Teaching and Learning with Design Thinking and Emerging Digital Technologies in K-12: Impact on Students and Teaching Recommendations

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Abstract. This paper presents insights from five case studies with 173 students aged 11–14 years old across three countries in Europe, exploring the integration of design thinking (DT) and emerging digital technologies in K-12 education. The study aimed to understand the impact of DT and digital technologies on the development of students' 21st-century skills and capture the challenges students and teachers face. The focus is to give evidence-based recommendations for teaching using the DT approach. Despite the positive student reports on developing communication, collaboration and programming skills, other skills related to research and reflection, and understanding of DT were rather less developed. The main challenges teachers faced were related to time constraints, difficulties in using the technologies, lack of clear instructions, and limited understanding of the DT process. Seven practical recommendations on how to effectively teach and learn DT with digital technologies are presented. These are accompanied by the Exten.(D.T.)^2 Digital Design Thinking Model, an innovative framework designed to guide the use of DT with specific digital technologies across K-12 education.

Keywords: Design thinking · digital technologies · 21st century skills · K-12

1 Introduction

Design thinking (DT) integrates creativity and problem-solving within the curriculum to foster students' development of 21st century skills such as critical thinking, collaboration, empathy, and argumentation. Due to a focus on the iterative prototyping of solutions,

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DT has been perceived as a means for developing a resilient or "fail early and often" mindset (Marks & Chase 2019). While DT has been recognised for its great education potential and has been increasingly used in K-12, there is still limited empirical evidence supporting its effectiveness when used in the classroom (Li & Zhan 2022). Emerging evidence points to the development of collaboration, communication, metacognition and critical thinking. Critical thinking was associated with empathy and reflection emerged from defining a problem (Rusmann & Ejsing-Duun 2022).

DT faces challenges when used in the classroom related to its effective integration into existing curricula, the need to develop teachers' skills and attitudes towards DT processes, and helping students become creative and more collaborative (Andersen & Pitkänen 2019). A range of digital technologies have been used in DT, yet challenges remain and relate to teachers' management of multiple digital and non-digital technologies, balancing different modes of teaching and navigating a complex design thinking process (Hjorth et al. 2016).

In this paper, we report on findings from five pilot case studies across three countries that used DT with digital technologies in K-12 education (11–14 years old). We address the following Research Questions (RQs): **RQ1:** What is the impact of teaching using DT and digital technologies on the development of students' 21st century skills? **RQ2:** What challenges have teachers and students reported during teaching using DT and digital technologies? **RQ3:** What evidence-based recommendations for the effective implementation of DT activities emerge from RQ1 and RQ2?

This study is part of the Horizon Europe and Innovate UK funded project: Extending Design Thinking with Emerging Digital Technologies – Exten. (D.T.) [2] (https://extendt2.eu) that aims to bring methodological innovation in K-12 education by applying, testing and scaling up a DT implementation and a suite of emerging digital technologies (Milrad et al. 2023). It builds on the premise that emerging digital technologies enable effective application of DT in the classroom and bring added value to existing practices. In the next section, we present literature on DT and learning.

2 Background Literature

DT has been applied in K-12 education in solving engineering problems (Mentzer et al. 2015), engage students in programming tasks (Avcu & Er, 2020) and teach students physics concepts (Simeon et al. 2022). DT can play a crucial role in K-12 education, for example, a recent study (Lin et al. 2024) employed DT to teach IT courses to junior middle school students and found that DT helped enhance students' creativity in their digital works and improved their awareness of using IT tools to solve everyday challenges. Another study (Cutumisu et al. 2020) taught middle school students DT strategies such as critical feedback-seeking and revising.

Despite promising learning outcomes, DT can be challenging due to students needing assistance with using tools such as 3D modelling (Weibert et al. 2014), lacking active interaction with digital and physical materials limiting their ideas, needing guidance about how to analyse and externalise ideas and justify decisions, taking things for granted (Weibert et al. 2014). Similar challenges were reported by teachers, including skills on how to use digital technologies and teach DT (Smith et al. 2016), how to think more creatively and innovatively (Razali et al. 2022), how to map assessment activities to learning objectives, especially given the non-linear nature of DT in which assessment frequently takes on informal forms (Veldhuis et al. 2022), and how to accommodate the extended time needed to implement a DT project (Andersen & Pitkänen 2019).

Various tools have been designed for DT such as tools for authoring DT-based learning activities (Bekker et al. 2019) and scaffolding DT processes (Gennari et al. 2022). However, technology has not been used to cover all stages of DT; there is a lack of dedicated tools to support stages such as empathy and capture students' learning progress in real time supporting distributed or online collaboration. The potential of emerging technologies to support DT in K-12 classroom has neither been sufficiently leveraged nor robustly evaluated. In the coming sections, we present our approach to addressing some of these gaps.

3 The Exten. (D.T.)^2 Tools Used in DT

We used a set of free digital technologies to support DT implementation at schools. These tools have been developed and are managed by project partners, thus enabling us to modify and use them as and when required. They were seen to support different stages of DT: the "empathise" stage of DT is enabled by **nQuire for students** while rapid prototyping and iteration are enabled by online games: **ChoiCo, SorBET, MaLT2** and **GearsBot.**

ChoiCo (https://extendt2.com/widgets/choico/) enables students to play, modify or create choice-driven simulation games online. The player makes choices with conflicting consequences in a map-based setting. The winner is the player who survives the longest. The game can help students develop decision-making, empathy, argumentation, and systems thinking. It can be used to explore contemporary socio-scientific issues such as climate change, balanced diet. An example of a game activity is the "Covid-19 risks" asking students to make choices of daily activities that will not lead them to catching Covid-19 (Grizioti et al. 2021).

SorBET (https://extendt2.com/widgets/sorbetExt/) enables students to design, modify, and play Tetris-like classification games. Players using the mouse, or their body movements must quickly classify falling objects into the categories they belong to. SorBET allows design and modification of game elements such as density, speed, rules, object and category definitions, with block-based programming and database affordances. It can help students to develop 21st century skills such as classification skills, critical thinking, and computational thinking.

MaLT2 (https://extendt2.com/widgets/malt/) allows students to create, animate and print 3D figural models with text-based programming and dynamic manipulation. The models can vary from simple cubes to complex DNA models, jewels and fractal trees. Ideas and concepts from mathematics, engineering, art and computer science are seamlessly combined in a creative and collaborative process of experimentation, tinkering and self-expression. An example activity is the creation and then printing of 3D jewels by students as a means to understand the importance of the degradation of material.

GearsBot (https://extendt2.com/widgets/gears/) is an open-source 3D robotics simulator with two programming and one simulation tabs. One of the programming tabs has a simple form of programming, namely block-coding that users can drag-and-drop blocks. The other tab requires that the users write their code in Python. An example activity is that students use a virtual "world" about "fire rescue" and try to improve how the robot is constructed and controlled to complete a rescue mission.

nQuire for students (https://learn.nquire.org.uk) is an online platform that enables students to design, pilot and manage research studies. Data can be collected from other students and teachers who are registered with the platform. A classroom management system allows teachers to create classes and student accounts and navigate within and between different schools. nQuire for students allows students to collect data in the form of text, numbers, images, and sensors such as light and sound data.

4 Methodology

Methods of Data Collection: In this paper, we report on five case studies in Country 1 (x2), Country 2 (x2), and Country 3 (x1). Each case study describes a school intervention occurring in the classroom, as part of the school day or after-school activities with students aged 11–14 years old. Within each case study, two groups of consented students were chosen to act as "focal groups". Ethical approvals were gained for all five case studies. Pre-intervention and post-intervention questionnaires (RQ1) were used as the primary medium to capture self-reported impact on learning and 21st century skills. Data were also collected through observations (video, screen recordings, audio and/or semi-structured written), small group interviews, and teacher interviews (RQ2 and RQ3). Interview data were transcribed and translated to English where applicable.

Methods of Data Analysis: The phases of analysis were as follows: a) constant comparative analysis to identify issues most pertinent to participants (interviews and observational data. b) Critical incidents were then used to identify events that were significant in the action and to explore them in depth (observations and interviews). c) Survey data were analysed using descriptive statistics to provide additional evidence and content to (a) and (b).

Contextual Information Per Case Study: Case study 1: Country 1 Case study 1 was conducted in an international private school with 58 students aged 11–14, most of whom had prior knowledge of programming with Scratch. The study was carried out in three classes. In each class, one researcher acted as the facilitator, while one teacher supported all actions as needed. The DT topic was: "How to improve cybersecurity and online awareness through a choice-and-consequence-based game", and technologies used: nQuire for students and ChoiCo. The DT sessions lasted 6 h (2 days x 3 h). Data were collected from 14 student interviews, 58 pre-intervention questionnaires, 56 post-intervention questionnaires and 3 teacher interviews. Case study 2: Country 1 Case study 2 was conducted in a public school with 15 students 15–16 years old, who had previous knowledge of block-based and Python programming. The study was carried out in a single classroom with one teacher overseeing and two researchers facilitating the sessions. Two one-hour-long sessions spanned 3 weeks (for a total of 2 h). The topic of the DT project was: "How to improve fire safety awareness through an educational virtual robot?" and the technology used was GearsBot. Data were collected from 4 student interviews, 15 pre-intervention questionnaires, 8 post-intervention questionnaires and 1 teacher interview.

Case study 3: Country 2 The study was conducted in a public junior high school. Thirty (N = 30) students from the after-school club Mathematics and Programming, aged 14–15 participated in the study for 8 h (4 sessions x 2 h per week. A teacher and a researcher jointly facilitated these sessions. The topic of the DT project was to design a 3D digital model of a vertical garden watering system. Technologies used were MalT2 and nQuire for students. Data were collected from 23 pre-intervention questionnaires, 26 post-intervention questions, 2 student interviews, 8 audio-visual recordings, and 1 teacher interview. Case study 4: Country 2 This study was conducted in a state-funded secondary school. Three classes of 67 students, aged 13–15 years old participated in the study for 8 h (4 sessions × 2 h). The role of the teacher was to provide support as needed. The topic of the DT project was: "Playing with Environmental Issues" and students used ChoiCo and nQuire for students. Data included 67 pre-intervention questionnaires, 59 post-intervention questionnaires, 3 student interviews, 8 audiovisual recordings, and one teacher interview.

Case study 5: Country 3 This study was conducted in a public secondary school. One third of students were eligible for free school meals. A class with 23 students, aged 11 to 13 participated. Four sessions of 45 min were conducted (3,5 h). The teacher facilitated the sessions. The topic of the DT project was saving electricity at school and technologies used were Choico and nQuire for students. Data were collected from 18 pre-intervention questionnaires, 7 post-intervention questionnaires, 2 focus group interviews, 8 audio-visual recordings, and screen recordings of students' interactions and discussions.

5 Findings

To address RQ1, we analysed questionnaire data: a) Pre-intervention questionnaires: 173 responses from students aged 11–14. 52% of them were male. 85% of them reported using desktop computers/laptops regularly and 92% smartphones. 25% used technology to create digital art and videos. The remaining used it to search the web, watch videos and play games. b) Post-intervention questionnaires: 152 responses of which 56.3% were male. Students agreed that they had participated in the various elements of a DT project. They agreed that they had 'helped make decisions about what their group would create (M = 4.33), had 'tested and improved the solution' (M = 4.23). Less than half agreed that they had 'found out about the needs of other people' (42.6%), with most (43.3%) choosing 'neither agree nor disagree' for this statement. The statement with the most negative responses - 'I was involved in presenting the solution to other people' (18.8% disagree) may reflect the fact that some DT activities were shortened due to time constraints. Most students agreed (M = 4.35) that they had worked well as part of a team. Students' responses (N = 135) to what skills they developed after taking part in a DT project revealed that cooperation was the most mentioned skill, followed by programming, teamwork, thinking and communication. Students stated confidence to use these skills in future projects. The least developed skills were research, reflection, patience, and design thinking.

To address RQ2, we analysed interview data and observation notes taken during the DT sessions. Case study 1 and 2 (Country 1): The challenges students reported were related: a) technology's limited functionalities: challenges were observed while students were coding with ChoiCo due to limited functionalities: "the coding part is a bit hard because it has a limited number of variables you could choose from and a limited amount of stuff you could make with it." b) limited time: A student commented: "I feel like we had some time, but there was a lot, there was not enough time to make a good game." Likewise, another group of students mentioned: "We didn't have a lot of time to think about a question before we had to move on to the next [session].", c) ideation: As explained: "Challenges faced… for me, it was about ideas. Like I put my best in trying to think of ideas of what to do for phishing and scamming." and d) task management: while tasks were easy to do, these were many making the process of keeping track of them rather overwhelming: "Making the code was a bit confusing, but not like [design thinking and coming up with choices]. It was easy, but just a lot of [things to do]. So, you have to keep track of everything."

The challenges teachers reported were related to: a) limited time: one teacher said, "We could have spent some more time showing them how the program works, or maybe there could have been a few examples of what you were sort of looking for. […] But, like here, we kind of gave them not that much time to really get into it." and b) the DT process: understanding what to do at each phase of the DT process was seen as another challenge: "Obviously, there were technical challenges, but that comes up all the time. I think the biggest challenge they had was trying to navigate how to solve the problems. Some other challenges they have[…], is knowing what it was that they were being asked to do in each stage".

Case study 3 and 4 (Country 2): The challenges students faced during the DT process were related to: a) limited time: students expressed a sense of dissatisfaction from the inability to fulfil initial objectives: "If time were more properly managed and we finished the project, it would be one of the most fun! It's a shame to put in so much effort and not see it completed!", b) understanding how to use technology: prior experience proved to be essential regarding the time students needed to finalise their designs. When students were not familiar with the technology tools, this has a negative impact on the learning process. A student mentioned: "It's not particularly difficult for someone who hasn't used it before, but it takes time and requires guidance." c) collaboration: as a student explained: "We had difficulties in communication, because we were a bigger team (i.e., three students instead of two) and we had disagreements about the values of the game that led to tensions between us." Students resolved these disagreements either by exploring a new solution or compromising: "We used to be more opinionated in the beginning. But now, if we had opposing opinions on a game element, we would come up with a third solution." d) the DT methodology: difficulties reported related to the open-ended nature of DT and feedback activities. Regarding the former, a student explained," The most challenging part of the process was the actual design phase, we had to consider various parameters before starting to design in Malt2. Factors such as the placement of the model in the garden, its shape, and the choice of materials all needed to be carefully combined to achieve a successful construction outcome". Though challenging, students acknowledged that this aspect made the process interesting: "The most difficult part was when we had to decide on the numbers of the game. It wasn't difficult. It was the cleverest part; the most challenging". During the feedback phase, the main issue that emerged was that students' comments on their peers' designs were not specific enough to enable them to make changes to their creations. A student explained, "we were told that our game was boring. So, what should we change? This comment didn't help us.", while another student added to this: "We respect their opinion and maybe our game is too easy for them, so they get bored when they play it. But when we asked them to explain to us how we could improve it, they said again that it was a boring game. So, we didn't understand what we could change to make it more interesting."

Accordingly, teachers faced challenges related to a) limited time, b) students' prior experience with technology and c) assessment of students' learning outcomes. Teachers stressed that the implementation of the DT methodology in a formal school context would require significant time, making it difficult to integrate it into the existing school programme unless the process is streamlined and well prepared. A teacher stated: "the time was not enough. I think that the duration of the activity plan was defined correctly. However, this time was enough for the game and the activity on the game, for the peer review, for the reconstruction of the game and in general for the actual stages of the design thinking. […] it was not enough for other stages.

Regarding students' prior experience with technology, another teacher said: "With MalT2 students had worked with before while nQuire had not. This had the effect of delaying the first phase quite a bit as it is a tool with many and open functionalities. They have to see it beforehand. I had to make a questionnaire for them to work on and direct them on what kind of questions they would make. The original design was changed as at first they were going to make it entirely by themselves". Finally, another important issue teachers mentioned was the difficulty to assess the learning outcomes of their students. When asked what skills he thinks the students have developed during the project, a teacher replied "I am not able to know in such a short and limited time precisely what kind of skills or competencies were developed and if students have developed any of them. Furthermore, a single project may not be enough to be able to extract confirmed results.

Case study 5 (Country 3): The challenges students faced were mainly related to a) students' engagement in DT sessions and b) the use of project technologies. The disengagement of some students was a major concern. As explained the instructions on how to engage in the DT sessions were not clear. In the first focal group, students highlighted that their classmates were disengaged from the activity most of the time. Both groups reported that there was a lack of instructions, which could potentially guide them as to how to use the project technologies. As explained: "the teacher could just [give] more instructions for the game so that we can understand better." Also, students expressed the need for individual support from the teacher to get explanations for tasks: "I found it hard trying to fill out the questionnaire [on nQuire for students], fill those questions for people to answer about my game […]I can't really think about any questions. Overall, there was a need for clear instructions on how to use technology.

Regarding the use of project technologies, students in both focus groups discussed the fact that games created in SorBET and ChoiCo had to be downloaded on local computers and others had to access them through these computers (instead of e.g., these being saved online and accessed via a URL). Students expressed very strongly that it was not feasible for their classmates to play the games as they could not upload the games online and then share it with others. As explained: "The game wouldn't download for me. So I had to just keep remaking it." In another example using ChoiCo, students had difficulties using the pins on a picture as these would immediately disappear. For nQuire for students, they found the interface not friendly enough as they had to scroll all the way down to select the response type after typing a question.

An interview was not conducted with the teacher, therefore challenges reported below emerged from the observation of lessons. There was limited time available for the teacher to implement the DT sessions. The teacher was new to both DT activities and project technologies while at the same time she was under pressure to complete the DT sessions within 4 to 5 sessions. This meant that she had to rush the implementation, skipping parts of it.

6 Discussion

In this paper, we reported on five case studies that took place across three countries, with 173 students in total, aged 11–14 years old. In these case studies, we used a set of technologies to enable delivery of DT in K-12 in an effort to understand how digital technologies could add value and facilitate effective implementation of DT in formal educational contexts. Students reported that they contributed to making decisions in their groups and that they tested and improved solutions. Yet, most of them did not find out about the needs of others or had an opportunity to present their work to others, revealing the stages of DT where emphasis was placed by teachers during the implementation. While early findings evidence impact on students' development of 21st century skills (as reported by students), several challenges were reported by both students and teachers while engaged with the DT process. We used these insights to produce a set of practical and evidence-informed recommendations for teachers to consider when designing, delivering and managing DT projects in formal education.

Regarding RQ1 and aligning with existing studies (Rusmann & Ejsing-Duun 2022), students reported development of social skills in the form of teamwork, cooperation and communication, as well as thinking, programming skills and increased confidence. In contrast, students were less likely to report development of research and reflection skills, and understanding of design thinking, necessitating the need to design DT activities that enable development of specific skills. For example, developing reflective skills would enable students to participate and find creative ways of learning and help them assume another person's perspective (empathy) (Rusmann & Ejsing-Duun 2022). The provision of feedback to other students, reported as a challenge in this study, would be an effective means to develop critical thinking skills. Critical feedback was shown to develop in DT studies with middle school students (Cutumisu et al. 2020).

Regarding RQ2 and RQ3, a major challenge noted across case studies was the availability of time to carry out DT projects in formal settings. Although DT activities were interesting for students, teachers had to rush between DT stages likely affecting students' engagement and understanding of activities. This finding with existing studies (Andersen & Pitkänen 2019) points to the significance of considering additional time when implementing DT projects in classrooms. Therefore, we recommend: **Recommendation 1:** Break down the DT process to separate sessions and factor in additional time to accommodate students' needs when interacting with the process. **Recommendation 2:** Identify which activities can be completed as homework by students to reduce time needed in the classroom.

Another challenge reported by teachers is the connection of DT activities with specific learning outcomes and ways of assessing these, a challenge also reported in the literature (Veldhuis et al. 2022). The use of a lesson plan as a preparatory tool for designing a DT project would enable teachers to reflect on how specific activities may relate to specific learning objectives and allow time to design formative and summative assessments to evaluate these. We recommend: **Recommendation 3:** Map activities to specific learning outcomes and identify assessment approaches for evaluating each.

Teachers and students' familiarity with using technologies and their functionalities emerged as another challenge which affected students' engagement in DT projects. Students required detailed guidance on how to use technologies (Weibert et al. 2014) and time to become familiar with tools functionalities. We recommend: **Recommendation 4:** Organise separate lesson plans in which students are asked to experiment with technology tools, as preparation for delivering a DT project. Effective engagement with the DT processes was also an obstacle for students. This related to a number of aspects including a) the implementation of certain stages of DT, such as the ideation stage which requires creativity and production of new ideas (Weibert et al. 2014), 2) decision making in groups aligning with existing studies that noted difficulties in reaching a consensus during for example the prototype development (Smith et al. 2016), 3) providing actionable feedback to others' creations that can help improve their work (Smith et al. 2016), and 4) managing multiple tasks within a single session. We recommend: **Recommendation 5:** Use a DT visual (model) to pinpoint to students the DT stage they work on, relevant tasks and timelines per activity. **Recommendation 6:** Give students opportunities to understand and practice decision making in groups, as preparation for delivering a DT project. **Recommendation 7:** Give students opportunities to provide feedback to the work of others, as preparation for delivering a DT project.

In response to the need of students to better understand each stage of the design thinking process (Recommendations 5 and 1) as well as the limited impact recorded on students' learning of design thinking processes, we produced a design thinking model for use in K-12 education, coined as the **Exten. (D.T.)^2 Digital Design Thinking Model** (see Fig. 1). While it builds on existing DT models, our model's unique contribution is that it details what students should be doing at each DT phase (through prompting questions) and which digital tool/s they should be using. It can be used to support teachers in designing activity or lesson plans for DT as well as a navigational tool to pinpoint to students the DT phase they are addressing. The starting point of the model is a challenge or a problem students decide to engage with while the end point is a range of outcomes including students' physical or digital creations, the development of new skills and knowledge and behaviour changes. The model features five phases as follows: empathise and understand, define and ideate, rapid prototyping and iteration, sharing and feedback, and respond and deliver. It has been integrated with an activity plan we produced to help teachers plan DT projects (https://extendt2.eu/dt-activity-plan-template/).

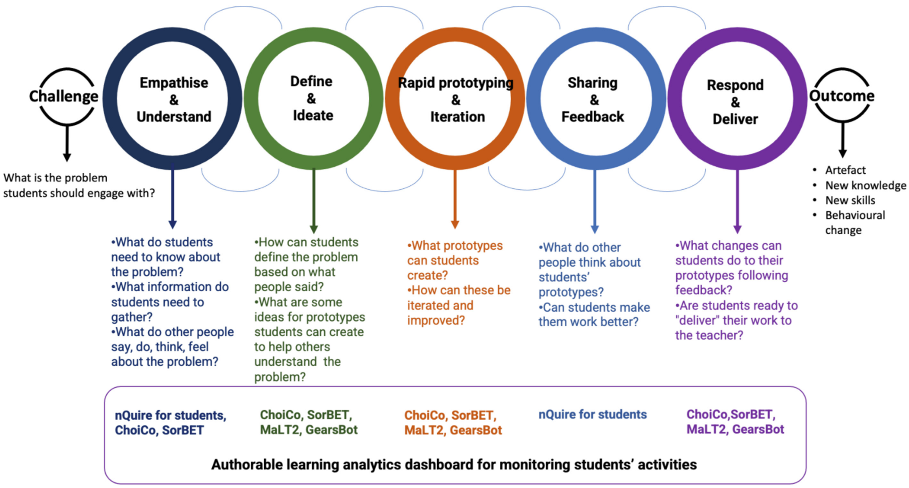

Fig. 1. The Exten. (D.T.)^2 Digital Design Thinking Model

7 Conclusions

In this study, both teachers and students reported facing challenges, notably in terms of time availability for implementing DT sessions and the readiness of the digital tools. Addressing the issue of time constraints, our approach involves clarifying to participating teachers the importance of allocating sufficient time to each stage of the DT process for successful implementation. Additionally, we aim to assist teachers in distributing learning activities across various sessions by collaboratively identifying tasks suitable for individual completion at home and those best suited for group work in the classroom. By doing so, we aim to minimize the amount of school time required to complete a DT project without compromising any essential aspects of the process.

Insights collected from this pilot implementation informed the redesign and further development of digital tools mentioned before with the aim to be user friendly and function smoothly. In addition, the tools have been extended to accommodate features including gesture-based interaction (SorBET), geolocation (Choico), 3D printing capabilities (MalT2), and scaffolding to provide feedback to research studies (nQuire for students). We aim to test, iterate and improve the new versions of the digital tools and Exten. (D.T.)^2 Digital Design Thinking Model (see Fig. 1) in the second and third years of the project, through collecting data from students and teachers while implementing DT projects. In addition, we aim to address two limitations of this study: a) analyse data considering for the sample's heterogeneity e.g., different ages, backgrounds, school type, locations, enabling comparisons between e.g., different types of schools, and an understanding of the conditions under which the proposed intervention may work (or not) well, and b) collect data to identify how and why the functionality of each technology triggers the development of specific 21st century skills.

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