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Learning science through a collaborative invention project in primary school

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Abstract

The study examines students' disciplinary learning in physics and interdisciplinary science learning opportunities that students encounter during a collaborative invention project. Thirteen student teams (aged 11 to 12, $N=46$) designed and constructed a prototype of a technology invention meant to solve one of the challenges students face in daily life. The data was collected from a physics achievement test taken both before and after the invention project and artifacts (student essays and process portfolios) that students constructed during the project. Seven inventions were categorized as physics-intensive and six as non-physics in nature. The change in students' achievement prior to and after the invention project was rather modest, and the increase was related to the level of physics-intensity of the inventions made during the project. However, the process portfolios revealed various interdisciplinary science learning opportunities and physics learning that could not be identified with the achievement test. Further, the co-occurrence analysis revealed several interdisciplinary learning opportunities that connected physics contents to the interdisciplinary themes. Working with varied materials and technologies and experimenting with them enabled the students to ponder different science topics and perhaps deepen their understanding through creative problem-solving. We conclude that such collaborative invention projects challenge teachers to take an active role in designing invention challenges so as to more explicitly interlink students' invention processes with science learning. In order to foster students' science learning opportunities, teachers should intensively evaluate each student-team's learning throughout the project and use portfolios to reflect on and scaffold their science learning systematically.

Keywords Elementary-level education, Physics learning, Science learning, Science and engineering practices, Invention pedagogy, Learning by making

Introduction

Adolescents need the skills and competencies to tackle future problems. There is a growing need to equip future generations with the disciplinary knowledge and transversal competencies that can contribute to solving wicked problems. Students need to practice such contributing competencies, so we are faced with the challenge of how to define an everyday problem that would generate a space for opportunities to learn and apply disciplinary knowledge in interdisciplinary settings. This paper reports on an Educational Design Research (EDR) (McKenney & Reeves, 2019) project in which students were engaged in the process of making technology inventions to solve everyday life problems. We call such teaching *invention pedagogy* (Korhonen et al., 2022). Invention pedagogy takes into consideration the education policy discourse that advocates for students learning transversal competencies (Council of the European Union, 2019; Finnish National Agency of Education [FNAE], 2016; Organization for Economic Co-operation

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and Development [OECD], 2005; 2019) so that they may actively solve complex problems and contribute to the building of a sustainable future (UNESCO, 2016). Educational research indicates that learning methods in which knowledge and artifacts are built collaboratively in iterative cycles and through working with real-life challenges can enhance the competence building of all students (Bao & Koenig, 2019; Hakkarainen & Seitamaa-Hakkarainen, 2022; Miller & Krajcik, 2019; Sormunen et al., 2020). Educational research has also highlighted the interdisciplinary nature of knowledge and learning (Sawyer, 2014; Tytler et al., 2021). Interdisciplinary teaching and learning integrate two or more subject areas into a meaningful association to enhance and enrich learning; facilitates higher-order, critical, creative, and analog thinking; helps students to make sense of phenomena and problems and learn disciplinary, such as science, core knowledge or ideas that are essential for deep understanding; makes learning realistic and valuable; and influences attitudes and motivation to learn (Silander et al., 2022; You, 2017). Science, Technology, Engineering, Arts, and Mathematics (STEAM) teaching and learning is one well-known form of interdisciplinary teaching and learning (Bevan, 2017; Jho et al., 2016; Krajcik & Shin, 2014; You, 2017). This article considers STEAM learning to be an example of interdisciplinary learning. Furthermore, in STEAM, the learning of school subjects is integrated, and mastering transversal competencies is explicitly stated as a learning objective. However, students' learning outcomes are typically assessed in a disciplinary manner, and there have been many critiques of interdisciplinary learning (Beane, 1995; Tani et al., 2013). Therefore, there is a need to better understand the opportunities to learn both disciplinary and interdisciplinary knowledge in STEAM education (Blikstein, 2013; Konopasky & Sheridan, 2020; Sinervo et al., 2021).

In this EDR, we will investigate students' opportunities to learn physics disciplinary knowledge and co-occurrences of interdisciplinary practices when students are guided to design and construct technology inventions. The study applies invention pedagogy designed for Finland's formal education context. By taking part in inventing, students can learn transversal competencies during the interdisciplinary, creative, and nonlinear technology-enhanced design and making processes (Hakkarainen & Seitamaa-Hakkarainen, 2022; Korhonen et al., 2022; Seitamaa-Hakkarainen et al., 2010). Furthermore, invention pedagogy highlights the important role of materials and tools in design and technology practices. During the invention process, students often work with disciplinary-specific core knowledge or ideas (Stevens et al., 2009). Tytler et al. (2021) and You (2017) argued that the interdisciplinary nature of STEAM teaching and learning helps students to make sense of complex phenomena and problems and supports learning disciplinary core knowledge or ideas. Learning the core ideas and technological know-how of engineering and physics are highlighted in invention projects when students build sustainable structures, working mechanisms, and automation systems for their inventions (King & English, 2016; Krajcik & Delen, 2017; Mills & Treagust, 2003). Moreover, invention projects encourage all kinds of students to participate, share expertise, and practice collaborative competence in more depth than would otherwise be the case (Sormunen & Viilo, 2022). Nevertheless, previously reported STEAM projects have typically focused on specific physics topics that students tackle by employing related scientific core ideas. Such topics have been, for example, the reflection of light in a fifth-grade optical instrument project (King & English, 2016), aerodynamics in a fourth-grade aerospace engineering challenge (English & King, 2015), and electricity in a fifth-grade scale-model house project (Sormunen et al., 2020). As Lehrer (2021) points out, organizing the learning of disciplinary core ideas within interdisciplinary STEAM teaching and learning is challenging. For example, planning this type of teaching and learning demands knowledge of students' conceptual and representational resources and the careful analysis of disciplinary core ideas. As a result, the teachers use strictly defined themes for the projects to ensure that the students learn the basics of the phenomena. This limits students' opportunities to work on a topic that motivates them (Markula & Aksela, 2022). However, with the teacher's careful planning of the learning situation, it is possible to support nonlinear, emergent, and open-ended invention projects (Sormunen & Viilo, 2022).

As noted, there is a paucity of studies on situations where science learning is assessed in the context of collaborative invention projects. To fill this gap, this research examines students' disciplinary learning in physics and interdisciplinary learning opportunities in science learning in a collaborative invention project that has features similar to project-based learning, emphasizing students' active construction of meaning: students face authentic challenges and collaborate and apply digital technology (Fortus et al., 2005; Krajcik & Shin, 2014; Markula & Aksela, 2022; Sormunen et al., 2022). More explicitly, we focus on evaluating the disciplinary learning of physics, such as rigid structures and electric circuits, because they are designated as core ideas in the Finnish national level curriculum, and the planned invention processes were especially aimed – along with transversal competencies – at covering physics core ideas and practices. However, invention projects are interdisciplinary and include elements of technology and engineering. Therefore, we analyzed students' interdisciplinary science learning opportunities during open-ended invention projects where they aimed to solve an everyday challenge. Before presenting further details about the methodology and findings, we will elaborate on the theoretical perspectives of collaborative invention projects.

Collaborative invention projects

In the context of elementary school science education, collaborative invention projects provide meaningful interdisciplinary learning environments in which students engage in complex and authentic invention processes, including failure, design, and redesign (Blikstein, 2013; Hakkarainen & Seitamaa-Hakkarainen, 2022; Sawyer, 2018). In general, in the field of learning sciences, there is increasing interest in exploring how to enable students to become active participants in the learning process (e.g., Konopasky & Sheridan, 2020; Martin, 2015). According to Bevan (2017; see also Kafai et al., 2014), students can learn problem-solving skills when engaging in collaborative invention projects; however, solving the problem is not necessarily the main aim of the invention project, but instead pursuing a pedagogical approach that supports the learning of curriculum aims holistically, including the learning of transversal competences. Furthermore, a growing body of research focusing on maker projects shows that collaborative invention processes in science and engineering may enhance critical technological skills and knowledge of the integrative design process (Bowler & Champagne, 2016; Sheridan et al., 2014). In addition, the approach can be utilized in cognitively diverse classrooms, as it provides a learning environment that supports the development of transversal competencies (Stehle & Peters-Burton, 2019) and prepares students from various cultural backgrounds for improved learning outcomes (Wahono et al., 2020).

Introducing collaborative invention projects into schools not only emphasizes the learning of transversal competences but also embodies engineering, design, and science. The design of collaborative inventions challenges the old way of learning science (Osborne, 2014), in which students solved basic problems from a textbook or performed experiments following detailed instructions. Collaborative invention projects are open-ended, and provide various learning opportunities depending on the nature of invention product and process. The open-ended theme challenges students to take more responsibility in problem solving based on their own lives and experiences (Bevan, 2017). Marshall and Harron (2018) emphasized five aspects of invention projects: empowerment; collaboration; the use of scientific, technological, engineering, and mathematical tools; maker habits; and the production of the artifact. Such projects require students to reflect, share, collaborate, and show their thinking (Marshall & Harron, 2018). It should be noted, however, that the students do not work without the teacher's support for learning. Still, the teacher facilitates collaboration and knowledge building in workshops, between the students, and helps students make connections to science concepts when tackling similar areas of the problem (Sormunen & Viilo, 2022). Previous studies on collaborative inventions show that they create opportunities to learn science core ideas as well as scientific and engineering practices, such as defining problems and designing solutions (Krajcik & Shin, 2014), and introduce multiple ways in which scientists and engineers explore, design, and understand the world (Krajick & Merritt, 2012). When an invention project is organized in a specific context, this context could influence students' engagement (Schmidt et al., 2018). Furthermore, as Miller and Krajcik (2019) indicate, problem-based design tasks help students understand complex phenomena and learn to solve problems simultaneously.

In the context of science education, collaborative invention projects draw inspiration from pedagogical traditions such as constructionism (Papert, 1980), knowledge-creating learning (Paavola et al., 2004), project-based learning (Krajcik & Shin, 2014), and design-based learning (Seitamaa-Hakkarainen et al., 2010; Fortus et al., 2005; Kolodner et al., 2003). These pedagogical approaches integrate designing and making with the learning of scientific subject matter and inquiry processes (Bevan, 2017; Kafai et al., 2014). Such activities emphasize active, hands-on working with artifacts designed to engage learners in creative processes under teacher guidance. The pedagogical approaches also represent nonlinear pedagogy, where the required knowledge and solutions cannot be determined beforehand but emerge interactively through repeated personal and collaborative efforts (Hakkarainen & Seitamaa-Hakkarainen, 2022). The teacher's role is to help students learn science core ideas, scientific and engineering practices, and such global competences as thinking skills (Blumenfeld et al., 1991). Stammes et al. (2020) noted that, from a chemistry perspective, the key to science design practices is to develop flexible and fluent skills that prepare students for future school projects and increase interest in science studies and careers.

Four basic elements characterize the invention pedagogy, including (1) an inclusive innovator mindset for both students and teachers, (2) selecting a multifaceted, real-world phenomenon as a starting point for a project, (3) the co-creation of knowledge and artifacts, and (4) utilizing technology-enriched tools and materials (Korhonen et al., 2022). The Finnish national level core curriculum suggests that collaborative learning, such as invention projects, supports students ability to achieve transversal competencies and emphasizes a new type of pedagogy (FNAE, 2016; Hakkarainen & Seitamaa-Hakkarainen, 2022). Thus, collaborative invention projects follow the general curriculum and are part of students' regular schoolwork (Marshall & Harron, 2018). In these projects, students solve real everyday problems to make living easier (Bevan, 2017).

The process of collaborative inventing engages students' creative and collaborative design of artefacts (Hakkarainen & Seitamaa-Hakkarainen, 2022). Using real-world problems encourages students to use technology-enriched materials that integrate traditional crafts with digital tools, such as 3D printing, sensors, robotics, and the internet of things (Blikstein, 2013; Martin, 2015), but also to apply their disciplinary knowledge of science, especially physics. Tala (2013) argued that physics and technology cannot be separated, that technology is a tool for doing physics, and that physics is a tool for making new technology. Thus, technology-rich invention projects provide opportunities to learn science core ideas, such as energy and electric currents, that are essential elements throughout the domains of physics, science in general, and engineering. Moreover, they are explanatory (i.e., used for explaining phenomena), generative (i.e., used for investigating and solving problems), and relevant (in the personal, local, and global contexts).

Research questions

The objectives in the open-ended invention projects are unconstrained, unlike typical STEAM projects (e.g., Markula & Aksela, 2022), and focus on learning transversal competencies and interdisciplinary learning. In particular, discipline-specific learning during an invention project has proven to be challenging to predict, because the students' invention ideas can be very broad and often go in unpredictable directions. Each team may have different learning opportunities depending on the nature of their invention product and process. This study examines students' disciplinary learning in physics and what kind of interdisciplinary science learning opportunities students encounter during an invention project. Based on the students' learning outcomes in achievement tests, the nature of the inventions, and the invention teams' process portfolios, we answer the following research questions:

1. What kind of inventions did student teams make?
2. To what extent did students learn physics disciplinary knowledge during the invention project, according to assessments of their pre- and post-test performance? How was their disciplinary learning related to the science-intensity of their inventions?
3. What kind of interdisciplinary science learning opportunities can be identified from the teams' process portfolios?

Method

Study context and participants

We conducted the collaborative invention project in close cooperation with teachers in the capital area of Helsinki, Finland, according to the principles of EDR (McKenney & Reeves, 2019). Finnish education relies on highly educated and strongly committed teachers that implement the national core curriculum based on research-based methods adapted from pre- and in-service teacher education (Lavonen, 2021). This provides unique possibilities to develop new ways of learning, such as invention projects and research, in teacher-researcher partnership (Blikstein, 2022; Juuti et al., 2021; Korhonen & Lavonen, 2017). Further, Blikstein (2022) argued that the Finnish system supports teachers' ability to apply new forms of learning that enable everyone to participate, not only the privileged. The Finnish educational system (https://okm.fi/en/education-system) is free of charge from pre-primary to higher education, and students are supported individually based on their learning needs, according to the agreed principles of inclusion (FNAE, 2016; UNESCO, 2016).

The participating primary school followed inclusive pedagogy and emphasized STEAM learning, especially technology and engineering education. The school was located in the capital area of Finland, in an area of heterogeneous socio-economic and ethnic backgrounds. Thus, the classes were diverse; 20% of the students had an ethnic background, and 17% of the students had identified special educational needs (SEN) and required the support of a special education teacher due to mental, physical, behavioral, cultural, linguistic, or other reasons. Altogether, 46 students (aged 11 to 12 years) participated in the study. Half of the participants were girls ($n=23$, 50%) and the other half were boys ($n=23$, 50%). Nine of the students had SEN, including only one girl. There were two class teachers (with master's degrees), one special education teacher (with a master's degree), and a teaching assistant in the class. The teachers had experience in STEAM and technology education, organizing open-ended projects with transversal competences, and using scientific and engineering practices to pursue learning goals. Various scientific and engineering practices and collaborative activities were gradually introduced and practiced with all students before the data collection. Due to the school's specialization in technology education, the students had a variety of earlier experiences with using digital technology (e.g., computers, tablet devices, Lego robotics), engineering and tinkering (e.g., electricity, pneumatics, levers), and fabrication tools (e.g., metal, textiles, wood).

Interdisciplinary learning module: making collaborative inventions

The overall topic of the collaborative inventions was "Everyday Challenges". A team of teachers and researchers designed the learning module to foster curriculum integration and the learning of transversal competencies. As typical in EDR projects (McKenney & Reeves, 2019), the teachers were the driving force in project planning. Teachers emphasized several technologies and tools (e.g., electrical circuits, programmable hardware, robotics, and fabrication tools). The goal of the invention task was for the students to design an intellectually challenging, aesthetically appealing, and personally meaningful complex technological artifact that integrated physical and digital elements. The students were encouraged to either improve an existing technological device or invent a new one to make daily life easier. The advantage of planning between teachers and researchers is that the planned activities can take into account the needs of the student group and the differentiation aspects so that everyone can actively participate (Juuti et al., 2021). This was taken into account in the students' grouping, which was based on the students' interests. The idea was that the project would start with a brainstorming session where students identified everyday challenges together. Based on that, the students would then choose the topic that interested them most. After co-planning the project, the teachers were responsible for implementing the associated activities. The first author of this article was present in all sessions, collecting data. She also helped the invention teams with problems related to programmable technology, when necessary.

The project lasted 16 sessions (approximately 90 min each) during the Spring of 2016 and 11 sessions in 2017. Students also studied other primary science topics during the project periods, such as life science and earth and space science, in the Fall of 2016. The teachers allocated two to three lessons for each project session. Some of the project sessions introduced new technological tools and made connections with the science core ideas as well as standard scientific and engineering practices (see more detailed description from Additional file 1). The students participated in three skill-building workshops that could be characterized as traditional teaching of a specific topic to ensure that students have the competence to apply these in their invention projects. The workshops focused on physics core ideas, engineering, and digital technology. Students were encouraged to utilize conductive materials, Lego robotics, or GoGo Board in their inventions. The conductive materials workshop aimed to learn electricity content such as conductivity, electric current and couplings, and components (e.g., battery and mechanical switches). In the conductive materials workshop, students worked with basic paper circuitry tools (e.g., copper tape, surface-mounted LEDs) and built electrical circuits (e.g., simple, series, and parallel circuits). The LEGO robotics and GoGo Board workshops focused on fostering students' skills in two programmable devices that they could use in their inventions. In the LEGO robotics workshop, students studied robotics and coding with LEGO Mindstorms EV3, focusing on operating principles and structures. The students had previously used this system in class, so this workshop built on previous knowledge and experience. The third workshop introduced a new programmable device, the GoGo Board. The workshop focused on the use of sensors in everyday life, and after the students had learned the basic skills of the hardware they then invented and built environmental and technological applications with it.

The actual invention teams were formed in the third session according to students' interests. In total, 13 groups were formed, each with two to five students. One of the groups was a mixed-gender group, and SEN students were divided into five groups. One invention group had only SEN students. The student teams addressed the invention challenge from different points of view. Although their topics differed, the main phases that their projects went through were similar.

Data collection and analysis

In EDR projects, the data is typically collected from multiple sources (McKenney & Reeves, 2019). In addition to physics achievement tests, we gathered artifacts that students were asked to construct during the invention project. The aim was to minimize interfering in the learning process with data gathering, which was especially important for SEN students (c.f. Sormunen, 2020). During the invention process, student teams were asked to write essays describing their invention and report on their process of making the invention in a portfolio (Fig. 1). The data was analyzed iteratively in line with the research questions. The data, and its acquisition and analysis, are described in more detail in the following subsections.

Data analysis of discipline-specific learning in physics

In order to examine physics-specific learning achievement, we used the pre- and post-tests. Students had relatively open possibilities to select the challenge and type of invention. Thus, the invention type may influence the learning opportunities they have during the process. The students described their inventions in written essays, a mother tongue assignment. Invention

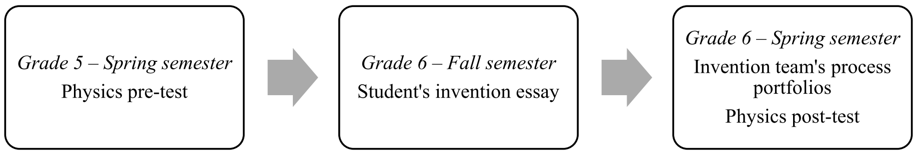


Fig. 1 Data collection

essays were analyzed, considering the national core curriculum description of aims and contents for physics within general science. It appeared that inventions could be classified as physics-intensive and not physics-intensive inventions (see Table 2 in the Results section). In the essay, students were asked to respond to six questions adapted from Barlex (2007): 1) why the invention is needed (need for), 2) what it is used for (use or function), 3) how it works (technical), 4) how it looks (appearance), 5) what parts it consists of and how the parts fit together (structure), and 5) whom it is designed for (user). The nature of the inventions varied greatly, but fell into three categories according to their primary functions: 1) improving cleanliness, 2) providing reminders, or 3) addressing well-being (Sinervo et al., 2021).

In this study, we analyzed student essays from the point of view of physics content from technical and structural perspectives. We categorized the students' inventions as either physics-intensive or non-physics inventions by analyzing the 42 student essays regarding the 13 co-inventions and then interpreting the intensity of the physics utilized and the applied digital technology. We identified an invention as physics-intensive if it included words or descriptions based on three curriculum-based criteria (FNAE, 2016; Stake, 2005; Weber, 1990): 1) students used tools related to technology or physics, e.g., Lego robotics, 3D printer, GoGo Board; 2) students used the core ideas of physics: thermodynamics, dynamics, and electronics; 3) students conducted experiments related to physics, e.g., testing, experimenting, and developing new ways to make inventions work. The physics-intensive invention category was coded as 1, and the non-physics invention category was coded as 0.

Before and after the invention project, students were asked to answer *a physics achievement test* explicitly designed for this project (pre- and post-test). Teachers administered the test to students at the beginning of a lesson. The test was done on paper, and the students could use the whole lesson to complete the test. The response time of individual students was not measured. Test items were designed according to the Finnish primary school physics curriculum (FNAE, 2016). They included items measuring the understanding of forces, simple machines, triangle and pipe structures, electric circuits, electric conductivity, properties of materials, thermodynamics, and, moreover, conducting a science experiment. Table 1 shows examples of the questions, question descriptions, and scoring used in these tests. The Item-response theory (IRT) approach was used to test the quality of the achievement test. All of the test items and the IRT analysis are presented in Additional file 2.

According to the Shapiro-Wilk test of normality, the pre-test and post-test data have a the normal distribution. Variance analysis was used to measure differences in test achievement between invention category groups. Due to the rather high kurtosis value in one invention-type group in the post-test, we applied the Independent-Samples Mann-Whitney U Test to compare groups in the

Table 1 Examples of test items

Item	*Rationale*	*Scoring*
2. Batteries for the remote control		
Attach a battery to the remote control by drawing a line	Attaching batteries to electric devices, everyday life technology, and electric circuits	1 point if student inserted both batteries correctly 0 points if student inserted one or both batteries incorrectly
3. Empty bottle in freezer		
An empty and closed lemonade bottle has been put into a freezer overnight. The bottle will be taken out in the morning. What is the question for which you would get the answer by doing this test? Write this question	Constructing a research question; Gay Lussac's law and thermodynamics: how the relation between volume and temperature stays the same, even when one of them changes	1 point if a student mentioned experimenting with air, observing the change in air pressure in the bottle, the relation between temperature and the volume of air, experimenting with pressure, cooling air or oxygen, or the behavior of the bottle 0 points for a blank or incorrect answer

post-test. We calculated the standard measurement of Cohen's d to evaluate the effect size of the mean difference between pre- and post-test scores, indicating learning of physics core ideas and scientific and engineering practices within invention-type. Cohen's d was calculated following formula (1).

$$\mathrm{d} = (\mathrm{M2} - \mathrm{M1})/\mathrm{SD}_{\mathrm{pooled}}, \text{ Where } SD_{\mathrm{pooled}} = \sqrt{((SD_1^2 + SD_2^2)/2)} \quad (1)$$

Data analysis of interdisciplinary learning

The level of interdisciplinary learning was analyzed using invention process portfolios, which each invention team wrote after every project session using a digital platform (Microsoft Office 365, OneNote Class Notebook) (see an example in Fig. 2). The aim was to discover more broadly what science topics the students tackled during the process and what kind of scientific and engineering practices they applied. We were also interested in what kind of topics and practices occurred together in the portfolio entries.

The teachers guided the writing of the portfolio entries by suggesting the following aspects to consider: 1) Take photos of the work you have done during the session. 2) Describe what your group has done during the session as precisely as you can. 3) How did you divide your tasks? 4) What kind of ideas did you have during the session? 5) What could you have done differently? 6) How will you continue your work next time? We analyzed the process portfolio entries using qualitative content analysis (Stake, 2005; Weber, 1990). The analysis process consisted of several analysis cycles, wherein we clarified the analysis categories through discussions and negotiation until we arrived at mutual agreement and consensus. We have compiled the main aspects of that analysis in Fig. 2.

In the first round (Fig. 2, first round), we looked for expressions related to the invention's structure, working with materials, science content, scientific and engineering practices, and technology and digital production, and then coded them accordingly – see colors green (scientific content), light blue (scientific and engineering practices), and yellow (technology and digital producing). We noticed several overlapping expressions between categories, and disciplinary knowledge was difficult to detect in the first phase. In the second round (Fig. 2, second round), we focused on reducing the number of categories and increased the abstraction of the coding. We ended up with four final categories that best described the richness of learning during the invention project: 1) *science topics*, 2) *experimenting*, 3) *working with materials*, and 4) *working with technologies*. See Additional file 3 for a complete account of the analytic categories.

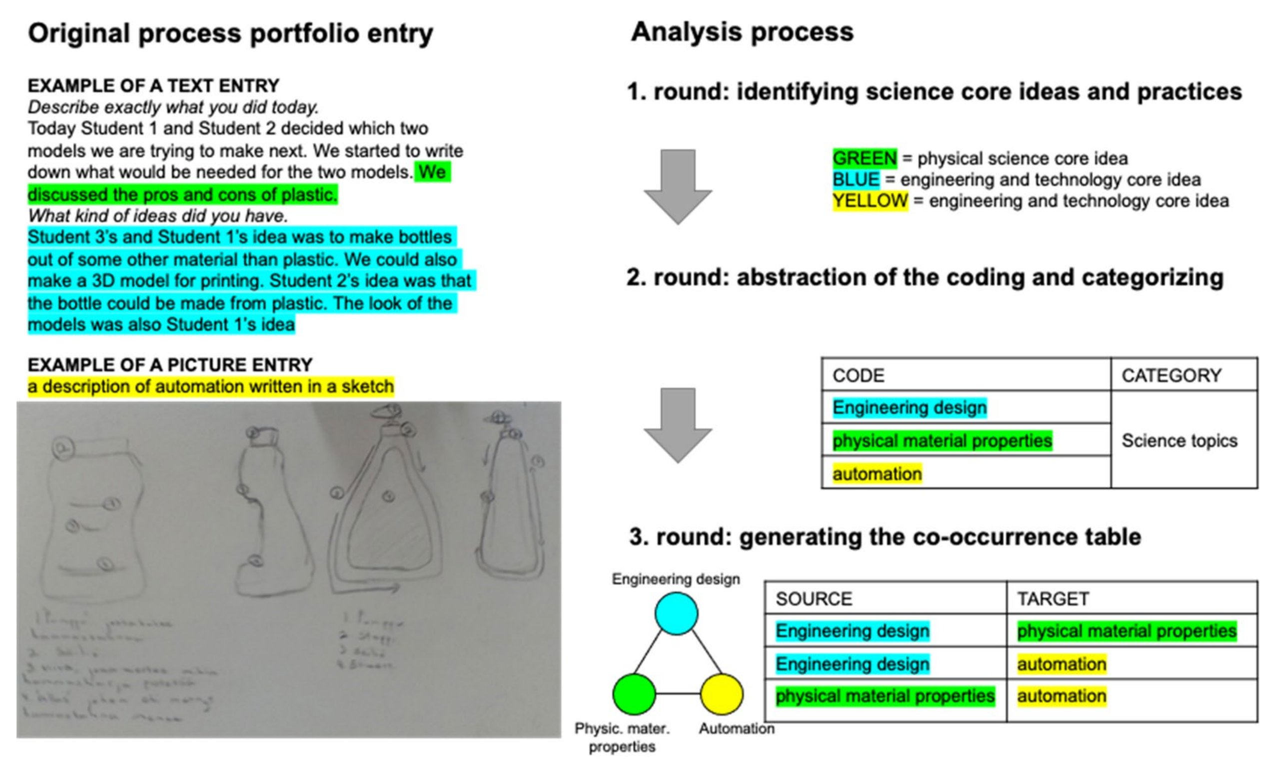


Fig. 2 Example of the analysis process used on the invention process portfolios. The highlighted areas illustrate the codes of physical material properties (green), engineering design (light blue), and automation (yellow), all belonging to the science topic category

The content analysis enabled us to identify the science knowledge and process skills utilized during the process in more detail, but we wanted to discover the underlying connections between the specified codes and categories. Thus, in the third round (see Fig. 2, third round) we enriched the analysis by employing co-occurrence network analysis (Bastian et al., 2009; Sormunen et al., 2019). For each portfolio entry, we listed the codes that appeared together. We identified up to nine learning opportunities from some session portfolio entries, while there was just one in other session portfolio entries. Next, we constructed and visualized a two-dimensional co-occurrence network of each invention team's learning opportunities using Gephi, open-source software for data visualization (Bastian et al., 2009). For the Gephi analysis program, we generated a co-occurrence table for all of the codes that appeared in the portfolio entry simultaneously, with each code having a link to the other codes, setting the codes in source and target columns (see Fig. 2, third round). We treated the created co-occurrence table as undirected, meaning that the codes have a two-way link, and thus the codes could be placed in either the source or target columns. If we could identify only one learning opportunity in a session entry, we linked it to a new *single-task activity* code. We then applied Yifan Hu, a force-directed algorithm (Hu, 2006), in which codes with a low number of links to others are pushed to the sides of the visualization while the codes with a higher number of links move towards each other (see Figs. 3 and 5). The complete network of connections consisted of 18 identified codes and 471 co-occurrences between codes we identified in the same session. We calculated the basic measures of the co-occurrence network and other factors, such as each node's frequency and related frequency.

Results

Students' inventions

To answer the first research question regarding the nature of students' inventions, we analyzed 42 student essays across 13 invention teams. Seven were classified as physics-intensive (student $n=27$), and the non-physics category included six inventions (student $n=19$) (Table 2). Essays describing these inventions did not contain technology or primary school physics curriculum-related content. There were significantly more girls ($n=18$) than boys ($n=9$) in the physics-intensive invention teams, while almost all SEN students ($n=8$) were on the non-physics teams.

Students' learning of physics disciplinary knowledge

To answer the second research question, we examined the extent to which students learned physics disciplinary knowledge during the invention project. Table 3 shows

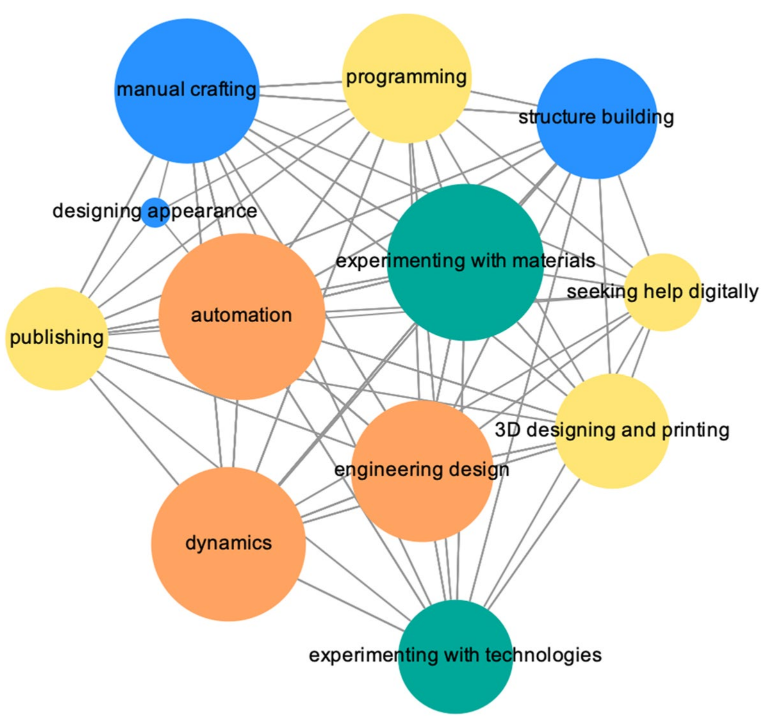


Fig. 3 The Box for Wires team's learning opportunities. Science topics are represented in orange, and the scientific and engineering practices of experimentation in green, working with materials in blue, and working with technologies in yellow

Table 2 Student teams' inventions

Name (No. students and background)	*Description (Artefact analysis based on essays)*	*Type*
1. Vacuuming Carpet (4 girls)	The invention sought to prevent rocks and sand from getting into a house. The Vacuuming Carpet is located in the hallway. The students' description of their invention prototype showed that they were thinking about physics-related phenomena. Specifically, they mentioned power, which would be needed to vacuum up small rocks and sand	physics-intensive
2. Box for Wires (3 girls, 1 boy)	The invention sought to help people organize their wires inside a box made of plastic. In one of the groups, the students explained levers and how they used levers in the box. They also mentioned buttons, wires, Legos, and suction cups. The description of the materials used made this invention prototype a physics-intensive invention	physics-intensive
3. Garbage Can (3 boys, one of them SEN)	The invention sought to detect and alert users when a garbage can is too full. Texts from this invention group showed that the students thought about using electronics during this invention, since they used magnets to make the invention prototype	physics-intensive
4. Key and Bus Card Locker (3 girls)	The invention was a smart key-holding stand that sounded an alarm if a user left home without their keys or wallet. The group produced two similar inventions related to holding keys. It was a physics-intensive invention because the students' texts described the use of smart technology	physics-intensive
5. Fitness Equipment (5 girls)	The invention sought to enhance the ability to train at home. The students described the objects' rotation around an axle in their texts. They did not report any digital technology use, but did describe the use of dynamics during the construction process	physics-intensive
6. Snack Machine (5 boys)	The invention was a machine that made snacks after school: for example, it made bread and dispensed juice. It was a physics-intensive invention because the students reported using Lego robotics during their invention-making process	physics-intensive
7. Smartboard (3 girls)	The invention involved notifying users of things they needed to do. The students described using and thinking about sensors during the making of the invention prototype. The description made the invention physics-intensive	physics-intensive
8. Gel Comb (5 boys, three of them SEN)	The invention of a gel comb was a non-physics invention. The students designed this invention for people who use gel in their hair, creating a product that applied gel while brushing a person's hair. This was a non-physics invention because the students' texts included no description of physics subject matter use during the construction process	non-physics
9. Toothpaste Bottle (2 girls)	The invention involved putting toothpaste into a pump bottle instead of a tube. The group's student text did not include any discussion of physics subject matter use; therefore, this was classified as a non-physics invention	non-physics
10. Flying Toilet Seat (3 boys, one of them SEN)	The invention was a toilet seat that could fly anywhere it was needed. The invention was imaginary and not possible to make	non-physics
11. Key Rack (3 girls, one of them SEN)	The key holder did not contain any smart technology, and the students' texts did not include any descriptions of physics-related content. The invention holds your keys in the same place	non-physics
12. Smoothie (3 boys)	The invention sought to help hungry people who wanted a snack. The students essentially designed an invention that made smoothies of different flavors. Their texts did not include any discussion of physics-related technology	non-physics
13. Spy-briefcase (3 boys, three of them SEN)	The spy briefcase was designed to help in a number of different situations. For example, the students described it acting as an alarm in the morning, luring and then driving away a little brother, and serving as an extra seat when riding in a full bus. The invention was a fantasy invention that was not fully thought out and did not include any physics-related content	non-physics

Table 3 Descriptive statistics of the achievement test

Test	*Non-physics invention group*			*Physics-intensive invention group*		
	N	*M*	*SD*	*N*	*M*	*SD*
Pretest	18	1.85	1.30	28	2.51	1.35
Posttest	20	2.11	1.02	26	3.26	1.19

descriptive statistics of the students' achievements in the physics tests. Students in the physics-intensive invention group have higher scores on the pre-test and post-test.

Analysis of variance demonstrated that the type of the invention did not have a statistically significant connection to pre-test score ($F(1, 44) = 2.71$, $p = 0.11$). At the end of the invention project, according to Independent-Samples Mann-Whitney U Test, the post-test distribution differed by the invention type ($U = 318$, $N = 46$, $p = 0.00$). Cohen's d was calculated for both invention type groups. Students who participated in the physics-intensive type learned more than students who participated in the non-physics type of invention team. In the physics invention group $d = 0.59$, while in the non-physics invention group $d = 0.23$.

Interdisciplinary learning opportunities

To answer the third research question, we analyzed the teams' process portfolios in order to trace interdisciplinary learning opportunities. The process portfolios revealed the extent to which the core tenets of science and scientific and engineering practices were available to the students while working with their inventions. The qualitative content analysis indicated that the portfolios provided a much broader perspective on the learning opportunities created during the project than the physics tests focusing entirely on physics content. From the portfolio entries, we identified 259 science topic entries from eight different content areas related to the science core ideas of life sciences, physics, engineering, and technology. A detailed description of these expressions and their frequencies can be found in Additional file 4.

The science core ideas were predominant in the session entries in the *science topic* category. In addition to the subjects of dynamics, automation, and electronics, which were also found in the essays, the students also worked with topics such as engineering design, physical material properties, the mixture of properties, magnetism, and life sciences. There were also many entries related to automation and engineering design, as the design task guided students to make technological and automated solutions. There were considerably more *science topic* expressions in the journal entries of physics-intensive inventions (75%) than non-physics inventions (25%). Nevertheless, the non-physics invention teams' portfolios also included physics expressions.

Most of the expressions found in the portfolios were related to three scientific and engineering practices categories. A total of 657 portfolio entries emphasized *experimenting*, *working with materials,* and *working with technologies*. These categories were interdisciplinary in nature, including aspects of crafts and design disciplines. This was especially the case in the *working with materials* category, which was the second-largest category, including 257 entries of codes for manual crafting, structure building, and designing appearance. This is unsurprising, as the students constructed tangible artifacts using both physics-intensive and non-physics approaches. Hence, the topics of crafting, particularly manual crafting, were self-evidently key learning areas. In addition to physical materials, all of the invention teams also *worked with technologies* ($f = 254$). Based on the related frequencies, the physics-intensive invention teams worked significantly more with materials and technologies than the non-physics teams. Their accounts also contained more expressions related to *experimenting* ($f = 146$), which as the smallest category included two types of experimenting: experimenting with materials and with technologies.

Notably, engineering design played a significant role in the non-physics inventions in the *science topics* category (see Additional file 4). At its simplest, the Briefcase team focused on building a box-like structural construction from wood for the briefcase. The learning opportunities mentioned in all of their portfolio entries included scientific and engineering processes (e.g., *working with materials* and *experimenting*) and, in the early stages of the process, the science topic of engineering design. In contrast, the Smoothie and Gel Comb teams worked more intensively with science content. Unlike the other non-physics invention teams, their science learning opportunities were richer in experimenting with materials. The Gel Comb team focused on building a suitable container for a gel-like substance. They aimed for a solution that would allow the gel to seep from the tank to the comb peaks. Their portfolio entries were rich in technical and ideational drawings. The Smoothie team did multiple tests trying to find the best texture for the smoothie, and when they solved it, they then focused on the product's nutritional content. They were the only team that worked with the topic of life sciences.

Although the pre- and post-tests indicated that the non-physics teams' science learning opportunities were limited, the portfolio analysis revealed that scientific aspects were present in every team's invention. Scientific and engineering practices were visible in all of the teams' processes, and science topics in all but two of the non-physics inventions (the Imaginary Toilet Seat and the Keyholder). Furthermore, the co-occurrence analysis revealed which learning opportunities appeared together in the teams' portfolio entries (Table 4).

Manual crafting was an essential part of the students' elaboration of their inventions, appearing in the six most common co-occurrences. Manual crafting and structure building appeared simultaneously in 28 portfolio entries, being the most common co-occurring expressions. Students worked with different materials, bending, cutting,

Table 4 The most common co-occurrences

The most common co-occurrences	*f*
Manual crafting – structure building	28
Automation – programming	19
Manual crafting – publishing	16
Experimenting with materials – manual crafting	15
Experimenting with materials – structure building	15
Manual crafting – programming	15
Automation – manual crafting	13
Designing appearance – manual crafting	13
Programming – publishing	13
Automation – publishing	12

drilling, sawing, and molding, among other techniques, when constructing their inventions. Manual crafting also appeared together with publishing and designing appearance. Both co-occurring expressions increased in the process portfolio entries at the end of the project. Students divided tasks so that some members worked on an advertisement while some focused on finishing the invention. The only *science topic* that rose to the list of the most common co-occurrences was automation, co-occurring with programming, manual crafting, and publishing. The following sections illustrate the interdisciplinary learning opportunities of the two teams' invention processes: one physics-intensive invention and one non-physics invention.

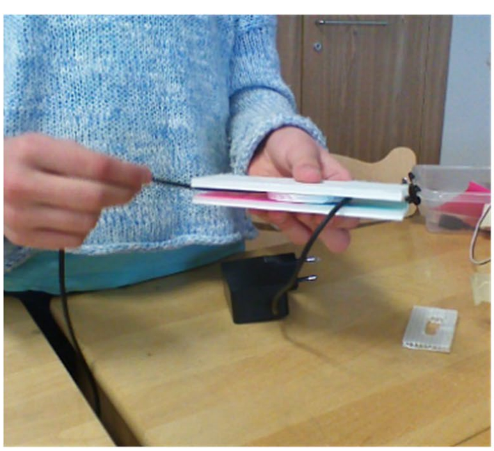
The learning opportunities of a physics-intensive invention – Box for Wires

We identified the highest number of science learning opportunities from the Box for Wires team's process portfolio entries. Figure 3 depicts that the expressions were related to specific *science topics* (in orange) and scientific and engineering practices (in green *experimenting*, in blue *working with materials*, and in yellow *working with technologies*). The expressions of experimenting with materials, automation, and engineering design, depicted in the middle of Fig. 3, were a vital part of the team's invention process, meaning that the team built an automation-related design solution by carrying out various material experiments.

The four students of the Box for Wires invention team aimed to build a rectangular container for messy smartphone charger wires, thus improving the chargers' usability by keeping the wires straight. From the first few session's portfolio entries, it was clear that the team's most significant challenge was to solve the problem of winding the wires. The students studied the wire's rotation using the GoGo Board's servo motor, attaching different sizes and shapes of cellular plastic pieces. At the end of the sixth lesson, students began to find a solution. The students made a portfolio entry for it, assembled the supplies, and left for lunch. However, the solution to the problem was so close that they returned to the class to finish their work. An additional text can be found in the sixth lesson's portfolio entry in Fig. 4.

The learning opportunities of a non-physics invention – Toothpaste Bottle

In contrast, we identified the lowest number of science learning opportunities in the Toothpaste Bottle team's process portfolio. The team of two students aimed to solve the problem of toothpaste tubes easily smudging. Even though their invention was identified as non-physics, their science learning opportunities were rich, even if limited in quantity. The team's co-occurrence visualization (Fig. 5) illustrated that engineering design had a significant role in their science learning.



After the lesson and lunch, [student] made the invention work! We really figured out which way the wire should be and how it would work! Awesome, now after a few weeks, we can accomplish more when there are just two of us than in previous lessons... well, that's a good thing! The last of the pictures above show how [student] invented it. She glued the lids and started spinning the wire between them; then, she realized that if we made the lid smaller, it would work, and if we put the wire differently than before, it would work! That way, the motor would twist the wire in the right way, the plug would not move, and everything would be in place.

Fig. 4 Translated excerpt of the Box for Wires' process portfolio entry for lesson 6

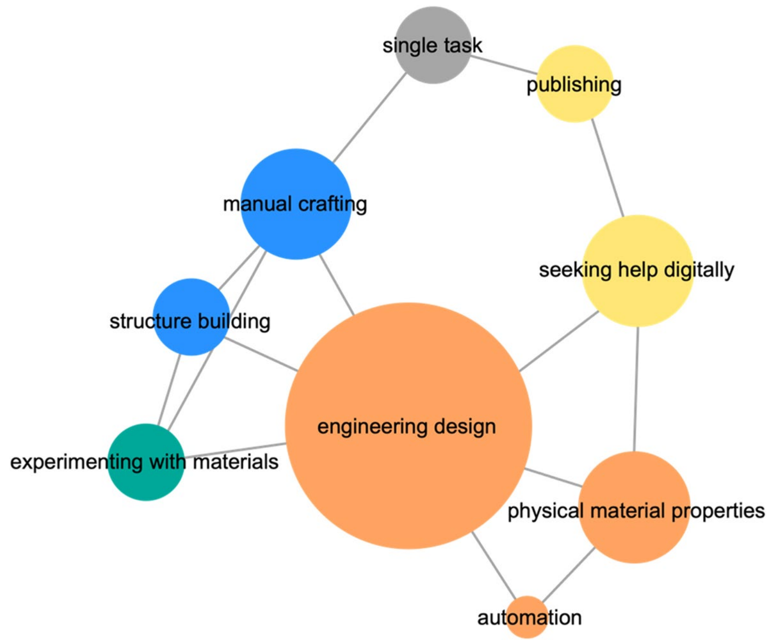


Fig. 5 The Toothpaste Bottle team's learning opportunities. The single task activity is represented in black, science topics in orange, scientific and engineering practices of experimentation in green, working with materials in blue, and working with technologies in yellow

The right side of Fig. 5 represents the team's work in the first four lessons, where they focused on designing a container suitable for the toothpaste's texture. First, the students focused on designing and sketching several ideas for the container and its appearance, structure, and function. Then they discussed material choices, pondering plastic's physical material properties and aiming to design and print a 3D model. One of the students was absent in the fourth lesson, but they still worked together through Snapchat; this was identified as seeking help digitally.

The left side of Fig. 5 represents the middle stage of the project. The team conducted material experiments, based on which they ended up using recycled material (a pump bottle for liquid soap), when they noticed that soap and toothpaste had similar textures. The students solved the invention's technical problem quite effortlessly, ending up building a box-like wooden case for it. In the final three lessons of the project, the students focused on finishing their invention. Since there were only two members in the team, they focused on only one task at a time, working side-by-side on making the advertisement. Working with only one learning opportunity at a time was coded as a *single-task activity.* The learning opportunities of these sessions are located at the top of Fig. 5.

Discussion

This study aimed to examine what physics disciplinary core ideas and practices students learn and what kind of interdisciplinary science learning opportunities students encounter in open-ended invention projects. The study was conducted in a class where a fifth of students identified SEN. Thirteen student teams aimed to design and construct technological inventions to tackle everyday challenges. Students had a high degree of freedom in their invention processes, which influenced their learning opportunities. The results of the first research question revealed that the students' inventions represented physics-intensive and non-physics types. Even though the mean of the pre-test scores did not differ between the physics-intensive invention group and the non-physics invention group, the second research question indicated that the post-test score mean was higher in the physic-intensive invention group, with medium effect size. The analyses regarding the third research question indicated that the students had diverse disciplinary and interdisciplinary learning opportunities during their invention processes.

In traditional STEAM projects, all students usually have the same science learning topic, which the teacher can easily identify and evaluate (e.g., English & King, 2015). In open-ended invention projects, however, students have the opportunity to make inventions according to their own interests, which leads to working with different inventions and different science topics. This makes it challenging for the teacher to identify and support discipline-specific learning. We uncovered this variety through a co-occurrence analysis of the process portfolios that detailed the interdisciplinary science learning opportunities, especially for the non-physics invention teams. Several science topics were identified in the non-physics invention teams' process portfolios, e.g., physical material properties and engineering design. Following the student teams' processes from the invention portfolios enabled us to identify how interdisciplinarity was present when students were involved in solving the invention problem. This observation is in line with, for example, the findings of Bevan (2007) and Marshall and Harron (2018).

The results suggest the importance of the teachers' role in ensuring that students have opportunities to learn science core ideas during their projects (e.g., Blumenfeld et al., 1991), especially in mixed-ability classrooms (Sormunen & Viilo, 2022). In the present study, the students were not necessarily aware that they were meant to learn specific science content. Although students may understand a phenomenon or its underlying processes, they usually cannot explain or apply the science knowledge without guidance (Bamberger et al., 2010; Sormunen et al., 2020). Especially considering the results of this study and the physics intensity of the inventions, the teams with SEN students would have benefited from more intensive learning process support from the teacher when selecting the problem to solve through technology invention. If one wants to ensure the learning of all students, the teacher should strive to introduce science content more effectively to mixed-ability teams (see Sormunen & Viilo, 2022). Previous research has shown that peers can support each other during the learning process in mixed-ability groups (e.g., Sormunen et al., 2020). In this study, however, students were allowed to form groups according to their interests, so teachers did not consider the peer-support aspect when creating the teams.

Conclusions

The study resulted in two important findings about science learning in a collaborative invention project. First, the results indicated that the science learning opportunities are manifested in various ways in diverse collaborative invention projects. It is noteworthy that four of the six non-physics invention teams made use of several of the core tenets of (interdisciplinary) science and used scientific and engineering practices. However, the pre- and post-tests suggested very limited physics disciplinary learning. Thus, there are diverse opportunities to learn science during a nonlinear invention project. A second finding is that, when focusing solely on the physics test results, it seems that while working in diverse teams, students cannot fully make sense of or conceptualize the phenomena when inventing. However, the process portfolios revealed rich opportunities for science learning in all except two invention teams (the Imaginary Toilet Seat and Keyholder). Future research may consider examining science learning in various ways across projects with different durations. Moreover, the role of a teacher, e.g. in scaffolding and project orchestration, should be better planned (c.f. Lehrer, 2021; Sormunen & Viilo, 2022).

As noted previously, there is an evident need to equip future generations with the science knowledge and transversal competencies to tackle our shared global challenges. Here, we have stressed the need for further research on invention projects that could further that goal. Such research would be crucial for providing teachers with the tools needed to guide students in learning science, and especially in gaining richly interdisciplinary science learning opportunities - opportunities to learn to apply technology and to contribute to our future challenges.

Abbreviations

EDR	Educational Design Research
FNAE	Finnish National Agency of Education
ITR	Item Response theory
OECD	Organization for Economic Co-Operation Development
SEN	Special educational needs
STEAM	Science, Technology, Engineering, Arts, and Mathematics
UNESCO	United Nations Educational, Scientific, and Cultural Organization

Supplementary Information

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Additional file 1. Schematic structure of the maker-centered co-invention project.

Additional file 2. Test items and IRT analysis.

Additional file 3. Analysis categories and codes.

Additional file 4. The frequencies of expressions related to learning opportunities.

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Authors' contributions
KS was responsible for the study design, data collection, data analysis of process portfolios, and writing of the manuscript. SV was responsible for the data analysis of the essays and pre- and post-tests, and the writing of the manuscript. KS and SV contributed equally to the study. KJ, JL, and PSH were responsible for the study design, interpretation of the data, and writing of the manuscript. KH was responsible for the study design and revising the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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