 2013; Vasudevan et al., 2015) and multiple designs of sensor, musical, and light wearables (Ananthanarayan & Boll, 2020; Buechley, 2013; Kafai et al., 2014; Schelhowe et al., 2013; Trappe, 2012).

Educational context in which e-textiles learning is approached in primary education

The results show a variety of educational ecosystems (Table 5), with non-formal education being the most recurrent in the projects analysed (71.4%). We found a large number of non-formal education studies that, despite being intentional and planned, were carried out outside the scope of compulsory schooling. After-school activities and computer clubs (44%) as well as workshops (40%) were the main contexts for non-formal educational spaces that address e-textiles with students aged 6 to 13.

If we analyse the selected papers that refer to a formal setting, there are different perspectives for their inclusion in schools. Some propose adapting e-textiles to US educational standards (Ball et al., 2017), as they support meaningful learning and facilitate the understanding of complex and abstract science concepts. Others are committed to including them within optional subjects or history and culture subjects, in a transdisciplinary way, to encourage the inclusion and participation of minorities who are less engaged with computer science. This interdisciplinary approach helps to foster a more holistic view of the world around them (Kafai et al., 2014; Nugent et al., 2019; Rigden et al., 2019; Searle & Kafai, 2015a, 2015b). Along these lines, Rigden et al. (2019) with the Femineer ™ program, and Nugent et al. (2019) with the Nebraska WearTec program, propose e-textiles as teaching resources that serve as an alternative or supplement to educational robotics with the goal of inspiring and empowering learners, and in particular girls and minorities, to pursue STEM careers.

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Table 5
Learning context of e-textile practices

Education	Context	Research
Non-formal	After-school classes/ Computer Club	Ananthanarayan and Boll (2020); Erete et al. (2016); Merkouris et al. (2017); Palaigeorgiou et al. (2019); Richard et al. (2018); Trappe (2012); Pedersen et al. (2020); Rode et al. (2015); Peppler and Glosson (2013); Weibert et al. (2014)
	Workshop	Buechley (2010); Buechley (2013); Kafai et al. (2011); Kafai et al. (2014); Koushik et al. (2017); Kuznetsov et al. (2011); Markvicka et al. (2018); Ngai, Chan, Leong et al. (2013); Ngai, Chan and Ng (2013); Norooz et al. (2015); Schelhowe et al. (2013)
	Museum/Art Gallery	Guler and Rule (2013)
	Makerspace Summer camp/ Course	Del Valle-Morales et al. (2020)Lau et al. (2009); Ngai et al. (2009a)
Formal	Classroom	Ball et al. (2017); Kafai and Vasudevan (2015); Peppler and Danish (2013); Rigden et al. (2019); Searle and Kafai (2015a); Searle and Kafai (2015b); Vasudevan et al. (2015)
Formal and Non-formal	Classroom/Workshop Classroom / After-school	Kafai et al. (2014) Nugent et al. (2019)

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DISCUSSION AND CONCLUSIONS

This document provides specific information on the work carried out with students aged 6 to 13 years that uses e-textiles as an action element in activities that seek to cultivate STEAM knowledge, skills, and abilities. The study shows that practices with e-textiles for primary education have been most prevalent in the United States (63.9%), where the maker movement and the concept of STEAM education emerged. The results show that e-textile practices have been integrated into the educational environment, in formal contexts, but particularly in non-formal contexts. As Halverson and Sheridan (2014) point out, this has great potential and opens up new opportunities for educational research. Publications on the subject warn that the diversity of learners, especially in terms of gender and ethnicity, should be taken into account, and accessible alternatives have been incorporated, both in economic and ethical terms, favouring open source technology.

To answer the first research question (Which STEAM areas are worked on through e-textiles and with which technologies?), the results of the review show that they have been used effectively across all STEAM areas, as the creation of these projects involves all disciplines of computer science, engineering, and the arts. In most studies, students explore the three interconnected fields of coding, production, and circuitry. As in educational robotics, this is beneficial for the development of computational thinking (Rich et al., 2022). In any case, e-textiles provide particularly compelling examples of transparent and high-quality learning tools, as they make technology visible to learners (Kafai & Peppler, 2014). The analysis of the selected publications shows that all STEAM areas are worked on, with the LilyPad kit being the preferred tool for experiences in this field (77.8%). In this regard, the importance of this kit has also been demonstrated in the field of fine arts, where there are also promising studies that show that it is a tool that allows artists and designers to explore new forms of artistic expression through the fusion of art and technology (Peppler et al., 2013).

With regard to the second research question, which focuses on the methodological approaches used to integrate e-textiles in primary education, studies using guided learning predominate. The aim of the studies analysed focuses mainly on students designing and building, through instruction and/or discovery, a textile project in which they include a circuit, sometimes programming it, and making it work. One of the most challenging aspects of teaching computation is the interaction of the multiplicity of elements that interconnect to make a system work. This points to the need to implement the design of new strategies and to promote the ongoing training of teachers, both pedagogically and technologically in its instrumental and methodological dimension, from skills-based approaches that allow the integration of e-textiles in primary education classrooms through the promotion of student participation and learning by doing (Valente & Blikstein, 2019). In this regard, it should be noted that the predominant learning situation, while relying on the use of guides, allows for the use of unusual and unfamiliar materials and resources, such as wires, encouraging tinkering (Timotheou & Ioannou, 2019). All this ensures that the innovative activity takes place in a motivating and playful environment where collaboration, trial-and-error learning, creativity, and artistic expression are encouraged. In the words of Resnick and Rosenbaum (2013), the mere fact of the transparency offered by e-textiles and working with this type of material allows students to "see the process" and "see the result" of their work, receiving "immediate feedback" on what they are doing, which facilitates meaningful learning.

To answer the third research question (In which contexts does e-textile take place?), the results show that non-formal learning environments predominate. These results can be justified by arguing that the learning process that takes place when making an e-textile focuses on the process of creating, designing, and building physical electronic or programmable objects, and this goes beyond the learning process offered by the most widespread model of teaching (Halverson & Sheridan, 2014). However, studies that do address the formal context show encouraging results for the use of e-textiles as a teaching resource with the aim of fostering integrated competence education, the development of skills in curricular areas, and the promotion of inclusive and equitable STEAM education.

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In short, the results of the systematic review show that the field of e-textiles is a promising area for STEAM-integrated teaching and offers new directions in teaching with educational technology from a competence and integrative approach. Faced with the need for scientific training at early ages, we consider this domain as a promising line of research, but we find limitations arising from the small number of countries that have implemented these educational approaches and research. Another aspect to highlight is that although the trend in the field of research and experimentation with e-textiles emphasises the potential of these resources to work on STEAM within the formal setting, there is limited scientific literature, to date, in this respect. It should also be pointed out that the field of e-textiles became open to education only relatively recently. Finally, we conclude the investigation by considering that the scientific community would benefit from studies focusing on issues related to the gender perspective and equity with e-textiles within this age range.

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APPENDIX

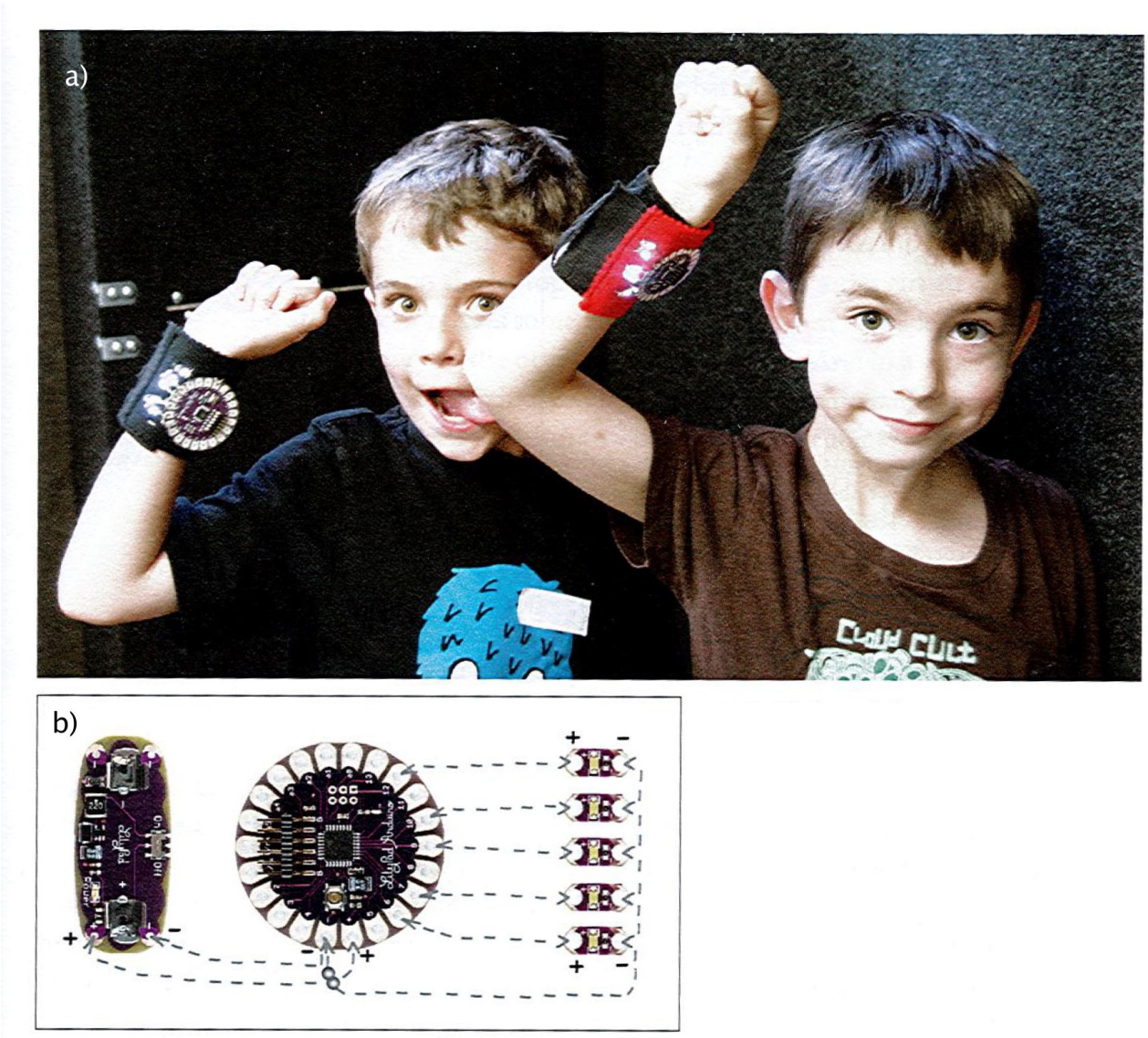


Figure 1

a) Light-up bracelets created with the LilyPad kit. b) Connection diagram that shows the different components of the circuit and indicates how to connect them with the conductive thread

This image shows two students showing off their glow bracelet with the Persistence of Vision (POV) effect created with the LilyPad kit. By carrying out this project they learned basic concepts of circuit theory such as polarity, voltage, and the difference between connecting a circuit in parallel and in series.

Note: Taken from the book *Textile Messages: Dispatches From the World of E-Textiles and Education.* (p.77), by Buechley et al., 2013. Peter Lang Publishing.

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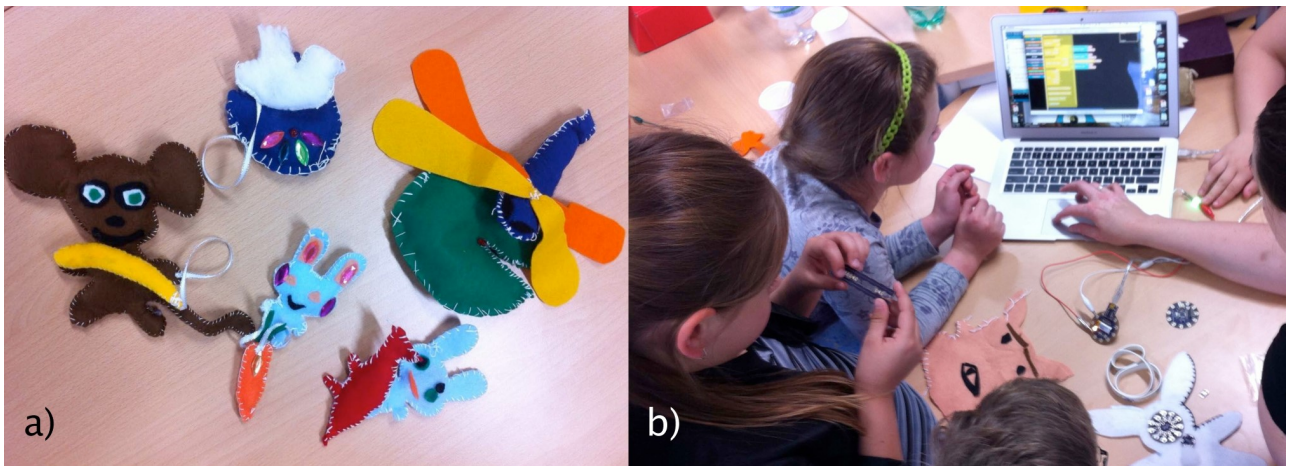


Figure 2

a) Examples of e-textiles projects b) Students collaborating and programming their e-textiles projects

The image on the left shows several e-textile projects, all of them created with the Bright Bunny kit, and on the right, several students collaborating and programming their projects in blocks.

Note: Taken from the article *From computational thinking to computational making*. (p.242 and p.243), Rode et al., 2015.



Figure 3

Interactive t-shirt created using the LilyPad kit

This image shows a t-shirt that enables the teacher to help the student visualise and understand body data that helps them learn about the human body.

Note: Taken from the article *BodyVis: A new approach to body learning through wearable sensing and visualization*. (p. 6), by Norooz et al., 2015.



Figure 4
Interactive t-shirt created with the low-cost pre-made i*CATch kit

This image shows an e-textiles project created with a kit that offers a plug-and-play system designed to introduce students to computational concepts in a friendly way.

Note: Taken from the article *Designing i* CATch: A multipurpose, education-friendly construction kit for physical and wearable computing.* (p.10), by Ngai et al., 2013.

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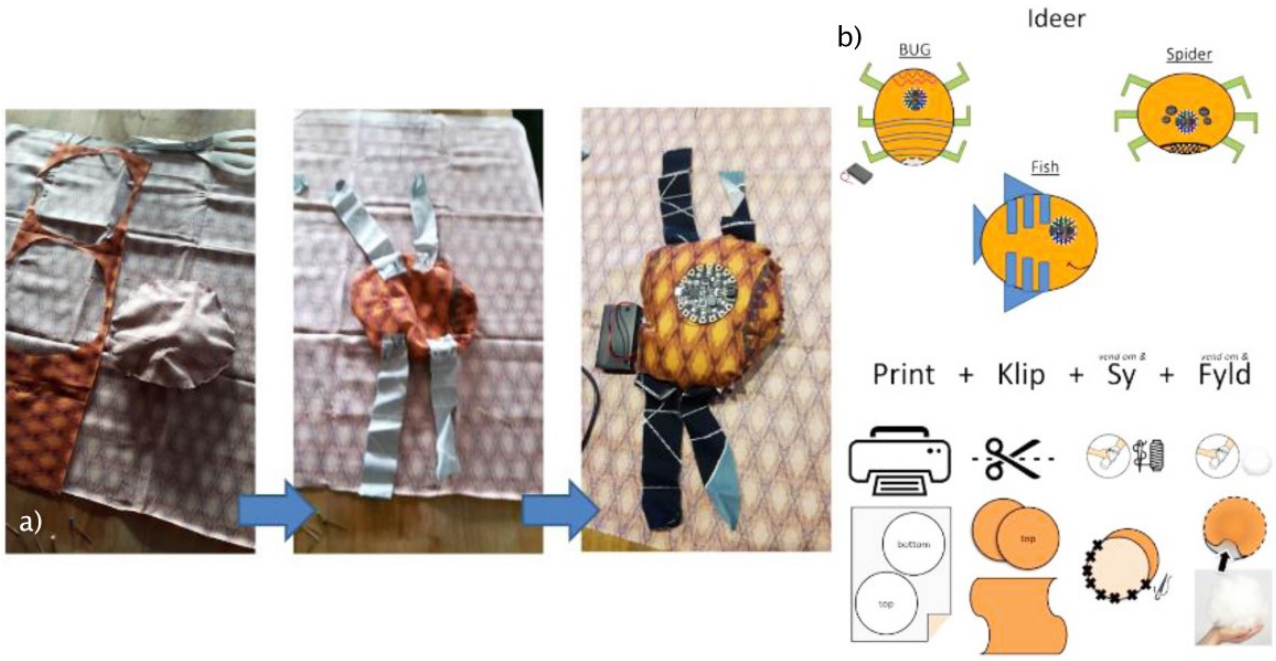


Figure 5

a) Step-by-step documentation for creating an interactive textile pet b) DIY tutorial and examples of project customisation

This image shows step-by-step images and the guide used by boys and girls to learn how to build and customize their e-textiles project

Note: Taken from the article F*abric robotics-lessons learned introducing soft robotics in a computational thinking course for children*. (p.9), by Pedersen et al., 2020.

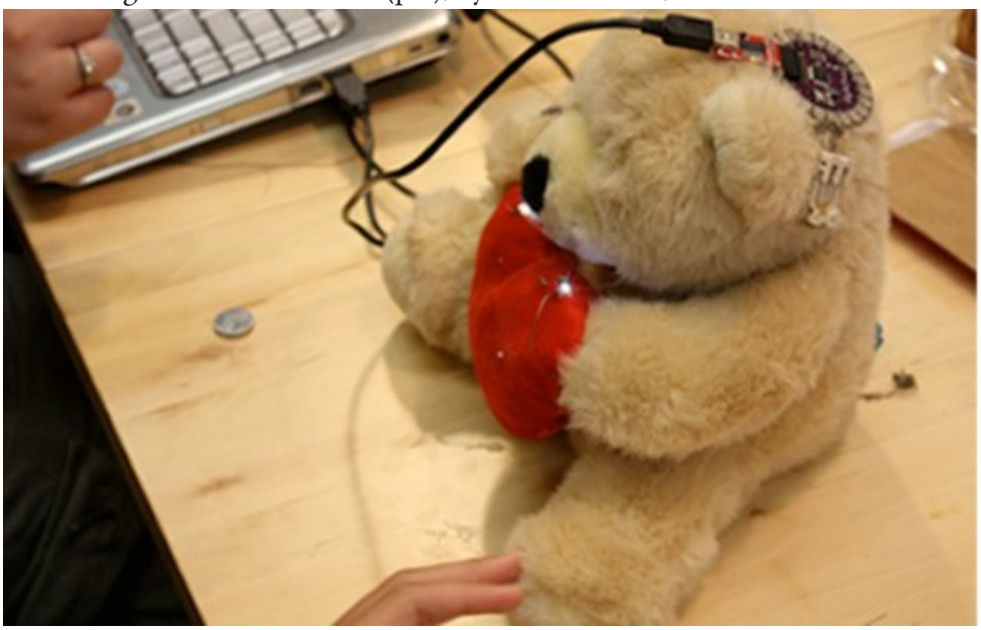


Figure 6

Light-up Teddy Bear created with the LilyPad kit

This image shows a light-up teddy bear in which the student has sewn a circuit using conductors and programmed several LEDs with the goal of creating a personally meaningful project.

Note: Taken from the article *Breaking boundaries: strategies for mentoring through textile computing workshops*. (p.2962), by Kuznetsov et al., 2011.

Notes

1 To incorporate all the research carried out in the English-speaking world, we included students between the ages of 6 and 13 (Primary and Middle School).

Información adicional

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