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DEVELOPMENT ARTICLE

DUDA: a digital didactic learning unit based on educational escape rooms and multisensory learning activities for primary school children during COVID-19 lockdown

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Abstract
The COVID-19 pandemic has accelerated digitization, access to IT resources, and digital inclusion in the Italian school system. This paper presents D-UDA (i.e., "*unità didattica di apprendimento digitale*", in Italian), a digital didactic unit for learning mathematics concepts. The presented approach combines teaching methodologies and game-based activities (e.g., the escape room) with a multisensory approach to designing and developing digital and multimodal technologies. D-UDA is divided into two parts: the first part consists of logic puzzles that adhere to the guidelines set by INVALSI (the Italian *Istituto Nazionale per la Valutazione del Sistema educativo di Istruzione e di formazione*) for mathematics learning, while the second part involves a series of multisensory games designed to promote the development of transversal competencies, such as cooperation and engagement. Moreover, D-UDA encourages children to create their own adventure using the same tools employed by the designers to develop the experience. The children who participated in testing D-UDA in June 2020 were asked to complete usability questionnaires after the experience. Preliminary results indicate the effectiveness of the educational intervention presented, which integrates recent pedagogical theories and teaching methodologies with a multisensory perspective and a technological design.

Keywords Distance learning · Educational games · Collaborative activities · Mathematical puzzles · Multisensory digital learning games

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Introduction

Digitalization is a necessary process that affects every aspect of our life, from business and industry (Andal-Ancion et al., 2003), to healthcare (Agarwal et al., 2010) and education (Bogdandy et al., 2020). The role of digital transformation is not just to enhance traditional solutions but to lead to innovative approaches, especially in the educational field (Maity et al., 2021; Robbins et al., 2020).

The COVID-19 pandemic has represented a point of acceleration in rethinking new learning experiences and the digitalization of education because both learning and teaching have witnessed a procedural transformation. Education was adapted to digital forms to guarantee the continuity of education and teachers started to deliver lectures digitally to prevent students from attending classes physically. Nevertheless, there was a lack of solutions fostering mutual learning among children, especially in the case of social and economic differences, and the inclusion of sensory impaired (e.g., blind or deaf) students through multisensory experiences.

To fill this gap, we proposed a novel multisensory digital didactic learning unit (DLU) for the primary schools in the area of Genoa, Italy. With the term multisensory for the activities presented in this paper, we refer to games providing audio-visual sensory feedback. The project was centered around three principal teaching methodologies: problem-based learning, game-based activities, and cooperative learning. The DLU's development was based on the escape room model, conceived on mathematical concepts and to be played in a virtual archeological site. We thus created D-UDA (i.e., "*unità didattica di apprendimento digitale*", in Italian) that was offered to schools during the first Italian lockdown in 2020. D-UDA, as an online game-based learning unit, was integrated in the curriculum children were involved in, in accordance with a didactic plan made in advance with the teachers of the classes involved in the experiment. Analogously, it can still be easily integrated in the school programs, since it is based on the Italian national curriculum for learning mathematics in the fifth year of primary school.

Background

Multisensory and experiential learning overview

In the last twenty years, there has been a progressive change in the school system, which has seen the transformation of curricular practices from an approach based on learning to one based on competencies, of which the DLU is the privileged tool. The European Council defines competencies as "those which all individuals need for personal fulfillment and development, employability, social inclusion, sustainable lifestyle, successful life in peaceful societies, health-conscious life management, and active citizenship" (Council Recommendation of 22 May 2018 on key competences for lifelong learning (Text with EEA relevance) (2018/C 189/01)). Nevertheless, despite the flourishing of multiple didactic innovation models in the last century, the traditional frontal lesson is still one of the most common teaching practices. Frontal classes, however, primarily focus on the teacher and exclude students from being active co-builders of their knowledge. Furthermore, scholarly lessons are mostly rendered visually, thus ignoring the benefits of multisensory learning (Ahissar & Hochstein, 2004; Barrett & Newell, 2015), even though many studies highlight the importance of sensory-motor integration and interaction with the external environment for functional cognitive development (Piaget & Duckworth, 1970; Vygotsky, 1978). Moreover, recent studies show the importance of multisensory and embodied learning in primary schools, especially for mathematics and science (e.g., Gori et al., 2021; Manches & O'Malley, 2016; Özkaya et al., 2024; Taljaard, 2016). Multisensory (or multimodal) learning is a concept widely used in different scientific areas, often without a real distinction between the terms "multisensory" and "multimodal". The idea behind this concept is that our everyday experience constantly involves multisensory stimulation. For instance, many of the tasks we perform without even noticing them require an integration between visual and auditory information. Already back in 2008, Shams and Seitz suggested that unisensory stimulus might not be optimal for learning (Shams & Seitz, 2008). Thus, for multisensory or multimodal learning we refer to an embodied learning situation based on multiple sensing systems engaging and interacting together and action systems of the learner, as stated by Massaro (2012).

Reflection on multisensory stimulation inevitably brings with it the need to confront a further area of scientific literature, which is that of experiential learning. Experiential learning is an engaged learning process whereby students "learn by doing" and by reflecting on their experience (e.g., Kolb & Kolb, 2009). Experiential learning theory defines learning as "the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience" (Kolb, 1984). For reasons of space, the authors cannot elaborate further on the examination of experiential learning theories, but refer to the literature on the subject (e.g., Ambrose et al., 2010; Burch et al., 2019; Linn et al., 2004; Moore, 2010). The development of research on the topics of multisensoriality, and multimodal and experiential learning has consequently led to a growing interest in these topics, especially in the field of educational and multimodal technologies (Dağhan & Gündüz, 2022).

Game-based activities, engagement, and participation in educational technology

Engagement stands as a cornerstone of academic success, proving indispensable within educational realms. Its dynamics are influenced by a myriad of factors, ranging from classroom atmosphere to students' prior engagement experiences and their inclination to participate in activities (Dunleavy & Milton, 2009; Olugbade et al., 2017). In both popular discourse and scholarly circles, engagement encapsulates traits often found lacking in modern students, notably dedication and active involvement. Scholarly discourse further delineates engagement as a complex construct, comprising three essential dimensions: behavioral, emotional, and cognitive engagement (Fredricks et al., 2004). Behavioral engagement builds upon the concept of participation, encompassing involvement in academic, social, or extracurricular pursuits, and is widely recognized as pivotal for nurturing positive academic outcomes and curbing dropout rates. Emotional engagement encompasses a spectrum of attitudes toward teachers, peers, academics, and the school environment, with its presumed impact on fostering a sense of belonging and influencing academic task engagement. Finally, cognitive engagement, rooted in commitment, entails thoughtful effort and readiness to grapple with intricate concepts and master challenging skills.

Motivation is also seen as a pre-requisite of students' engagement in learning, defined as the extent to which students put effort into and focus on learning to achieve their outcomes successfully (Meyer, 2010; Ryan & Deci, 2000). Saeed and Zyngier (2012) stated that intrinsic motivation is associated with authentic students' engagement and that the latter does not only refer to complete their learning tasks, but put effort and concentration in understanding of the contents (Newmann, 1992). Recent research has shown how it is possible to increase academic motivation through appropriate strategies to avoid negative feelings such as boredom or anxiety which might lead to the complete abandonment of the task proposed by the teacher (Chanel et al., 2008).

In this context, appropriate technologies are the most indicated tools to foster behavioral engagement and promote activities that can facilitate cooperative and learning outcomes. A novel approach to developing new collective learning experiences and methods consists of introducing multimodal kinesthetic technology and serious games in education. The incorporation of game-based activities in the classroom emphasizes anticipation, self-confidence, and enjoyment through play (Adams & Dormans, 2012). Furthermore, these games are intentionally crafted to boost interactivity among students by facilitating active, problem-based, and experiential learning (Oblinger, 2004). They encourage students to actively participate and employ cooperative learning techniques to foster collaboration, ensuring their continuous engagement in problem-solving and experiential learning throughout gameplay. Specifically, D-UDA offers modules that enable direct interaction with the content, incorporating multimedia elements like videos, interactive quizzes, drag-and-drop activities, games, tools, and simulations, all aimed at providing an immersive and dynamic learning experience.

Among the various game-based experiences, the one that has been chosen for this project is the escape room format. Escape rooms are collaborative games in which groups of people find themselves locked in a room. To exit, the participants must explore the environment while searching for cues and solving a series of logic enigmas in a fixed time. Digital escape rooms are modern educational tools that offer various benefits, including enhanced engagement, collaboration, and flexibility for customization to specific learning objectives. In educational settings, digital escape rooms have shown effectiveness in enhancing scholar outcomes (Fotaris & Mastoras, 2019; Makri et al., 2021; Veldkamp et al., 2020). These are the main reasons why we decided to use this format.

James Sanders and Mark Hammons applied for the first time the escape room-based model in an educational context (Martens & Crawford, 2019). The two teachers developed the open-source Break-Out EDU project where students open boxes locked by padlocks, discovering codes by solving puzzles (Rouse, 2017). We applied this format also to design some of the activities in D-UDA. Specifically, we relied on the EscapED theoretical model conceived at Coventry University (Clarke et al., 2017) and on the theories by Nicholson (2015) about the ways that puzzles can be organized: open, sequential, or path-based puzzle organization. We applied the sequential structure, where players must solve the puzzles one at a time, and the final puzzle allows them to win the game. Furthermore, the methods chosen for the educational experience were game-based activities, on the one hand, and cooperative learning, on the other one.

For what it concerns findings about game-based mathematics learning, literature encompasses many studies (e.g., Byun & Joung, 2018; Hwa, 2018; Tokac et al., 2019; Vankúš, 2021). The meta-review by Tokac et al. (2019) reveal that videogames may be slightly effective as an instructional strategy for teaching mathematics to PreK-12 grade levels. Analogously, a similar result was found by Byun and colleagues. Both the meta-reviews, however, lack of numerosity of the papers included in the study, due to a lack of homogeneity in the methodology used in the studies on digital game-based learning. Brezovszky and colleagues (Brezovszky et al., 2019) tested the effects of a game-based learning environment in supporting primary school students' adaptive number knowledge and related arithmetic skills. Their findings suggest that the experimental group outperformed the control group on adaptive number knowledge and math fluency. Results show varying effects of the training in different grade levels, with more pronounced improvement of students' adaptive number knowledge in grade five. Game performance was related to the experimental group's post-test scores even after controlling for pre-test scores and grade. Hung et al., (2014) presented a mathematical game-based learning (GBL) environment to support children in reducing learning anxiety and improve learning motivation, their self-efficacy, and coherently their mathematical achievements. Results are positive for the experimental group that used the GBL environment, while no differences are found between the experimental and control groups for what it concerns mathematics anxiety.

The dimensione L'UDA project: problem, definition, and scope

The D-UDA experience drew inspiration from the *Dimensione L'UDA* project, which started in January 2019 and finished in the first months of 2023. The project aimed to promote school inclusion, by addressing the issue of drop-out and isolation among children with special educational needs in low social contexts within the metropolitan area of Genoa, Italy. Built upon the participatory action research (PAR) framework as outlined by Walker (1993), Dimensione L'UDA integrated intervention, training, and research components. It centered entirely on the concept of a playful learning environment, which was further developed through the digital learning universe (DLU). At its core, the project engaged 4th and 5th-grade students through a playful DLU experience initiated in the classroom, where students engage in activities aligned with their scholar curriculum. Then, the experiences were extended to an archaeological site situated in the historical center of Genoa, where ad hoc designed multisensory activities involved the children, incorporating not only visual elements but also sounds and bodily movements. As a result, students have the flexibility to utilize their preferred sensory modality to solve the games, thus promoting social inclusion for all children, including those with sensory disabilities such as blindness or deafness. These serious-games were based on the use of full-body multimodal technologies that enrich the archeological site.

As done in Dimensione L'UDA, we also recruited teachers as spokespeople from the established institutions. The first subject to test this methodology was mathematics, following teachers' indications of difficulties found in their experience. As we already mentioned, when during Spring 2020 the national lockdown caused by the COVID-19 pandemic required teachers and students to have lessons remotely, we re-designed the escape room for the archeological site in a digital playful didactic unit, which resulted in D-UDA.

Activities definition and pedagogical support

The research goal of this work is to address the gap in digital educational solutions by proposing a novel multisensory DLU for primary schools, aimed at fostering mutual learning among children, regardless of social and economic differences, and promoting the inclusion of sensory-impaired students through multisensory audio-visual activities.

The D-UDA experience was divided into two parts: the virtual classroom and the virtual archeological site. We took, as a reference, the Italian primary school 5th-grade learning and academic objectives in three areas: numbers; space and figures; relations, data, and forecasts (Cerini et al., 2012).

For the design of the activities and the puzzles of the virtual classroom, we followed the scheme of the "INVALSI National Tests," whose reference framework is partially in line with that of the TIMMSS and PISA surveys (INVALSI: the reference framework of the tests of mathematics of the national evaluation system,[1] see Tables 1–3 in the Supplementary Material Section). The activities presented in D-UDA are simple logic and mathematics games, developed following workshops with primary school teachers to ensure that all students, regardless of their prior mathematical knowledge or learning, could engage with them. To prevent frustration among children who might struggle with the tasks, the cooperative activities in D-UDA were conducted under the supervision of at least one teacher and the experimenter, who intervened and provided guidance in case students encountered difficulties.

We structured the virtual archaeological area activities around multisensory (i.e., audio-visual) educational experiences to enhance engagement and develop transversal skills. These skills include visual and auditory short-term memory, eye-hand coordination, rhythm training inspired by Stamback's methods, and logical reasoning. Specifically, with D-UDA, our aim was to highlight the effects of such activities on teamwork and, consequently, their potential to enhance students' behavioral engagement.

The D-UDA activities follows a meticulously structured virtual pathway, mirroring the activity in the Dimensione L'UDA project, which was never fully executed due to the COVID-19 pandemic. They start with the classroom activities where children engage in games that enhance their logical and linguistic skills. Then, they move to the virtual archaeological site, where children are involved in activities emphasizing mathematical abilities, while also reinforcing classroom-learned concepts such as the golden ratio or Roman culture. Lastly, at the end of D-UDA, children are empowered to create their own games from scratch, fostering creativity and technological development.

As part of the pedagogical choices, we developed all the activities, games, and narrative components, with completely free and easy-to-use tools to enable children to create their learning units with riddles and escape rooms. Considering the context of lockdown and indefinite school closure, when we implemented D-UDA, our proposal had the pedagogical objective of creating relationships and cooperation, albeit virtual, between the children and facilitating the use of educational contents remotely. Beside the COVID-19 pandemic, an activity like D-UDA has the potential to introduce a new methodology for school learning, suitable also for events such as physical or weather-related impossibility of attending school. By means of a web application, children at home can still have the opportunity to engage and learn with their classmates through collaborative activities like the ones we propose.

Materials and methods

Design process and architecture

D-UDA was developed as an educational digital learning environment. Our purpose was to create a digital product to which the children themselves could contribute by sending us their projects. Thus, we chose to work only with freely available technologies and materials such as the Scratch block-coding environment and the G-Suite from Google to foster the inclusion of children with economic difficulties. The narrative scenario envisioned was an escape room.

[1] Document available at https://invalsi-areaprove.cineca.it/docs/file/QdR_MATEMATICA.pdf.

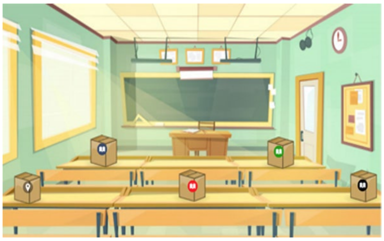


Fig. 1 The virtual classroom. The Figure shows a virtual classroom with boxes that contain the riddles. The image of the classroom was downloaded from a royalty-free website (https://publicdomainvectors.org/). This interactive image was created with Thinglink (https://www.thinglink.com/). Four of the depicted boxes are provided with a virtual button, which displays an open book that, when clicked, brings up the riddle. The box with the position button contains the geographical information of the riddles

Fig. 2 Geographic and historical information. The Figure shows the geographical and historical details of the places described in the riddles hidden in the boxes. Each of the four depicted buttons links to a Wikipedia page that gives information about the ancient Gaul, the Italian town Golasecca, the painting of the destruction of the temple of Jerusalem, and Giza's pyramids (respectively, the red, yellow, green, and white buttons)

We worked primarily to define what interdisciplinary contents could be applied to mathematical subjects. A consistent part of the work was carried out to understand how multisensory input and multimodal associations could be maintained by working specifically on game design and the development of all the activities. We then focused on re-developing storytelling to create a narrative link between all the enigmas. We created a character named Hinrik, a cycling-traveler archaeologist, who would guide the children throughout the experience with short animations and videos.

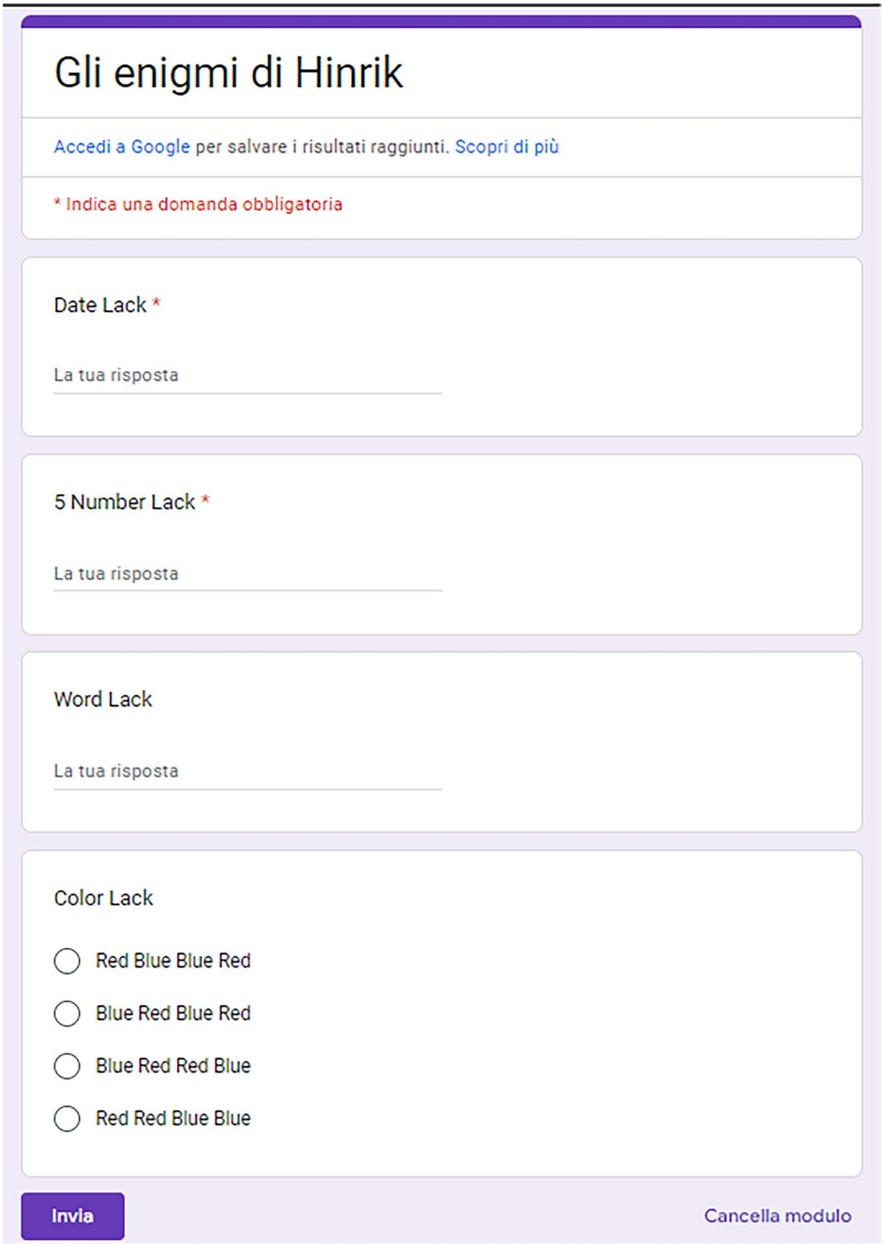
The first part of the experience consists of a series of logical enigmas embedded in boxes to be unlocked in a classroom environment to be coherent with the original DLU (Figs. 1 and 2). In this first part of the experience, children solve all the quizzes through an animated image made in ThingLink.[2] Answers are collected through a Google Form[3] available on the same page of the website (Fig. 3).

The second part of the D-UDA website presents a series of Scratch[4] games to be solved to obtain a second code that links to another escape room, a *domus* (i.e., an ancient Roman house). Lastly, as a connection point between the D-UDA and the original DLU of

[2] https://www.thinglink.com.

[3] https://www.google.com/forms/about/.

[4] https://scratch.mit.edu.


Gli enigmi di Hinrik

Accedi a Google per salvare i risultati raggiunti. Scopri di più

* Indica una domanda obbligatoria

Date Lack *

La tua risposta

5 Number Lack *

La tua risposta

Word Lack

La tua risposta

Color Lack

- Red Blue Blue Red
- Blue Red Blue Red
- Blue Red Red Blue
- Red Red Blue Blue

Invia

Cancella modulo

Fig. 3 The Google Form children used to solve the enigma. The Figure shows the Google Form children used to complete their breakout experience

Dimensione L'UDA, we developed an activity with OpenRoberta,[5] a drag-and-drop visual programming language available online for educational robots coding. Children are asked

[5] https://lab.open-roberta.org/

Fig. 4 "X-Scape Carrugi". This is a snapshot of the OpenRoberta website page created for the "X-Scape Carrugi" activity, in which children are asked to develop an easy program to move a robot from the archeological site at Giardini Luzzati in Genoa, Italy (highlighted as a red square on the map) to the closest subway station (highlighted as a green square)

to program a robot to move virtually from the archeological site to a close subway station (Fig. 4).

Furthermore, we published some walkthrough options for each activity to ensure the possibility of playing alone without the help of classmates, teachers, or caregivers. In such a way, D-UDA can become a helpful tool for distance learning, guaranteeing educational activities remotely.

D-UDA activities

The D-UDA website is available online at the link https://sites.google.com/view/d-uda/. The experience is divided into the virtual classroom and the archeological site.

Virtual classroom

In the first activity of D-UDA, children are asked to solve logical and mathematical puzzles hidden inside the boxes of a virtual classroom (Fig. 1). We developed four enigmas for the virtual classroom experience (Fig. 5), embedded in the boxes with the book symbols depicted in Fig. 1:

- **Enigma 1:** When was Emperor Titus Flavius Vespasian born?
  Purpose: To calculate the age of Emperor Titus. To solve the enigma, children have to use the Caesar's cipher to decipher a text and solve the logical-mathematical problem.
  - **Dimensions:** Knowing, arguing
  - **Areas:** Numbers, Data and forecasts/Relations and functions
  - **Achievements:** Codes T1, T7
- **Enigma 2:** The pearls of the woman from Golasecca.

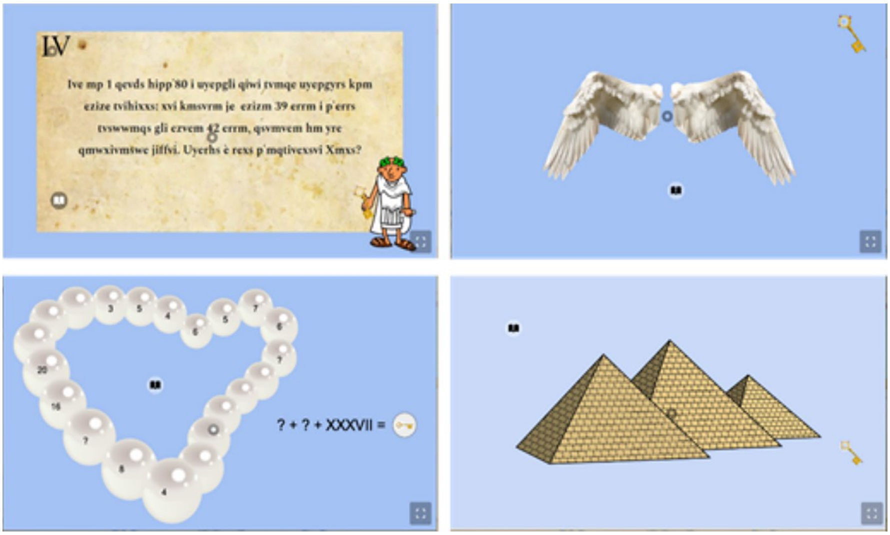


Fig. 5 The riddles hidden inside the boxes. The Figure shows the four riddles hidden in the boxes. Each puzzle is provided with three virtual buttons: a golden key, a gray circle (one or two), and an open book. When pressed, the golden key shows the clues and, ultimately, the solution to solve the puzzle. The book refers to the riddle's text, while the gray circle refers to an additional activity (a game or a puzzle) that helps to solve the riddle. From left to right, the puzzles are named: *When was Emperor Titus Flavius Vespasian born?*, *Messages from Ancient Gaul*, *The pearls of the woman from Golasecca*, and *The colored pyramid*

Purpose: To find out the number of pearls in the necklace by finding the missing digits of a sequence and by solving an equation with Roman numerals to be converted into Arabic numbers.

– **Dimension:** Knowing, arguing
– **Areas:** Numbers, Data and forecasts/Relations and functions
– **Achievements:** Codes T1, T7

- **Enigma 3:** Messages from the ancient Gaul.
  Purpose: To convert a message into a code. Children compose a puzzle, solve anagrams with visual clues, and form a word with the first letter of each word highlighted.

  – **Dimensions:** Solving problems, arguing
  – **Areas:** Space and figures, Data and forecasts/Relations and functions
  – **Achievements:** Codes T2, T7

- **Enigma 4:** The colored pyramid.
  Purpose: To complete the pyramid with the correct sequence of colors by following a logic schema.

  – **Dimension:** Knowing, solving problems, arguing
  – **Areas:** Numbers, Space and figures, Data and forecasts/Relations and functions
  – **Achievements:** Codes T1, T2, T7

Achievement codes: see Table 3 in the Supplementary Material Section about Achievements based on the INVALSI framework for the 5th grade primary school students for the mathematical curriculum.

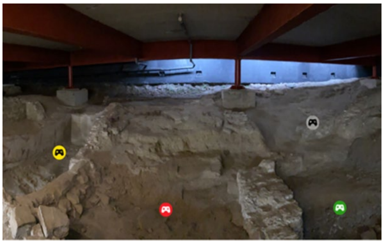


Fig. 6 Archeological area of Giardini Luzzati, Genoa (Italy). The Figure shows the archeological area of Giardini Luzzati in Genoa, Italy. The area is divided into four sites, each marked by a joystick that represents a link to a Scratch game

The box marked with the location symbol is an interactive image containing the geographical and historical details of the riddles listed above (Fig. 1).

Virtual archeological site

This part of the digital activities consists of Scratch interactive games based on multisensory associations and discriminations concepts. We used ThingLink to recreate the actual archeological environment (Fig. 6). After children complete the games, they receive a puzzle piece created with an online free tool (i.e., the JigSaw website[6]). The final puzzle represents a feather, which is the secret word necessary to proceed to the last part of the adventure.

These activities are imaginarily proposed, coherently within the original project, in the archeological area of Giardini Luzzati in Genoa (see Fig. 6 for details). The area is divided into four sites, each connected to a Scratch game[7]:

- **Archeo-Dobble, yellow joystick.** We took inspiration from the card game Dobble.[8] In each round, players select two cards and must find the only figure presented on both cards as quickly as possible. In the Archeo-Dobble, the images represent archeological finds of the area and illustrations as visual stimuli. We set a fixed time (one minute) to complete the game (Fig. 7). Each game begins with an introductory part that explains the rules and, at the end of the activity, a piece of a puzzle is assigned. These pieces are then used to compose a feather, using the JigSaw website[9] that will unlock the last action of D-UDA, the virtual escape room, made with Scratch too. In this game eye-hand coordination is at play because participants have to identify common figures in two circles and select them using the mouse.
- **Archeo-Memory, gray joystick.** The game is a multisensory version of the standard game "Memory". The child has to find all the coupled cards by matching visual and acoustic stimuli. Each card is indeed associated with a sound (a letter) that is reproduced when the card is turned over. This game works on visuo-audio memory abilities.
- **Beat the Rhythm, red joystick.** In this game (Fig. 8), a digital version of Stambak's rhythmic tests (Stamback & Zazzo, 1992) is presented. The game shows five cards, colored differently and associated with different musical values printed on the card. At each round, a rhythmic pattern is played composed of flash cards. The cards flash for

6 https://www.jigsawplanet.com/?rc=play&pid=3ef3470bccb6.

7 https://scratch.mit.edu/search/projects?q=ericavolta.

8 https://www.dobblegame.com/en/homepage/.

9 https://www.jigsawplanet.com/?rc=play&pid=3ef3470bccb6.

Fig. 7 Archeo-Dobble. Both cards share a common element: the child has to locate and select items from a list displayed at the bottom of the screen within a specified time frame (1 min) to identify as many pictures as possible

Fig. 8 Beat the Rhythm. The game is a digital version of Stenbak's rhythmic test, in which the child has to remember the sequence of rhythmic and visual patterns randomly reproduced by the game

a certain number of times and a percussive rhythm is reproduced simultaneously with the flashes. The child has to indicate the correct cards' number sequence. Each round presents a one-step longer sequence than the previous one.

- **Fibonacci Music, green joystick.** In this game, children discover the logic behind the numerical sequence of Fibonacci, its relationship with music, and the harmonic forms present in nature. The game requires to build the sequence step by step by relying on the mathematical-music association. We created a musical scale based on the natural harmonic scale: in acoustics, the numerical relationship between the natural harmonics in the different octaves of a scale is indeed a golden relationship, which therefore directly links to the Fibonacci sequence. At each round, the child is asked to choose the next item in the sequence among three different numbers (Fig. 9, left image). In the left upper part of the screen, the last and second-to-last numbers of the series are presented.

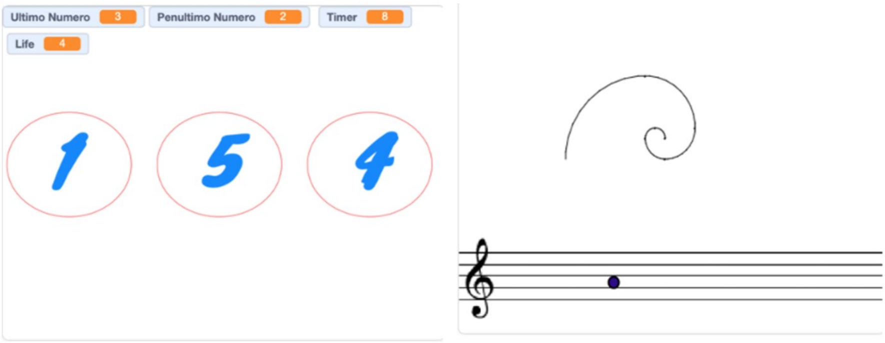


Fig. 9 Fibonacci Music. In this game, children have to identify the correct following number of the Fibonacci sequence. The last and second-to-last numbers are presented in the left upper part of the screen. The spiral representation of the sequence (on the right) and the musical notation of the sound stimuli are presented in Fibonacci Music to suggest to the children that they will discover real examples of the relationship between numbers and sounds at the end of the game

Fig. 10 Domus Escape. A Scratch escape room based on the illustration of an ancient Roman house. Riddles and activable objects are disseminated in the space (e.g., lyra and drum instruments, scrolls, and the key)

When the correct option is chosen, the child sees a spiral while hearing the corresponding sound (Fig. 9, right image). At the conclusion of the game, a detailed explanation is provided to the children, illustrating the connection between the sounds they heard during the game, which belong to the natural harmonic scale, and the Fibonacci sequence. This elucidates the reason why the game was based on the spontaneous association between the acoustic sequence of the harmonic scale notes and the progression of the mathematical sequence.

Domus escape

Domus Escape is an escape room based on the idea of being locked in a Roman *domus* (see Fig. 10). We used a cartoon illustration of an authentic Roman home reconstruction, and we hid a series of riddles and animated objects in the scenario. Exiting from the Domus, children are introduced to the last section of the website: "X-Scape Caruggi".

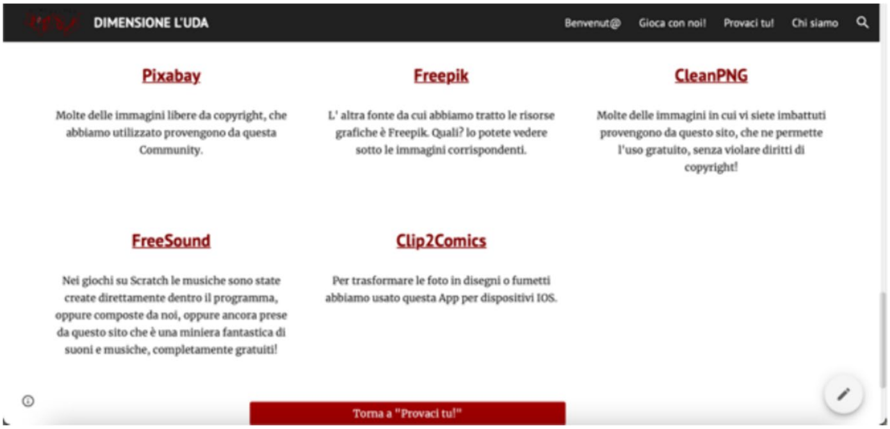


Fig. 11 The DIY page. This page of the D-UDA website is presented to the children at the end of the experience, to invite them to create their games and materials

X-scape caruggi

We used OpenRoberta lab, a website offering a drag-and-drop visual programming language for educational robots coding, to engage students in programming a robot and guide it from the archeological site, in the historical city center of Genoa, to the closest subway station. We preloaded the program to ease children's and teachers' approach to this environment (Fig. 4). This activity is intended to be a class-based work, allowing children to work together, even remotely, with the support of their teacher.

Open challenge: do it Yourself (DIY) your escape rooms!

At the end of all the activities, we listed the free online tools used to design and program D-UDA. We published the hyperlinks and descriptions to those services, thus encouraging the children to create their games and send them to us (Fig. 11).

Data collection and analysis

Participants

We recruited fifty-four fifth graders from four different classrooms involved in the Dimensione L'UDA project. None of the participants submitted incomplete surveys, but only forty-four of the kids completed the questionnaires at the end of the sessions. Therefore, only their responses were considered in the analysis. Informed parental written consent was obtained for all the participants.

Procedure

Three of the four classrooms surfed the website remotely connected with the classmates and the teacher during the scholarly hours. Only one classroom (17 children) was involved in the "flipped" experience. The students navigated D-UDA, and the day after, they repeated the experience together with the teacher and the other classmates. At the end of the experience, both groups were presented with the "classroom questionnaire" (18 questions), filled out by all students. Instead, the "flipped questionnaire" (9 questions) was given only to the children involved in the flipped experience. Both questionnaires were administered using Google Forms, and the children were instructed to fill them in as soon as both activities ended. The questions presented in the surveys match specific usability and self-assessment statements. To the best of our knowledge, no survey for primary school children considering mathematical learning, multimodal technology usability, and self-perception of learning was available in the literature at the time of the evaluation; for this reason, the questions were not well-established, but the questionnaires were created ad hoc by the authors, based on literature findings. Mainly, for the usability issues of multimodal technologies, we deeply based our questions on (Darin et al., 2018) and for the psychological and educational processes we grounded on SSWQ, Student Subjective Wellbeing Questionnaire (Renshaw et al., 2015) and on Amos 8–15, Study Motivation Questionnaire (Cornoldi et al., 2005). The first six questions listed in the classroom survey investigate the sense of belonging to the classroom and the perception of one's value as an individual and student. Indeed, there exists a strong correlation between a positive school climate and academic achievement (MacAulay, 1990), which can even counterbalance the adverse effects of a low socioeconomic status (SES) background (Berkowits et al., 2017). Additionally, positive psychological factors, such as having a growth mindset, play a pivotal role in motivation and achievement (Dweck, 1986, 2015), along with appropriate attribution processes (Weiner, 1972). The other 12 questions match specific usability statements, such as working in a group or navigating and understanding the website quickly. The items listed in the flipped questionnaire refer to the ability to navigate D-UDA and learn new concepts, along with the difficulties encountered in distance learning. The children rated the statements using a 4-point Likert-type scale (1 = Strongly Disagree, 2 = Somewhat Disagree, 3 = Somewhat Agree, and 4 = Strongly Agree).

Data analytic approach

All the analyses were carried out in RStudio (RStudio 1.3.1093). The answers to the surveys were analyzed using an exploratory factor analysis (EFA) to extract the scale's underlying factor structure. EFA is a statistical technique that groups items related to a common underlying factor (Preacher & MacCallum, 2003). When elements are thought to cause ratings, factor analysis constitutes an appropriate way to explore the data (Teasley & Buchanan, 2013). Under the correlation hypothesis among the factors, we used oblique rotations (*oblimin*). The number of factors was selected based on the results of the scree plot and the parallel analysis. For each question of the two surveys, we analyzed the loadings that indicate the correlation between the variables and the factors, to extract the simple structure. The latter is obtained when each item loads on just one factor in the analyses. We wanted things to load only on one aspect, and we set the minimum loading of the variables on an element to .30, based on previous literature (Preacher & MacCallum, 2003). The questions that did not fulfill the criteria mentioned above were discarded. Indeed, items with loadings over .30 on multiple factors were considered to "split" (Preacher & MacCallum, 2003), which would thus lead to exclusion.

Maximum likelihood estimation was used to calculate question loadings for each analysis. To assess the model fit, we used the following metrics:

- The root mean square of error approximation (RMSEA) (Jöreskog & Sörbom, 1982; Steiger, 1990). Low values of this index show good model fit (< .06 excellent, < .10 moderate fit) (Browne & Cudeck, 1993).
- The Tucker-Lewis Index of factoring reliability (TLI) and the comparative fit index (CFI) (Bentler & Bonett, 1980; Tucker & Lewis, 1973). Contrary to the RMSEA, high values of TLI and CFI indicate good model fit (> .90) (Bryant & Yarnold, 1995).

We also calculated Cronbach's alpha (< .70 is considered poor) for the two surveys to assess their reliability, that is particularly important for scales with few items. The scores of the classroom questionnaire were compared between the children involved in the flipped experience and the children involved only in the classroom experience. Seventeen children filled the flipped survey in, but seven of them did not send back the classroom questionnaire. Finally, we calculated the coefficient of variation (CV), that is the ratio between the standard deviation (SD) and the mean of the sample, the lower the value of CV, the more precise the estimate. In detail, distributions having a coefficient of variation smaller than one are considered low variance, whereas those with a CV bigger than one are regarded as high variance. Thus, the lower the CV, the closer the points are to the average (Setti et al., 2021). This value helped us understand whether the score points were close to the global average.

Results

We initially checked missing information, multivariate assumptions, and outliers (using Mahalanobis distance as a criterion). We found neither outlier nor missing information, and all the other premises were satisfactory. We designed the advising scale for the classroom questionnaire to examine usability, sense of belonging to the class group, and interest in learning new concepts.

Parallel analyses and scree plot examination indicated that two and three-factor models would be the most appropriate for the set of the classroom questionnaire items. We first ran the three-factor model. Ten out of 18 questions loaded cleanly on only one factor. Six of the remaining eight questions were removed because they double loaded on more factors or did not load on any factor. After the removal of these items, we noticed that the third factor was composed of only two questions, both referred to the desire and the possibility to learn new things (*I think it is hard for me to learn new concepts* and *Do you think that learning computer programming now will be useful in your future?*). Therefore, we removed them from the list, and the parallel analysis was re-run with only two factors (see Table 4 in the Supplementary Material Section for details). The removed items are listed at the bottom of Table 4. Factor 1 reflects questions about group membership and the sense of belonging to the classroom. We thus named it "Sense of group belonging". Factor 2 instead contains questions regarding the usability of D-UDA and the ease in the navigation of the website therefore it was named "Usability in-group". The reliability for factors 1 and

2 was measured with an α of .80 and .84, respectively. The mean score for Factor 1 was 3.27 (SD = .62, CV = .19), while for Factor 2, it was 3.25 (SD = .6, CV = .18). We did not find any significant difference between the two groups for both Factor 1 (Wilcoxon signed-rank test: zval = 1.25, p = .22) and Factor 2 (Wilcoxon signed-rank test: zval = .42, p = .66). Regarding the second questionnaire, the parallel analysis and the scree plot indicated two factors as the most suitable model (see Table 5 in the Supplementary Material for details). In this case, Factor 1 reflects the effect of the actual pandemic on learning new concepts in remote (i.e., through D-UDA). We thus named Factor 1 "Distance learning ease." Factor 2 instead refers to the website's usability that, in this case, was surfed by the children while at home without the help of the teachers and the other classmates. We named Factor 2 "Alone usability". The reliability for factors 1 and 2 was measured with an α of .73 and .76, respectively. The mean score for Factor 1 was 2.63 (SD = .32, CV = .12) while for Factor 2 it was 3.21 (SD = .53, CV = .16). Table 6 in the Supplementary Material section shows the fit indices for both surveys.

Conclusions

This paper presents D-UDA, a website solution for distance learning units based on multisensory technologies combined with game-based activities. Our pedagogical and technological approach starts from the scientific literature supporting the design of innovative educational interventions. We also show the results obtained from an evaluation conducted with children after the D-UDA experience. They are encouraging, thus demonstrating a positive impact of this proposal for children's involvement, even remotely. Furthermore, the low CVs values (i.e., less than 1) indicates that score points are close to the global average, thus suggesting that the ease of D-UDA navigation is perceived similarly across children.

Even though the data collected so far are not sufficient to generalize our conclusions due to the small sample size, results indicate that children could easily navigate D-UDA alone in the flipped experience and in the group (i.e., an average score above 2, see the Results section).

In addition to the small sample size, the limitations of D-UDA lie in the lack of control over how the flipped activity is carried out by the children, as well as the fact that the tools used are very basic and not easily usable on all browsers. Future research may involve redesigning the website using more scalable tools and developing games specifically aimed at reinforcing scholarly concepts. This could help determine whether D-UDA has a significant impact on how children learn academic subjects. Additionally, future studies may investigate whether D-UDA could serve as a valuable training tool for the archaeological experience, as originally intended in the Dimensione L'UDA project.

The results of this study provide valuable insights for future game-based learning design and implementation, especially concerning the integration of teaching methodologies with game-based activities like the escape room concept. Additionally, D-UDA activities align with educational standards and promote the development of essential skills through multisensory gaming experiences. These features can inspire designers and researchers to explore similar approaches, creating engaging learning experiences that leverage the benefits of multisensory game-based activities to accommodate diverse learning styles and preferences more effectively.

In conclusion, we believe that the presented website may serve as an effective solution to help students cultivate collaborative learning skills in remote learning settings. Furthermore, D-UDA was developed using freely available tools accessible to children from all social and economic backgrounds, thereby promoting social inclusion in educational environments.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11423-024-10407-4.

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Data availability The only data concerns the questionnaire the children filled in at the end of the experience. For legal reasons, usage of such data is restricted to the team who conducted the research.

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