International Journal of Serious Games
ISSN: 2384-8766
https://journal.seriousgamessociety.org/

Article

Activity Theory in Digital Game-Based Learning: A Geometry Case Study

Oriol Sors, Anna Puig[1], Inmaculada Rodriguez[2]

Department de Matemàtiques i Informàtica, [1]IMUB Research Institute, [2]UBICS Research Institute
Universitat de Barcelona, Barcelona, Spain;
{*annapuig, inmarodriguez*}@*ub.edu*

Keywords:
Activity Theory,
Digital Game-Based Learning,
Serious Game,
Geometry learning

Received: November 2024
Accepted: April 2025
Published: May 2025
DOI:10.17083/ijsg.v12i2.916

Abstract

Digital Game-Based Learning (DGBL) is a complementary methodology to traditional instruction, yet it often faces conceptual and practical limitations in evolving educational environments. These include the closed nature of games and a narrow focus on single competencies. To address these challenges, this study explores DGBL through the third generation of Activity Theory (AT) and applies the Expansive Learning framework. Specifically, we investigate the following research questions: RQ1: *"How does Expansive Learning designed in a game influence the learning experience in terms of learning outcomes and engagement?"*, and RQ2: *"How do game challenges created by students impact their peers' learning experience?"*. To answer these questions, a quasi-experimental study was conducted with secondary students, including a control group (players) and an experimental group (players+creators), using GeoBuild, a geometry game based on Expansive Learning principles. Learning outcomes were assessed via pre- and post-tests, motivation and enjoyment through questionnaires, and engagement using in-game analytics and qualitative feedback. Although all students improved their learning outcomes, the control group outscored the experimental group in the final exam. However, they made more errors in peer-created challenges, which were harder than those set by the teacher. Challenge completion rates were similar, and students found the experience engaging, suggesting promising grounds for further research.

1. Introduction

Activity Theory, AT, is a framework for analysing human activities in dynamic contexts involving *subjects*, *purposes*, and *tools*. It has been applied in fields such as information systems [1] [2], health [3], and education [4] [5]. Rooted in Vygotsky and Leontiev's cultural-historical psychology [6] [7], AT was later expanded by Engeström [8] [9] [10] [11], who introduced the second generation of AT. This generation added rules (social conventions) and division of labour (task allocation based on skills and tools), emphasizing the community aspects of activities.
Engeström developed the Expansive Learning (EL) theory, or the third generation of AT [10], which analyses innovations through two interconnected activity systems (AS). Schuh et al. [12] applied this approach to studying e-textbooks, highlighting their role as a learning mediator between teachers and students rather than a learning object on which each actor acts independently. Moreover, *EL* explored subject dynamics, revealing new ways to analyse agency, experience, and emotion.

Engeström also introduced *Expansive Learning* as the movement in the zone of proximal development, which consists of the historical analysis of certain criteria that can be charted to identify the contradictions that should be solved in the activity system. He viewed contradictions as the driving force of change, manifesting as tensions, conflicts, dilemmas, or breakdowns [13] [14]. In education, they appear in limited infrastructure and teacher training, incorrect pedagogy models, assessment, and student diversity [15]. In fact, these contradictions can drive changes and improvements in traditional education systems.

A popular method to address these limitations and enhance traditional educational systems, tailored to the profiles of today's students, is Digital Game-Based Learning (DBGL), which involves using video games - particularly serious games [16] - as a tool for learning [17]. Indeed, a myriad of games were developed for learning mathematics [18], [19], [20]. However, in most cases, they had limitations. First, playful learning in DGBL [21] is most often approached via pre-established rules and game goals. It then neglects the "authored play" (i.e without the game designer role) approach, which can better promote students' creativity and sense of belonging. Second, serious games are usually designed as 'closed' artifacts, meaning that their core content and the structure of the challenges often cannot be modified by teachers without technical expertise. While some platforms offer customization tools [22][23] and recent proposals relied on AI to facilitate the creation of educational games [24], it is still challenging for educators to adapt game-based learning to their specific pedagogical needs [25]. Thus, this game-design approach places the responsibility for both game creation and updates primarily on the game designer, who often focuses on specific competencies, which can create obstacles when trying to develop interrelated skills within a single game [26].

Therefore, an holistic and systemic analysis in DGBL is necessary to address these limitations. Specifically, in this paper we propose an analysis performed within the framework of the third generation of Activity Theory (AT), where DGBL is considered under the umbrella of three Activity Systems: Learning, Teaching and Game Designing. We put forward a collective view of DGBL as a socio-technological system, with human assets and tools analysed from the perspective of *Expansive Learning*. This analysis allow us to explore the "zone of proximal development" of DGBL and thereby define a model for a new way of learning/teaching through games and designing games.

Our proposed model emphasises the *division of labour* of the Activity Systems giving agency to: (i) students and teachers since they will act not only as players and facilitators, respectively, but also as creators of game challenges, and (ii) game designers due to the fact that they will act as orchestrators of scaffolded competences through the game instead of focusing on just one competence. That is, game designers will provide the students with appropriate challenges and supports at different stages of the game, which are designed to help them grow and master new skills in a structured manner. Finally, we validate this model through a quasi-experimental study of a serious game oriented to learning geometry named GeoBuild, consisting of four mini-games that provide a scaffolded approach to developing 3D spatial skills, and an experiment with children who play the role of players but also creators of challenges in the last mini-game, *GeoSudoku*.

2. The theory of *Expansive Learning* and DGBL

In this section, based on the theory of *Expansive Learning* [27], we first study the relationships between the three Activity Systems (AS) involved in DGBL (Learning, Teaching and Game Development). Then, we put the focus on a zone of proximal development of DGBL, which allows it to evolve towards more flexible and enriched forms of learning through games.

2.1 The three Activity Systems: Teaching, Learning, Game Development

An Activity System is usually depicted using a triangle with components around it. Figures 1, 2, and 3 highlight with a dark background the concrete components of the three AS in DGBL that our study focuses on, clockwise from the top: Tools, Object, Division of Labour, and Rules. First, Figure 1 depicts the Learning Activity System, where students have access to Tools (digital content, in this study represented by games for learning) to support their learning and so reach the Object, which is to attain learning competences. Moreover, students' Division of Labour situates them as consumers of learning content, and they are subjected to different assessment methods, regarding both knowledge and transversal competences.

Second, Figure 2 shows the Teaching Activity System, where teaching methodologies and other Tools, such as digital games, give support to the curriculum teaching, which is the teachers' Object. Regarding the Division of Labour, historically, teachers are mainly *producers* (with their own materials) or *facilitators* (e-books, games) of other learning content. The assessment method is defined likewise in the Learning AS.

Third, Figure 3 describes the Game Designing Activity System, where game designers are responsible for providing

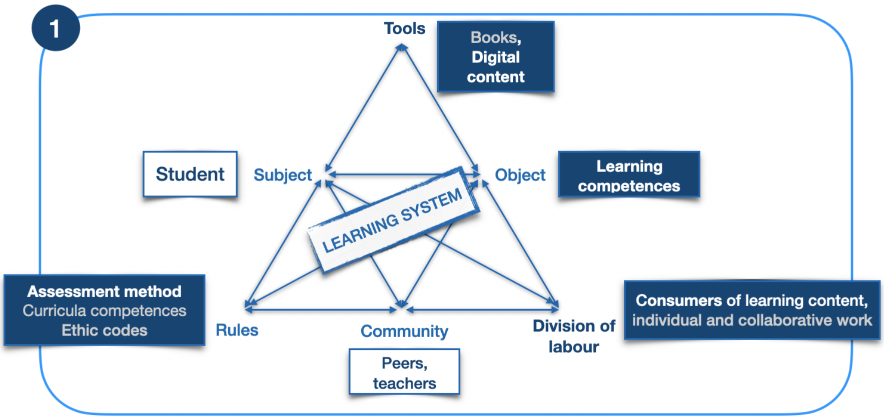


Figure 1 Learning Activity System.

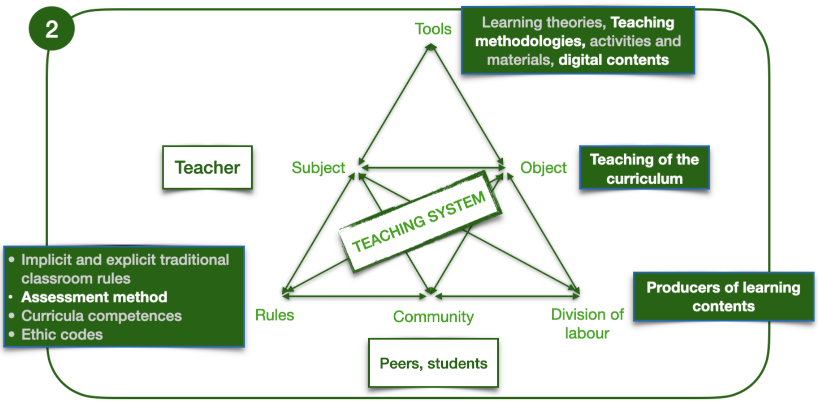


Figure 2 Teaching Activity System.

tools for game authoring for the community (students and teachers).

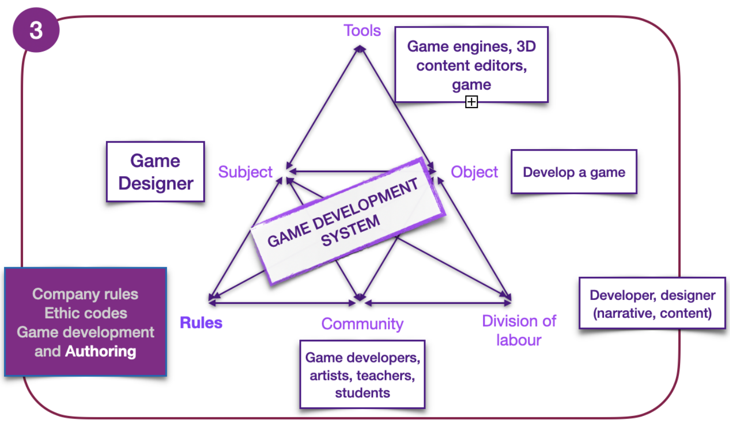


Figure 3 Game Development Activity System.

Although each Activity System (AS) has its own focus, their interconnection is key to understanding the dynamics of DGBL (Digital Game-Based Learning). In particular, the Learning AS and the Teaching AS are closely linked, as teaching strategies determine how students interact with games as learning tools [28]. On the other hand, the Game Designing AS plays a fundamental role in how games are developed and used within the other two systems. In educational environments, the interaction between these systems can vary depending on the context. For example, in programs where teachers have been trained in game design [29], the barrier between the Teaching AS and the Game Designing AS becomes less well-defined, allowing for a greater co-creation of educational content. Similarly, if students actively participate in game creation [30], direct feedback is generated between the Learning AS and the Game Designing AS.

2.2 Exploring the transformation of AS in DGBL

Next, we analyse the contradictions that may drive transformations in DGBL Activity Systems, focusing on the dilemma of games as closed, single-competence artifacts versus open, evolving tools to which both teachers and students contribute.

To identify contradictions, we chart two criteria in a two-dimensional diagram (Figure 4): i) the learning methodology, ranging from *concept-oriented* to *student-oriented*, and ii) the game's geometrical content, from *isolated* to *interrelated* concepts. The green arrow in Figure 4 illustrates the shift from "Teachers and Game Designers" to "Students, Teachers, and Game Designers" as protagonists in DGBL's zone of proximal development.

Here, students are not mere "consumers of games", as depicted previously in Figure 1, but active "consumers and producers," designing challenges for peers under teacher supervision. Meanwhile, teachers evolve from being sole designers of single-competence games to facilitators integrating scaffolded competences into serious games.

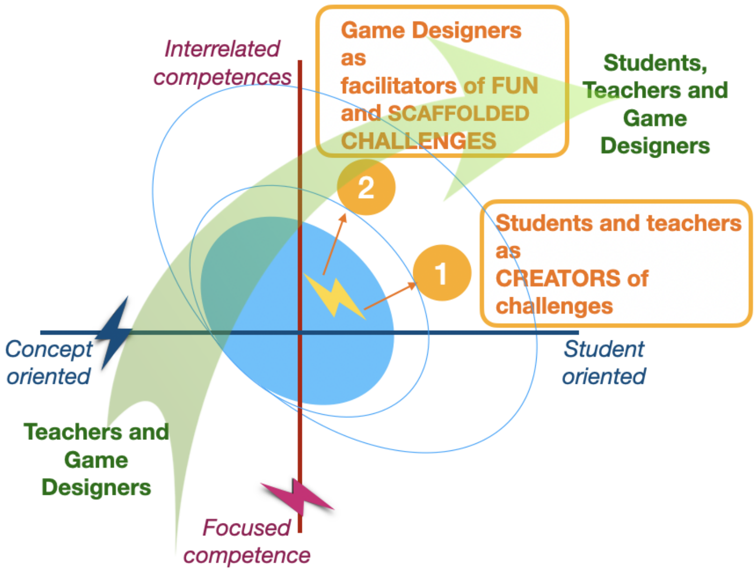


Figure 4 The zone of proximal development of DGBL.

The first criteria (horizontal axis of Figure 4) examines the evolution of teaching-learning methodologies. *Concept-oriented* learning features an educator delivering content to a passive audience, while *student-oriented* learning involves active, collaborative participation among peers. This shift in Digital Game Based Learning is marked by an evolution from expert-teacher co-design to the inclusion of students in the game design process. Ultimately, in the zone of proximal development (indicated by the orange number 1), both teachers and students are empowered in design, use, and ongoing growth of the game, thereby extending its life.

The second criteria (vertical axis in Figure 4) illustrates the continuum from isolated to interrelated educational content. In geometry DGBL, while some games address 2D figures or 3D projections [31, 32], few integrate multiple aspects (e.g., properties of 2D/3D solids, spatial orientation, and projections). This holistic approach (purple square in Figure 3) reveals contradictions in shifting to a *student-oriented* methodology. When we run our attention to the top part of blue oval in Figure 4 which is the zone of proximal development as defined by Engeström, we see the contradictions that arise when we aim to evolve towards a *student-oriented* methodology and *interrelated* concepts integrated in games. These contradictions manifest themselves as the lack of tools that help in this shift, underscoring the need for tools that enable designers to facilitate scaffolded learning (see orange number 2).

To demonstrate this innovative vision of DGBL, in section 4.2.3 we present a quasi-experimental study of an educational game, GeoBuild, where game designers act as facilitators of challenges integrating scaffolded competences, and, although we focus on students as creators of challenges, both teachers and students are able to extend a game with new challenges.

3. Related work

In this section, we review relevant studies on serious games designed for geometry learning and present the use of Activity Theory in learning in general, and in Serious Games in particular.

3.1 Serious games for geometry learning

Several digital platforms and games have successfully incorporated elements that focus on spatial reasoning, the manipulation of geometric figures, and user-generated content. For instance, Minecraft: Education Edition [22] provides a sandbox environment where learners can build complex structures, honing their spatial and geometric skills through creative exploration. The game's open-ended design encourages students to experiment with three-dimensional construction and share their creations.
Similarly, DragonBox Elements [33] integrates engaging puzzles with core mathematical concepts. This platform uses game mechanics—such as rewards, time challenges, and level progression—to scaffold learning and maintain engagement. While its primary focus is on introducing abstract mathematical ideas through interactive challenges, it is committed to active learning through guided exploration.
Digital tools like GeoGebra [34] allow users to construct and manipulate geometric figures dynamically, fostering a deeper understanding of spatial relationships and geometric properties. Although it is primarily an interactive mathematics tool rather than a full-fledged game, it emphasizes user-driven exploration and content creation. Similarly, other digital platforms [18], [19] incorporate dynamic visualization and guided problem-solving to support mathematical understanding. Meanwhile, game-based applications [20] take a more immersive approach, integrating challenge-driven mechanics to engage users in playful yet structured mathematical learning experiences.
On the commercial side, platforms such as Brilliant [35] and emerging products like Duolingo Math [36] have adopted adaptive, gamified approaches to teaching mathematics. These systems deliver bite-sized challenges that adjust to individual learner progress and use immediate feedback and reward mechanisms to motivate users. Although these platforms typically offer a more linear progression through pre-designed tasks, their underlying goal of promoting engagement through game-like experiences remains consistent.

3.2 Activity Theory used in Serious Games development

Activity Theory has been widely used as an analytical framework in education, including evaluating learning in digital games [37], informing serious game design [38], and analysing gameplay interactions to identify breakdowns such as confusion and disorientation [39].
Aligned with our approach of identifying contradictions in DGBL through AT, a recent study [40] examined online learning during the pandemic. Authors highlighted challenges with Tools, limited Community interactions, and conflicting student roles (self-directed learners). In our case, we focused on the Division of Labour component instead of Tools and Community components.
AT has also been applied in DGBL for language learning [41], health [42], science [43], and science and math [28]. In Maths, scaffolding strategies in DGBL have proven effective [44, 45]. Hou et al. [46] demonstrated how combining physical board game cards with mobile scaffolding improved learning and reduced anxiety. While both scaffolding and DGBL integration have been studied, there has been little research combining AT with scaffolding in DGBL. Additionally, Hou et al. [46] proposed a game editor for teachers, aligning with our focus on shifting student and teacher roles in game design.
Several case studies have applied Activity Theory (AT) to enhance DGBL in language learning [41], medical simulation [42], science [43], and Maths [28]. AT also underpins scaffold-oriented activities in DGBL, with studies [44, 45] emphasizing whole-class and one-on-one scaffolding in Maths. Moreover, Hou et al. [46] developed an educational game that combines board game cards with mobile-based scaffolding, significantly improving learning effectiveness and reducing student anxiety in high school chemistry. Although these studies integrate scaffolding with DGBL, recent research specifically merging AT with scaffolding is scarce. Additionally, Hou et al. [46] proposed a game editor for teachers to design scaffolded activities, aligning with our proposed shift in the roles of students and teachers in game design.

Activity Theory's versatility in analysing Digital Game-Based Learning makes it valuable for literature reviews and comparisons between serious games [47]. For example, a systematic review of 96 empirical studies on game-based learning for learners with disabilities [48] examined various AT components, notably the Division of Labour, identifying learners, special education professionals, experts, and family members as key actors. Learners were primarily involved in baseline assessments, practice trials, experiments, post-test evaluations, and providing feedback on their reactions to game-based learning. However, these studies did not consider students as *challenge creators*, as we propose.

4. Quasi-experimental study: GeoBuild game in action

This section presents the research questions of this study, the method designed to answer these questions, and finally the results.

4.1 Research Questions

Our study on the framework of Expansive Learning for games aims to address the following research questions:

- RQ1: How does the Expansive Learning designed in a game influence the learning experience (in terms of learning outcomes and engagement)?
- RQ2: How did the game challenges created by students impact the learning experience of their peers (in terms of learning performance and engagement)?

To answer these research questions, we designed a quasi-experimental study focused on secondary students who played GeoBuild, a game designed using the Expansive Learning theory. We employed a range of metrics to evaluate learning outcomes, engagement, and enjoyment. Knowledge acquisition was assessed through pre- and post-tests measuring students' understanding of geometric concepts. Motivation and enjoyment were analysed using self-reported questionnaires. Engagement levels were inferred from in-game analytics, including interaction frequency, and completion rates. Additionally, qualitative feedback was gathered from students and teachers to provide deeper insights into the learning process.

4.2 Method and materials

This section presents the experimental design, the participants, the game mechanics of GeoBuild, and the scheduled game sessions.

4.2.1 Experimental Design

We carried out a quasi-experimental with a **between-subject design** on two groups. The control group, Group A, played challenges in which they had to explore geometrical properties in the first three mini-games, and then solve 3D constructions in the *GeoSudoku*. The experimental group, Group B, played the game but also performed the role of "creators", which involves them proposing new 3D figures to be played by their peers as challenges in the *GeoSudoku* game.

We planned to select students of a same Secondary Cycle of 4th grade of ESO (Compulsory Secondary Education), who were all from the same class, and were not explicitly aware of the different conditions, minimizing possible bias as they might have altered their behaviour based on what they believe the researchers expected (Hawthorne effect [49]). Our study used naturally occurring classroom groups rather than random assignments because it is more practical and ethical, avoiding disruption in the groups dynamics of a course that was already in progress. Moreover, we planned to analyse the initial conditions of both groups in terms of levels of knowledge, motivation and game experience.

4.2.2 Participants

We recruited 30 volunteers in their first year of secondary school (13 years old) and one teacher at one school in the city of Sabadell, Barcelona. Participation was voluntary, parents read and signed a formal consent form that informed them about the details of the study, including student anonymity and the confidentiality of test results.

In the initial phase of recruitment, gender was distributed as follows: 19 females (63%) and 11 males (37%). Among the females, only 16% played games frequently, while all males did so. Table 1 shows the demographics and the motivation of the sample.
However, in our posterior analysis, we discarded the students who did not attend all the sessions of the DGBL experience, and the total number of participants dropped to 25, with the percentages of gender varying slightly with 56% females and 44% males. The final number of students in the two groups was 14 in Group A (control group) and 11 in Group B (experimental group).
On the other hand, we used the Situational Motivation Scale (SIMS) questionnaire to measure students' motivation on a scale of seven. The questionnaire consists of four questions on intrinsic motivation (IMotivation) and four on amotivation (AMotivation, i.e., lack of motivation), all from the validated Spanish version by [50]. We measured the participant's motivation at the beginning of the experience. The scores shown are I-motivation (5.42 out of 7), and A-motivation (2.45 out of 7), showing a high value for intrinsic motivation and a low value for A-motivation, suggesting that participants were remarkably motivated to engage in the game.

Table 1. Demographics and initial engagement of the sampled population

Participants	Females	Males	I-Motivation	A-Motivation
25 (30)*	56% (63%)*	44% (37%)*	5.42/7.0	2.45/7.0

Note. * Values in parentheses indicate the demographics of the initial recruitment phase.

Moreover, we analysed the initial conditions of both groups of students separately (see Table 2). In fact, both groups began with very **similar levels of motivation and gaming experience**, as no significant differences were detected. There are slight differences in the mean values between the groups (for instance, regarding intrinsic motivation, Group A scored 5.25 out of 7, compared to 5.59 for Group B), but this difference was not statistically significant (U Mann–Whitney, p-value = 0.3498; $p > 0.05$, thus supporting the null hypothesis). Since similar patterns were observed in A-Motivation and the Gamer profile (see the two last columns in Table 2), these findings underscore the fact that the experiment began with both groups operating under comparable conditions.

Table 2. Two groups (A-Control, B-Experimental) of the quasi-experimental study: demographics and initial motivation means.

Group	Role	Participants	I-Motivation	A-Motivation	Gamer
A	Player	14	5.25/7	2.55/7	0.545/1
B	Creator	11	5.59/7	2.34/7	0.5/1
p-value			0.3498	0.9338	0.8495

Note. We used a U Mann-Whitney test to analyse the statistical significance.

4.2.3 The serious game: GeoBuild

GeoBuild is a serious game designed based on Expansive Learning theory, which we utilized to investigate the research questions. This section first presents the learning objectives (competences) included in its design. We then detail the fun part of the game, specifically its game mechanics. As recommended by serious games design principles [51], we focus especially on using popular game mechanics that can engage students in the game-play.

Learning objectives

Three-dimensional geometry is introduced intuitively in upper primary education, with advanced concepts like volume explored by the end of the first Secondary Cycle (4th grade of ESO). This game targets children of 4th grade, aged 14 to 16, and aims to develop the following competences:

1. Recognition of Solids and Geometric Properties (`C1.SOLIDS-GEOPROP`): Users should identify regular and convex polyhedra, distinguishing them from irregular ones, and classify these solids while addressing symmetry, faces, vertices, edges, uniformity, and duality.

2. Rotations and Spatial Orientation (`C2.ORIENT`): The project enhances students' spatial orientation since they must rotate and position the camera correctly in 3D space to display the desired content.
3. Projections (`C3.PROJECT`): Projections onto a plane, explored through shadows or grids, help students understand projection planes and construct shapes based on them.
4. Construction of 3D Figures (`C4.3DCONSTR`): Tied in with the previous two competences, users should learn to assemble figures while orienting themselves in space and aligning with axes.

Game Overview

GeoBuild is a sequel to GeoPieces [31], which mainly focused on 2D geometry and basic 3D concepts. Inspired by tools like Building with Blocks [52] and Isometric Drawing Tool [53], GeoBuild enhances users' 3D coordination. The game uses an arcade-style approach, guiding students through four mini-games of increasing difficulty (see Figure 5). In the first three mini-games (*GeoCollect*, *GeoTatami*, *GeoFootball*), students explore Platonic solids and geometric features, earning the necessary pieces to unlock the fourth mini-game,*GeoSudoku*, which challenges students to navigate 3D space using 2D projections and avoid non-manifold designs.

(a) *GeoCollect* **(b)** *GeoTatami* **(c)** *GeoFootball* **(d)** *GeoSudoku*

Figure 5 The four mini-games related to the 3D missions.

Next, we detail how each mini-game aims to develop the specific competences as presented above:

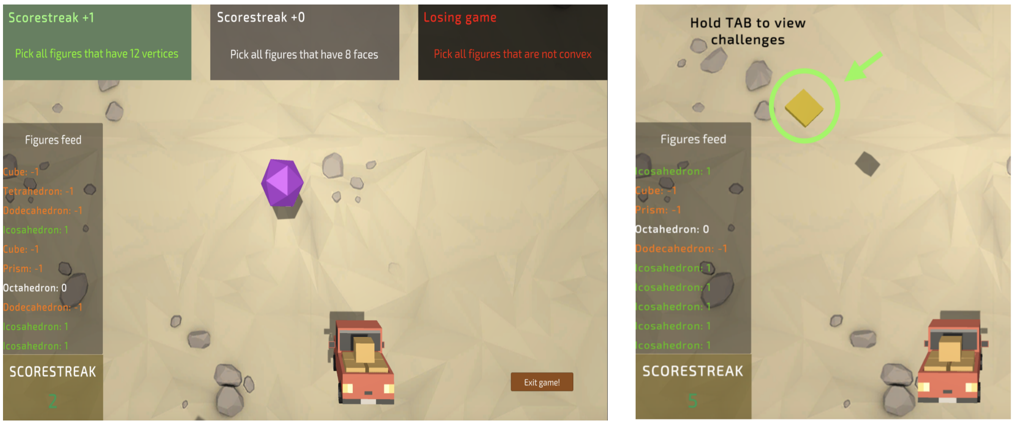
- In the first mini-game, *GeoCollect* (see Figure 5a), users will hone their ability to identify different solids based on the characteristics designated by the teacher, thus focusing on competency `C1.SOLIDS-GEOPROP`.
- In the mini-games *GeoTatami* (Figure 5b) and *GeoFootball* (Figure 5c), students answer geometric questions tailored by teachers to reinforce concepts from competency `C1.SOLIDS-GEOPROP`. Players also practice spatial orientation through camera rotations, targeting competences `C1.SOLIDS-GEOPROP` and `C2.ORIENT`.
- In the final mini-game, *GeoSudoku* (see Figure 5d), students aim to create a final construction, which is the target object designed by the teacher based on certain projection planes. This clearly enhances competences `C2.ORIENT`, `C3.PROJECT`, `C4.3DCONSTR`.
- An additional feature allows students to create new 3D constructions as challenges, offering more opportunities to achieve the objectives and reach higher levels of Bloom's Taxonomy, such as Synthesis and Evaluation [54].

GeoBuild's uniqueness lies in allowing both teachers and students to design geometric challenges. In the fourth mini-game, students create new 3D figures, fostering spatial creativity and motivation by solving challenges from peers. Teachers design challenges in the first three mini-games, customizing missions based on students' needs. During registration, users choose whether to play as a player or a designer.

Game mechanics

In GeoBuild, the players engage in an interactive geometry journey. In the first three mini-games, they collect pieces to complete missions while solving spatial geometry questions, accumulating cubes in their inventory. The goal is to complete missions and achieve the highest score in the fourth mini-game. Players can access their inventory to check collected items and assigned missions. Next, we outline the mechanics of each mini-game.

In the first mini-game (*GeoCollect*), players identify solids based on teacher-assigned characteristics as figures fall, casting shadows on the wall. They must collect five consecutive figures matching the geometric property in the green square (see *"Pick all figures that have 12 vertices"* in Figure 6a). Figures in the gray square (*"Pick all figures that have 8 faces"*) continue the streak, while those in the black square (*"Pick all figures that are not convex"*) end the game. A golden piece appears after a 5-match streak (Figure 6b), serving as the basic unit for the final construction.



(a) *GeoCollect: identification* **(b)** Golden piece collected.

Figure 6 Screenshots of the *GeoCollect* mini-game.

In the second (*GeoTatami*) and third (*GeoFootball*) mini-games, players answer geometry questions to earn rewards. They must adapt to camera rotations, enhancing spatial orientation. These level-based mini-games occasionally feature a gold piece, which, once collected, does not reappear in that level, requiring progression to obtain more.

(a) *GeoTatami environment.* **(b)** Multiple-choice geometry question.

Figure 7 Screenshots of the *GeoTatami* mini-game.

In the *GeoTatami* mini-game (Figure 7a), players control a sphere, avoiding falls while eliminating moving enemies. They navigate by rotating the camera. A level bonus activates a 3D geometry question set by the teacher; answering correctly stops enemy movement.

The third mini-game, *GeoFootball*, is set in a soccer match context. The objective is to get enemy balls into their goal while preventing them from entering the player's goal. If the score reaches "Own Goals - Goals Scored = 5", the game is lost. The bonuses associated to geometric questions and figure acquisitions when questions are answered correctly follow the same pattern as in the *GeoTatami*.

When players complete the required inventory for a mission, they unlock the final mini-game, GeoSudoku. Their goal is to reconstruct a 3D target design created by the teacher or peers (as detailed in the next section). To assist them, three grids display the figure's projections on the XY, ZY, and XZ planes (see the first column of grids in the top right-hand part of Figure 9). Each grid position represents the number of pieces of the 3D target construction projected in the same cell. Just besides this, a second set of grids shows their current construction, allowing real-time comparison. A color-coded legend guides adjustments: purple (missing pieces), orange (extra pieces), black (no piece should be there), and green (correct placement). Players can verify their construction's accuracy anytime by selecting the "Check" button.

Students and teachers as creators of game activities

A key feature of GeoBuild is that teachers design the missions (3D constructions) for the fourth mini-game (*GeoSudoku*). To enhance engagement and learning, students also transition from passive consumers to active creators, reinforcing spatial orientation (`C2.ORIENT`) and 3D figure construction (`C4.3DCONSTR`). In this paradigm, students

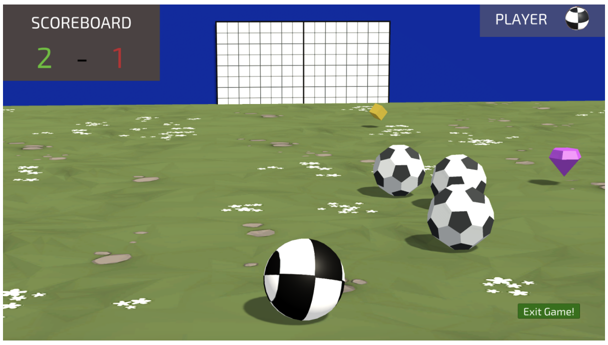


Figure 8 *GeoFootball.*

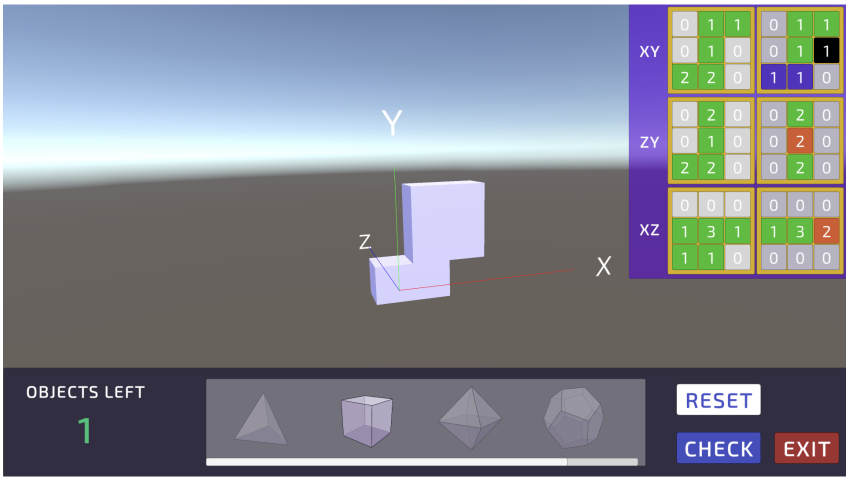


Figure 9 *GeoSudoku* building. The first column of grids represents the objective construction (in green, all the cells where the objective construction is projected along the XY, ZY and XZ planes). In the second column of grids, purple cells indicate missing pieces, orange cells showcase an overabundance, black cells means that no piece should be there, and green all pieces are correctly placed.

not only navigate predefined challenges but also create their own 3D figures, fostering ownership, creativity, and peer-to-peer learning. They can name their designs and receive feedback through a "like/dislike" system.

An authoring tool enables both teachers and students to build target 3D figures (see Figure 10). Designed based on principles such as power, usability, and reusability [55], it allows users to define the maximum number of pieces, connect hexahedra, and freely adjust the camera. A minimap provides a global view, with options for camera repositioning. To ensure fairness and real-world grounding, figures must follow physical principles and avoid non-manifold geometry (see Figure 11). Furthermore, a 16-piece limit balances creativity and complexity, ensuring that figures remain solvable and equitably challenging.

Finally, tracking and evaluating the performance of these student/teacher-generated activities are crucial for both educators and creators. Control variables such as *average time solved*, *number of figures*, and *cube positions* help assess difficulty, with higher values generally indicating more challenging figures. The *ratio of likes to dislikes* reflects user reception, where higher values suggest greater approval. Additionally, the *list of players* and *designer of the mission* provide insights into engagement and attribution, while the *mission's name* serves to categorize content. This data not only facilitates educators when curating and refining future sessions but also provides student creators with actionable insights into the appeal and solvability of their designs, perpetually refining the learning and creative process within *GeoBuild*.

4.2.4 Scheduled sessions

The study consisted of five sessions (Figure 12): two 2-hour sessions at the start and end, and three 1-hour sessions in between, scheduled over two weeks. Students, already familiar with basic geometry, spent the first half of each session in Group A and the second half in Group B. In Session 1, students took an initial exam, *Exam1*, and filled out a pre-motivation questionnaire before played simple challenges for 15 minutes to familiarize themselves

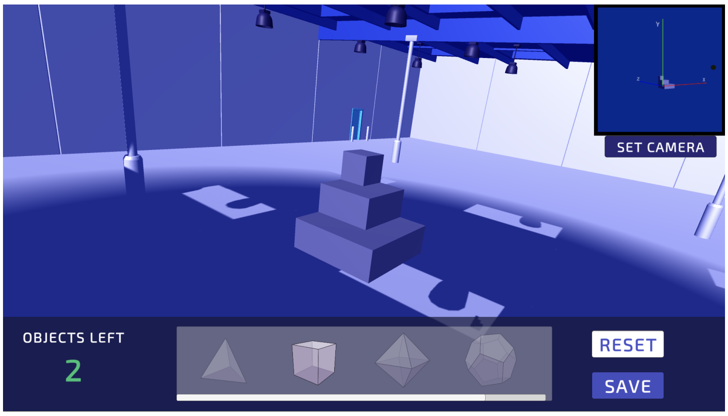


Figure 10 Authoring tool.

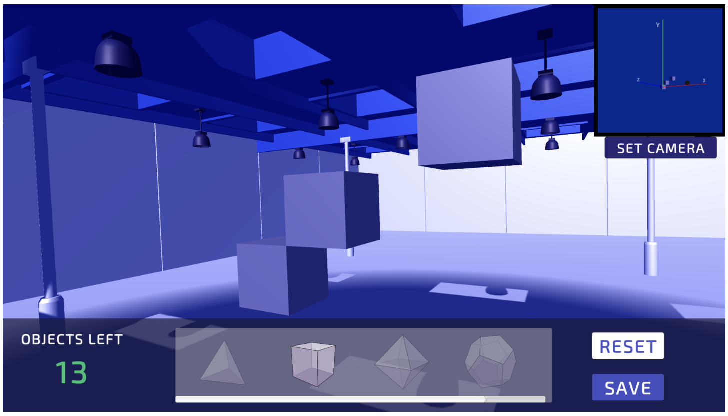


Figure 11 Invalid construction: non-manifold geometry.

with the game. In Session 2, students solved challenges with five 3D figures at varying difficulty levels (based on the number of cubes and the arrangement of these cubes) to track student progress and assign levels for the next sessions.

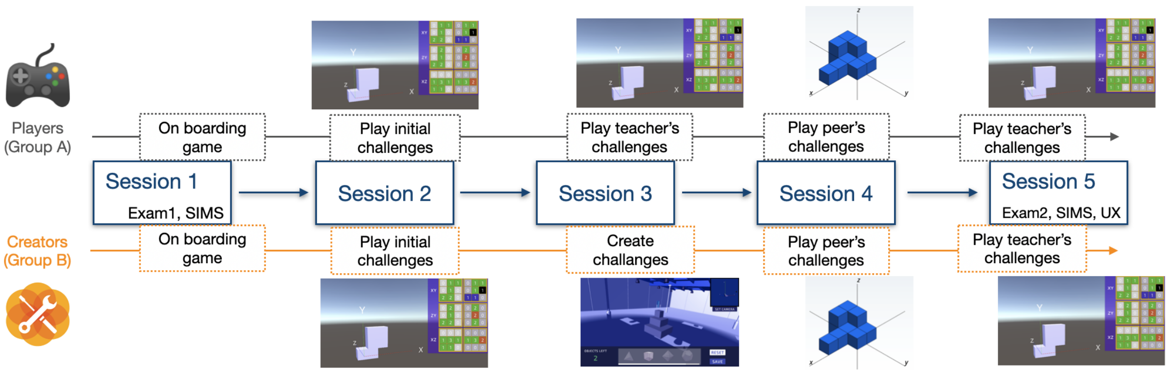


Figure 12 Organization of the experiment divided in five 2h-long sessions.

The control group (Group A, Players) had two more sessions: i) building 3D figures designed by the teacher in Session 3, and ii) solving peer-created challenges in Session 4, based on their assigned level from Session 2. To ensure unbiased experiences, students were unaware of the identity of the challenge creators. Conversely, the experimental group (Group B, Players+Creators, hereafter referred to as Creators) followed a different approach: i) creating challenges within a six-cube limit in Session 3, and ii) solving peer-created challenges in Session 4, based on their level from Session 2. The cube limit ensured challenge difficulty remained manageable.

In Session 5, both groups tackled complex (14–16 cubes) teacher-created challenges to guarantee additional exposure. Finally, all the students completed *Exam2* (10–15 min) and filled in a post-motivation and UX questionnaires, while the teacher also provided feedback.

4.3 Results

Our evaluation focuses on the last mini-game, *GeoSudoku*, the one in which the scaffolding learning process concludes. That is, students before playing *GeoSudoku* pass through the first three mini-games in GeoBuild to reinforce the basic competences `C1.SOLIDS-GEOPROP`, `C2.ORIENT` and `C3.PROJECT`.
In this section we analyse the results of two research questions related to the *Expansive Learning* design in *GeoSudoku*. We have structured our analysis based on the differences in learning experiences between players and creators (RQ1), and the differences between the challenges created by peers and those proposed by the teacher, along with their varying impacts on students (RQ2). In the two RQs, we first describe the rationale of measures taken to answer it and then we provide the gathered data in tables of results. Finally, we briefly present the teacher's feedback that we gathered in an interview conducted after the intervention.

4.3.1 Statistical analysis

In our analysis of all the collected data, we first conducted normality and equal variance tests to determine the most appropriate statistical methods for our study. Depending on the results, we applied either parametric tests, such as the t-test, or non-parametric alternatives, including the Mann-Whitney test, the Wilcoxon signed-rank test, Normalized Gain Index and ANCOVA. These tests allowed us to assess differences between groups while accounting for potential deviations from normality and variance homogeneity, while also taking into account baseline differences. For each statistical test performed, we reported the test statistic, its corresponding p_value, and the effect size when relevant.

4.3.2 RQ1: Results

RQ1: How does the *Expansive Learning* designed in *GeoSudoku* influence students' learning outcomes and engagement in geometry?

Rationale of measures

First of all, we tested whether the *GeoSudoku* game reinforced learning competences in geometry related to the `C2.ORIENT`, `C3.PROJECT`, and `C4.3DCONSTR` competences. To do so, we gathered data from exams' scores (**summative assessment**) and players' performance when playing the game throughout the five sessions (**formative assessment**).
Regarding the exams, students completed an initial exam, *Exam1*, comprising a total of 11 questions, eight of which focus on competences `C2.ORIENT` and `C3.PROJECT`, and three questions centred around `C4.3DCONSTRUCT`, with basic levels of difficulty, from 1 to 2 for `C2` and `C3` competences, and a level of difficulty of three for the exercises related to `C4`, which fitted the current level of knowledge of students according to their teacher.
In the final exam, *Exam2*, there were seven questions, two addressing `C2.ORIENT` and `C3.PROJECT` competences, and the remaining five dedicated to assessing the `C4.3DCONSTRUCT` competence with higher levels of difficulty, from 3 to 5. Note that the final exam contained more questions related to the competence (`C4`) since we wanted to assess how far they had gone in learning this competence, which groups together the other competences. Indeed, these questions asked the students about 3D figures with complex configurations that had not been presented to them in the first exam, as the teacher deemed them too difficult to be solved at that time.
Regarding **players' performance**, we collected the total number of challenges played (with a maximum number of 48 challenges in the game, of which 21 were created by the teacher sand 27 by students), the difficulty level of each challenge, and the number of completed vs failed challenges. From the completed challenges, we also gathered the time spent and the number of errors.
In this study, we initially selected the time metric based on the assumption that more self-confident students complete tasks faster [56]. Similarly, the same rationale applies to the number of completed challenges and the number of errors, among other factors. However, we later discarded these values due to concerns about their reliability as an indicator of performance. Since each student completed the challenges at their own pace, without an evaluator supervising or standardizing the conditions, various external factors — such as distractions and individual reasoning speed — introduced inconsistencies in the recorded times [57]. As a result, we ultimately decided to discard these values, as they did not provide a stable measure of student progress.
To perform an **engagement analysis** of the students who created challenges, we designed a **final UX survey** to ask about the *Expansive Learning* design in GeoBuild [58]. This survey included questions to gather students' opinions and feelings about the playing&building experience (feelings while playing challenges and perceptions

of creating challenges for others, among others). Moreover, during the game students could score the challenges using **like** and **dislike** as introduced in Section 4.2.3.

Results

In relation to **the summative assessment** of learning, first and foremost, we wish to highlight that the GeoBuilder game offered additional learning opportunities in geometry for both groups. Note that the teacher designed *Exam1* to test the basic geometric competences that students had acquired in the first session (before playing the game), while, in Exam2 the teacher aimed to evaluate the acquired competences after the three weeks of DGBL experience (after playing the game). Thus, the questions in the first exam were rated 1-3 in difficulty, while those in the final exam were rated 3-5, a fact that indicates a **positive progression in the learning outcomes**. The decision to use the same exam before and after the experience was deliberately discarded by teacher because the increase in question difficulty reflects the expected learning progression throughout the weeks. We observed a mean score of 5.6±1.62 out of 10 in *Exam1* compared to 6.10±2.33 in *Exam2* for both groups, though this difference is not statistically significant (Mann-Whitney U test, $p\_value = 0.25$). Nevertheless, when analysing the Normalized Gain Index (g) - a measure used to assess the learning progress of students between two points in time [59] -, the mean gain of 0.10 (median 0.31) indicates an improvement.
In addition to the normalized g-index results — which showed that Group A achieved a mean gain of 0.407 (with most students improving) while Group B experienced a decrease in scores—, we conducted an ANCOVA to further examine the differences in final exam performance while controlling for baseline scores. The model showed an adjusted R^2 of 0.191, indicating that approximately 19.1% of the variance in the final scores is explained by the predictors. The overall model was marginally significant with an F-statistic of 2.892 (p = 0.0595). When testing for differential effects by including an interaction term between the group and baseline scores, the interaction was non-significant (p = 0.945), suggesting that, after controlling for baseline scores, there is no significant difference in how initial scores influence final outcomes between the two groups.

Table 3 shows the analysis of Normalized Gain Index by groups, showing that Group A achieved a mean gain of 0.407 (median 0.48), indicating significant improvement, while the negative values of gain index for group B indicate that, on average, students experienced a small decrease in their score from *Exam1* to *Exam2*, trends that are similar regarding competence C4 (C4 g-Index). Notice that the median's g-index value of Group B (-0.66), which is larger than the average value (-0.30), indicates that more than half of the students experienced a more pronounced decrease in their scores. Overall, this suggests that student performance decreased between the two exams, but the magnitude of this decrease varies among individuals. This difference may be related to the fact that Group B spent more time creating challenges rather than solving them, while Group A focused more on the outcomes assessed in *Exam2*. In fact, Group A is more highly trained and more confident when solving challenges than Group B (we must remember that they practised challenge solving in Session 3, whereas Group B were creating challenges).

Table 3. Exam 1 (Ex1) and Exam 2 (Ex2), analysing competence C4, see 4.2.3 (out of 10), and normalized gain index (Hake's g) of mean (avg) and median (med).

Group	Ex1	Ex2	g-Index	Ex1-C4	Ex2-C4	C4 g-Index
A	4.85	6.95	avg 0.407 med 0.48	4.04	7.9	avg 0.66 med 0.74
B	6.54	5.03	avg -0.43 med -0.41	6.36	5.25	avg -0.30 med -0.66

Finally, in relation to the **formative assessment**, we analysed players' performance throughout the sessions 2, 4 and 5 in terms of errors made and proportion of achieved challenges, Tables 4 and 5 show the main results, respectively.

Regarding the errors made by students while playing challenges (see Figure 13), there is a significant difference in the number of errors per challenge between Groups A and B (average 65.8 vs 28.68, respectively in Session 5). A log analysis of student behaviour suggests that Group A primarily relied on a trial-and-error approach, as evidenced by repeated clicks on the validation button within the same challenge. In contrast, Group B generally adopted a more reflective strategy, as indicated by their lower number of validation attempts. Similarly, although the results in terms of the percentage of completed challenges show that the different strategies used by both groups are successful because both achieved very similar percentages of completed challenges, the more reflective strategy (group B) seems somewhat more effective (see Figure 14).

Table 4. Average number of errors along sessions S2, S4 and S5.

Group	**Errors**			**Within**
	S2	**S4**	**After S5**	**p-value**
A	40.71	83.61	65.08	0.48
B	23.92	39.15	28.68	0.81
Between p-value	0.44 (U Mann-W.)	0.50 (U Mann-W.)	0.04* (U Mann-W.)	

Table 5. % of achieved challenges along sessions S2, S4 and S5.

Group	**% of Challenges**			**Within**
	S2	**S4**	**After S5**	**p-value**
A	60%	41%	46%	0.23
B	52%	43%	55%	0.50
Between p-value	0.43 (t-test)	0.88 (t-test)	0.09 (Fisher)	

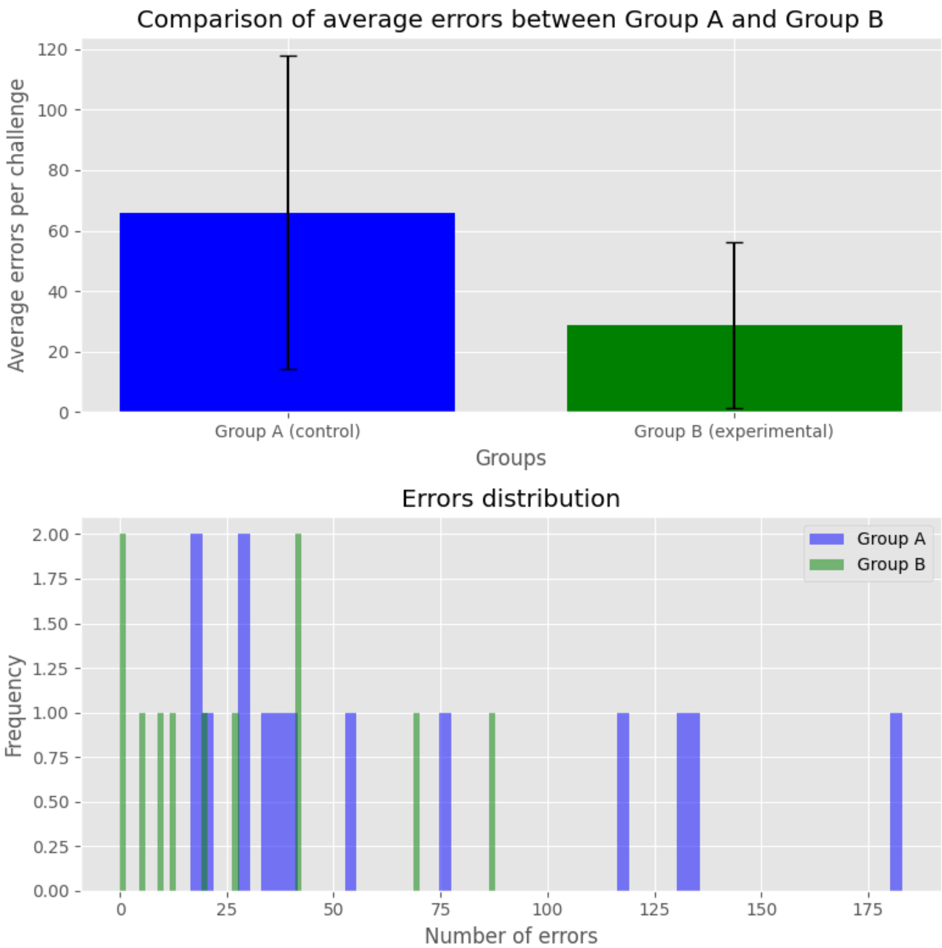


Figure 13 Results of Average Errors.

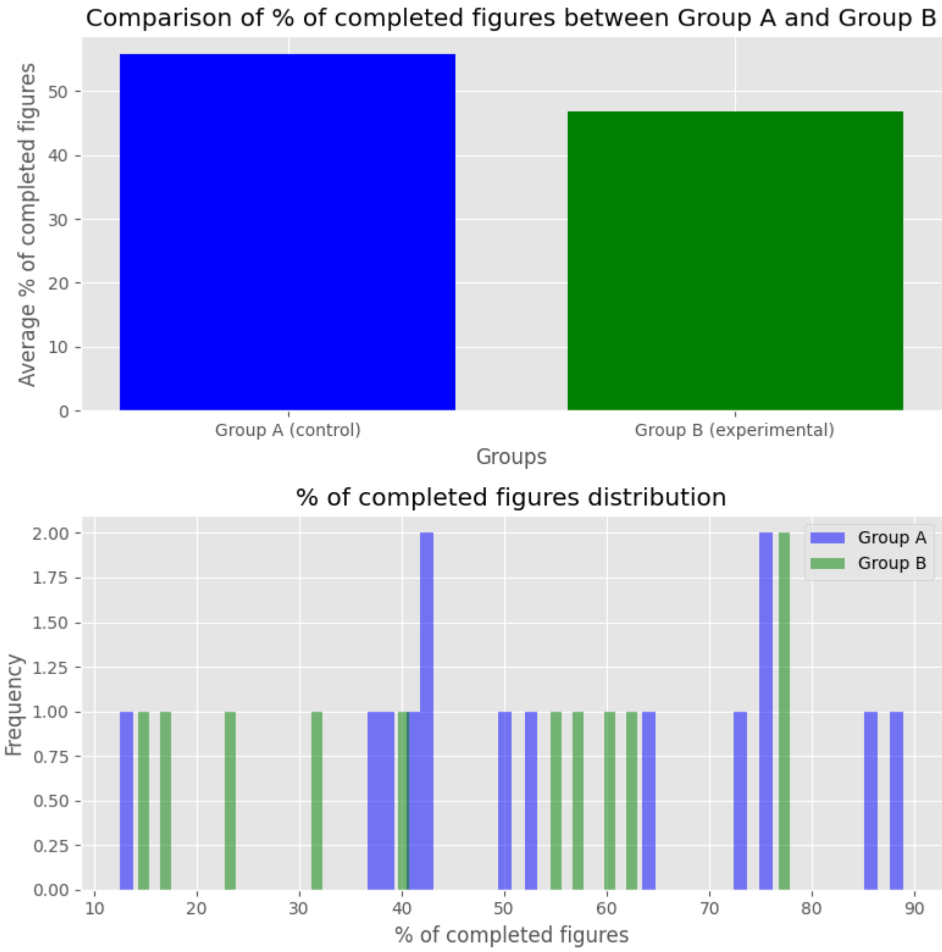


Figure 14 Results of % of achieved challenges.

Note that during the intermediate sessions, the statistical tests confirm in Tables 4 and 5, no significant differences exist between sessions (S2 and S3). Given the relatively short duration of these sessions, it is understandable that no significant differences were observed between the two groups or across sessions within the same group—on in any of the measured variables.

In relation to the **engagement**, as Table 6 shows, the post-questionnaire was designed with a number of questions that aimed to focus on the specific task of creating challenges for peers. Although subjective, this data let us know how the students who were acting as creator felt.

Table 6. Questions in the post-questionnaire about the experience of creating challenges for peers

Group	Question	Description
B	Q1-EasyCreate	I found it easy to create new challenges.
B	Q2-EnjoyCreate	I enjoyed creating challenges.
B	Q3-ChallDifficult	I think my challenges were difficult to solve.

Note. The first column indicates the group that answered each question.

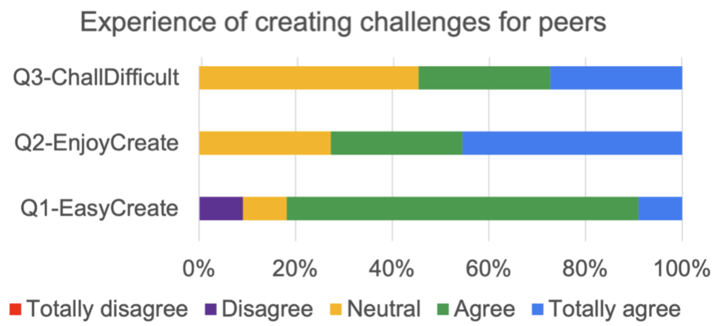


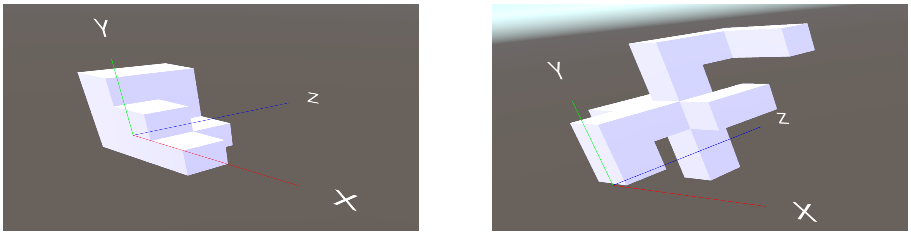
Figure 15 Results of questions in Table 6 about the experience of creating challenges.

The results in Figure 15 show neutral responses to almost all the questions. Even so, the majority of Creators found it easy to create challenges for their peers and enjoyed it. Nevertheless, half of them were not able to assess the difficulty of the challenges they created. We think that may be due to the fact that they did not have a frame of reference to assess the difficulty of challenges, for example relating difficulty with the number of cubes in the challenge. Neither did they have well established goals since they were free to construct any figure they imagined. Moreover, another reason may be that they had no opportunity to receive feedback from their peers.
Finally, regarding the **General score of likes/dislikes** both group A and B scored over 90% of the challenges as Liked, that confirms they enjoyed the experience and were engage in solving the game's challenges.

4.3.3 RQ2: Results

RQ2: How did the challenges created by students impact the learning experience of their peers (in terms of learning performance and engagement)?

Rationale of measures
To answer this research question, we first gathered **logs** comparing the peers-created challenges were to those created by the teacher. Concretely, we measured the difficulty level of the challenges (i.e., the number of cubes, and the simple vs complex spatial distribution of cubes). In Figure 16 we show some examples of simple and complex figures.
Finally, regarding the **impact of student created challenges on peers' engagement**, we used data coming from the likes and dislikes that players scored during the game, taking into account the creator of the challenges(teacher or peers).

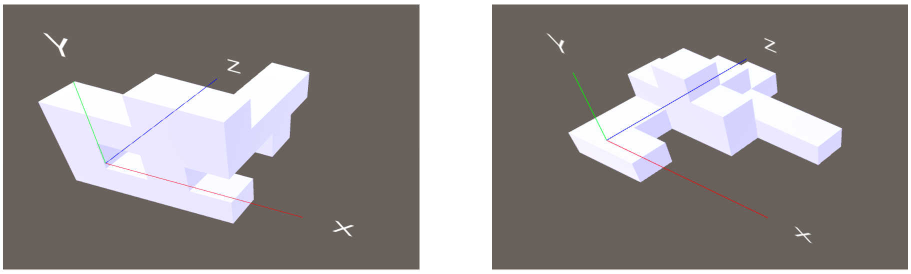


(a) *Simple 3D figure.* **(b)** Complex 3D figure.

Figure 16 Screenshots of simple and complex 3D figures.

Results

Firstly, we observed that both challenges created by the teacher and peers seem very similar regarding the complexity of the generated 3D figures (see Figure 17). This allows for a meaningful comparison of the performance metrics between the two experimental groups as they performed challenges of similar difficulty. The results of the performance evaluation between groups A and B, considering whether the challenge creator was the teacher or peers, are shown in Table 7.



(a) *Teacher's 3D figure.* **(b)** Student's 3D figure.

Figure 17 Screenshots of 3D figures created by teacher and by peers.

When the **challenge creator was the teacher**, the **mean error rate for teacher-created challenges** shows a notable and statistically significant difference, similar to the trend observed in the analysis of errors during the formative learning assessment (RQ1). In that analysis, group A also made significantly more errors than group B. Despite this higher error average, it is important to note that group A still **completed** a comparable percentage of figures to group B.

Table 7. Values of errors and achieved challenges segmented by challenge creator

	Errors			**Challenges**		
Created by	**A**	**B**	**p-value**	**A**	**B**	**p-value**
Teacher	61.14	26.14	$< 0.05^*$ (U Mann-W.)	59%	52%	0.12 (t-test)
Students	102.84	54.90	0.42 (U Mann-W.)	54%	37%	0.61 (Fisher)

Note. p-values were computed using different statistical tests: Mann-Whitney U test for errors and t-test/Fisher's exact test for challenges. A significance level of < 0.05 is marked with *.

On the other hand, when **challenges were created by peers** (as shown in Table 7), the analysis of **errors** shows a trend similar to that in RQ1. Group B demonstrated more efficient and consistent behaviour, likely due to the critical thinking and problem-solving skills they faced when creating challenges. However, **the proportion of challenges completed** by group A was higher than that of group B (54% vs. 37%), though this difference was not statistically significant. This result can likely be attributed again to the greater practice time group A had compared

to group B.
Analysing errors within groups, students struggled more with peer-created challenges (61.14 errors in teacher-created vs. 102.84 in peer-created). The teacher explained that his challenges followed a structured difficulty progression, unlike peer-created ones, which tended to have more cubes. Despite this, Group A maintained a similar success rate, while Group B achieved fewer challenges, reinforcing that Group B had less practice solving challenges than Group A.
Finally, the analysis of likes and dislikes based on the challenge creator shows that students preferred teacher-created challenges over those by their peers, though peer-created challenges were still positively rated (see Table 8). These results indicating that teacher-designed challenges were perceived as more engaging than peer-created challenges align with the previously presented error analysis, in which students made fewer errors with figures created by the teacher. This finding underscores the importance of providing guidance and support to students when they take on the role of challenge creators.

Table 8. Percentages of likes and dislikes segmented by creator

Created by	Total Likes + Dislikes	% Likes	% Dislikes
Teacher	98	90.81%	9.19%
Students	37	83.78%	16.22%

Note. Fisher p-value = 0.35.
The difference in total likes/dislikes between teacher-created and student-created challenges is reasonable (98 vs 37), as students played more of the teacher's challenges overall (recall that students only played peer-created challenges in session 4).

Teacher's feedback

Concerning the teacher's opinions and suggestions about the digital game-based learning (DGBL) experience, he considered that the activity has the potential to be a valuable educational tool for learning spatial geometry in secondary education since the game can motivate students and make the content more engaging. However, he wondered whether the application could have been implemented at a lower grade, as the proposal also seems suitable for those stages. He found the design of the activity, which differentiates between creating and solving (rather than just solving), to be very appropriate, with a clear objective of identifying improvements in learning. The activity focuses on a single goal (recognition of a shape), and he suggested that it would be a good idea to expand the objectives to include elements such as volume, for example.
In conclusion, he believed it was a good activity and one that could be repeated to reinforce spatial geometry. Additionally, the game's structure could be leveraged to create hands-on materials based on the same idea, reaching students who have difficulties with digital tasks.

5. Discussion

This study examined Digital Game-Based Learning (DGBL) using Activity Theory (AT) [6], focusing on contradictions from game designs that limit student and teacher authorship, resulting in passive consumption, reduced engagement, misaligned curriculum, and limited adaptability. We highlight the benefits of student-created game content as an alternative to approaches that rely on the automatic generation of game challenges [60], which deepens learning competences and fosters critical thinking and creativity.
Our findings indicate that students who both played and created challenges (experimental group) were more engaged than those who only played (control group), as shown by UX and SIMS questionnaires, consistent with earlier studies [61, 62]. However, challenge creators exhibited higher A-Motivation, possibly due to self-doubt regarding their ability to design effective challenges.
Regarding learning competences, playing GeoBuild improved outcomes for all students [63], though the experimental group did not consistently outperform the control group. The experimental group, which spent less time playing due to creating challenges, engaged in higher-order skills (creativity, critical thinking) that our exams did not specifically assess. Analysis of challenges, and errors revealed slightly better outcomes for the experimental group, with significant differences only in error rates, suggesting a more reflective strategy compared to the control group's trial-and-error approach [64, 65]. Further, when comparing challenge creators (teacher vs. peers), students

found peer-created challenges more difficult — evidenced by higher errors and longer completion times — likely due to insufficient guidelines or lack of teacher review.

Although promising, the study has limitations. During the experience, we detected some students who experienced difficulties manipulating 3D objects, which may have hindered their engagement with geometry, and some were uncomfortable in the creator role, expressing uncertainty about challenge difficulty. Addressing these usability issues and providing clearer guidelines could improve the overall experience [61].

The study also identified teacher barriers in using DGBL, such as limited technical skills requiring ongoing technician support. This aligns with previous research [66] emphasizing the need for proper training and support in using digital tools and applying assessment logs. Regarding the Teaching Activity System, the teacher can be helped in terms of the Tools (i.e. how to introduce and produce digital contents) as well in terms of Rules used (i.e. picking up logs during the game to help the assessment of learning).

Finally, given the limited sample size and short duration, future research should examine the long-term effects of involving students in game creation and its impact on learning across various subjects and educational levels.

6. Conclusions

This paper analyses the three Activities Systems involved in Digital Game-Based Learning (DGBL) through the lenses of the third generation of Activity Theory (AT). Specifically, we based our approach on Engeström's *Expansive Learning* theory [10], where learners, accompanied by teachers and supported by game designers, not only acquire knowledge but also transform their practices and roles within the Activity System itself. Therefore, we conducted a quasi-experimental study to answer the following two research questions: RQ1: *"How does Expansive Learning designed in a game influence the learning experience in terms of learning outcomes and engagement?"*, and RQ2: *"How do game challenges created by students impact their peers' learning experience?"*. We designed and developed a geometry game (GeoBuild and GeoSoduku) targeting secondary students based on the Expansive Learning principles. Learning outcomes were assessed via pre- and post-tests, motivation and enjoyment through questionnaires, and engagement using in-game analytics and qualitative feedback. The results confirm that when learners take an active role in the creation of game content, their experience is enhanced in terms of engagement and motivation. While challenges remain in ensuring the usability of such tools and providing adequate support to teachers, these findings suggest that authoring-enabled DGBL environments show potential for supporting active learning and creativity in educational settings.

Exploring results with larger sample sizes will be a key aspect of future work, along with the study of design guidelines and collaborative tools to help students co-create challenges, fostering peer learning and easing the cognitive load involved in individual challenge design. Additionally, expanding DGBL to other subject areas such as language learning, history, or science would enable the assessment of the transferability of authoring tools across disciplines and their impact on motivation and outcomes.

Acknowledgments

To Col·legi Tarrés (Sabadell) and Professor Josep Mª Granados. This work was supported by the SGR CLiC project (2021 SGR 00313), FairTransNLP-Language (PID2021-124361OB-C33), and ACISUD (PID2022-136787NB-I00 funded by MICIU/AEI/10.13039/501100011033).

Conflicts of interest

None

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