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From LEGO® bricks to virtual reality: Experimenting collaboration across physical, screen-based, and immersive settings

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A B S T R A C T

Collaboration is widely acknowledged as a critical competence for contemporary organizations, yet it remains insufficiently addressed in management education. This study explores how simulation-based training (SBT) can be used to teach collaboration across physical, screen-based, and immersive (VR) modalities. Drawing on survey and qualitative data from 40 undergraduate students who experienced the three simulation modalities, the study builds on O'Leary et al.'s (2020) framework of distributed collaboration to examine how social and material factors interact in shaping learners' understanding of teamwork dynamics. The results extend the framework by showing that endemic-social, endemic-material, relational-social, and relational-material dimensions vary in prominence depending on the technological and contextual configurations of the learning environment. The study contributes theoretically by contextualizing O'Leary et al.'s model within educational settings and demonstrating how experiential design can reveal the interplay between social and material conditions of teamwork. Practically, it provides a structured design process and guiding principles for integrating multimodal simulations into management education, supporting the deliberate development of adaptive and reflective collaboration skills.

1. Introduction

Collaboration is widely recognized as a key factor in organizational performance, supporting both innovation and adaptability in a changing business environment (Kwan, 2019). Employees now spend a substantial portion of their work time in collaborative efforts, reflecting the integral role of teamwork in achieving shared goals (Mashek, 2022). Yet, while collaboration is essential, it often brings challenges: when demands for collaboration become excessive, they can reduce productivity and the quality of outcomes (Cross et al., 2019), digital connectivity overload may hinder focus and creativity (Bernstein et al., 2019), and group dynamics may further complicate teamwork (Kwan, 2019).

Although central to professional life, collaboration is rarely taught in higher education, leaving many graduates to learn through trial and error in the workplace (Mashek, 2022). This gap reveals not only a mismatch between the recognized importance of collaboration and the limited pedagogical attention it receives, but also a second, less addressed issue: the growing diversity of technological modalities available to support collaboration, ranging from physical co-presence to digital platforms and immersive–VR, whose educational value remains insufficiently understood. The recent advent of VR further broadens these possibilities, offering novel affordances for presence and creativity (Purdy, 2022; Vogel et al., 2021), while also raising fresh questions about its challenges and underexplored learning outcomes (Alazmi & Alemtairy, 2024; Elaish et al., 2024).

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In response to these gaps, namely the lack of structured pedagogical approaches for teaching collaboration and the limited understanding of how different technological modalities shape it, this study designed and tested a three-fold simulation-based training (SBT) with university students. The same collaborative task, the “LEGO® Challenge”, was carried out in three different technological modalities: (1) a physical setting with LEGO® bricks (Physical–LEGO®), (2) a screen-based digital environment using Minecraft Education (ME) on a traditional screen (Screen-based–ME), and (3) an immersive environment using Minecraft in virtual reality headsets (Immersive–VR).

The LEGO® Challenge was chosen because it is a highly collaborative task: its success depends entirely on coordination, shared understanding, and non-verbal communication among participants. Typically conducted in silence, it compels teams to organize, interpret others’ intentions, and adjust strategies dynamically. By keeping the task constant while varying the medium, the study compares how each modality shaped teamwork, thereby identifying the specific benefits, limitations, and complementarities of Physical–LEGO®, Screen-based–ME, and Immersive–VR for collaboration learning.

This study explores how SBT can be used to foster collaboration as a transversal competence. It contributes in two ways. Theoretically, it extends O'Leary et al.’s (2020) framework of distributed collaboration by analyzing how endemic-social, endemic-material, relational-social, and relational-material factors play out across distinct modalities. Practically, it provides educators with design principles, empirical insights, and critical reflections for integrating Physical–LEGO®, Screen-based–ME, and Immersive–VR into management education.

The paper first introduces the theoretical foundations of collaboration and the rationale for using simulation-based training. It then describes the three technological modalities together with the study design, data collection, and analysis. The results combine quantitative and qualitative insights, interpreted through O'Leary et al.’s (2020) framework. The article concludes with the main theoretical and practical implications, its limitations, and avenues for future research.

2. Conceptual background

2.1. Collaboration and its learning challenges

Although the literature presents a range of definitions, collaboration is commonly understood as the process where multiple parties engage jointly in an effort to achieve shared goals using shared rules, norms, and structures (Wood & Gray, 1991). Schmidt and Bannon (1992) further elaborate that successful collaboration extends beyond primary tasks to include managing interpersonal relationships, task allocation, accountability, and coordination efforts to support a collective aim.

Over the last decades, IT has transformed how teams collaborate, enabling distributed teams to operate continuously across time zones and providing access to a wider range of global expertise beyond the traditional co-located environments (Gupta et al., 2009). Collaboration can therefore unfold in diverse settings, encompassing both spatially distributed scenarios—where participants are either co-located or in different locations—and temporal dynamics, including synchronous (same-time) and asynchronous (different times) interactions (O'Leary & Cummings, 2007). The success of these collaborative efforts significantly depends on the media capabilities, highlighting the critical role of technology in facilitating effective communication, coordination, and cooperation across diverse work arrangements (Harrison & Windeler, 2020).

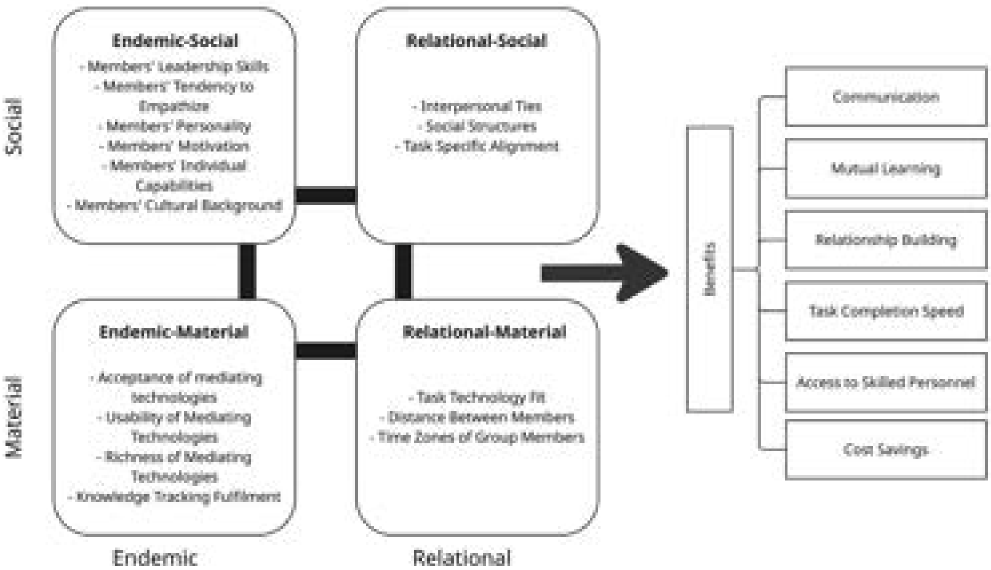

Fig. 1. O'Leary et al. (2020)'S model of distributed collaboration.

While the challenges of distributed collaboration and virtual teams were already recognized, the COVID-19 pandemic emphasized these difficulties. Many companies have struggled with remote productivity and team cohesion, facing communication barriers and the need for new leadership skills and capabilities (Leinwand et al., 2021). To delve deeper into this issue, O'Leary et al. (2020) introduce a comprehensive framework to understand the success factors behind distributed collaboration. Their model positions contributing factors along two intersecting axes: social versus material (distinguishing human-centered attributes from technological affordances) and endemic versus relational (contrasting general traits that cut across contexts with those that emerge in specific relationships). This dual classification not only synthesizes a wide range of prior findings but also clarifies how factors interact rather than operate in isolation.

Within this framework, *Endemic-Social* elements include recurring traits such as leadership, empathy, motivation, or cultural background, which shape how members contribute across collaborative settings. *Endemic-Material* factors encompass acceptance, usability, and richness of mediating technologies, complemented by knowledge-tracking functionalities that create digital traces and influence motivation, reputation, and trust. *Relational-Social* factors are more fine-grained and cover interpersonal ties (trust, communication, prior history), social structures (norms, governance, networks), and task-specific alignment (shared understanding, coordination, mutual learning). Finally, *Relational-Material* considerations refer to task–technology fit, geographical distance, and temporal dispersion, which act both as enablers and constraints depending on their alignment with group processes.

A key contribution of O'Leary et al. (2020) lies in showing that these dimensions do not operate independently but complement and moderate one another. For instance, empathy can compensate for weak leadership, usability of technologies enhances communication and trust, and cultural diversity interacts with communication standards to either fuel conflict or support shared understanding. By explicitly linking these dynamics to six outcomes—communication, mutual learning, relationship building, task-completion speed, access to skilled personnel, and cost savings—the framework provides not just a taxonomy of factors but a relational perspective on how distributed collaboration succeeds. The framework is depicted in Fig. 1.

This framework is central to our study. While originally developed to explain collaboration dynamics in organizational contexts, it is especially pertinent in pedagogical settings, where students are preparing to join organizations and where collaborative experience can be examined as both a learning process and a precursor to professional practice. We therefore aimed to provide students with a direct experience and a deeper awareness of the four categories of factors: Endemic-Social factors (e.g., leadership, empathy), Endemic-Material factors (e.g., technology acceptance, usability), Relational-Material factors (e.g., task–technology fit, communication constraints), and Relational-Social factors (e.g., trust, presence). By keeping the task constant and varying the technological medium, our pedagogical objective was to make these factors visible and show how social and material elements jointly shape collaborative dynamics. For this purpose, we chose simulation-based training (SBT) as our pedagogical approach (Gegenfurtner et al., 2014).

2.2. Simulation-based training for collaboration

Simulation-Based Training (SBT) is a practice environment designed to develop competencies such as knowledge, skills, attitudes, and behaviors to improve performance (Salas et al., 2009, p. 560). Its effectiveness in facilitating learning and knowledge retention is well documented (Sitzmann, 2011; Tiwari et al., 2014). Grounded in Kolb's experiential learning cycle (2014), SBT provides opportunities to experience, reflect, think, and act, thereby promoting critical thinking, hypothesis testing, and the application of theory to practice (Kolb, 2014). Importantly, it also supports collaborative learning: team-based scenarios encourage peer interaction and the co-construction of knowledge (Callaghan, 2016), with meta-analyses confirming strong effects on the acquisition of complex skills (Chernikova et al., 2020).

Despite these benefits, SBT is challenging to develop and implement. It requires significant technical, financial, and pedagogical resources, and its effectiveness depends on tailoring content to learner diversity, creating engaging scenarios, and fostering a supportive social learning environment (Bell et al., 2008; Silva et al., 2019). Scholars have highlighted the importance of applying theory-based guidelines for designing and developing simulation-based training to ensure educational effectiveness, emphasizing the need for careful planning and execution (Bell et al., 2008; Jamil & Isiaq, 2019; Salas et al., 2012). Indeed, developing a SBT is a systematic process that starts with a thorough needs analysis to tailor the content, followed by crafting a robust strategy and design, with a special focus on enhancing learners' self-efficacy and motivation (Salas et al., 2012). Ensuring SBT is engaging is crucial (Bell et al., 2008) and can be greatly enhanced by crafting experiences that promote immersion, social interaction, challenge, and control (Fu et al., 2009), while also ensuring they are enjoyable and playful (Bourdeau, Barki, & Legoux, 2021). While SBT has been widely applied in different domains, such as healthcare and aviation, its potential for teaching transversal competences like collaboration in organizational settings remains underexplored.

To structure our study and ensure comparability across settings, we proceeded in four main steps. We first selected three technological modalities— Physical–LEGO®, Screen-based–ME, and Immersive–VR—that represent distinct ways of supporting collaborative work. For each modality, we then examined how O'Leary et al.'s four categories of factors (endemic-social, endemic-material, relational-social, and relational-material) could be made visible, clarifying the pedagogical potential of each environment. We also reviewed the literature on simulation-based training to extract design principles that could guide the implementation of our activities. Finally, we deliberately designed the simulations to foreground additional factors of O'Leary framework, such as non-verbal communication in Physical–LEGO® and text-based coordination in Screen-based–ME, thereby providing students with a broader experiential understanding of how collaborative dynamics vary across technological contexts.

By participating in the simulations, students are expected to develop collaborative competencies by engaging in diverse environments that require the adaptation of communication, coordination, cooperation, and problem-solving strategies across

Physical–LEGO®, Screen-based–ME, and Immersive–VR contexts. In doing so, they will foster a critical awareness of the strengths and limitations inherent in each modality, recognizing that the most recent technological innovation is not necessarily always the most effective approach. Ultimately, this process will cultivate informed decision-making skills, enabling students to select and apply the modality that best aligns with the requirements of future collaborative tasks and challenges.

2.3. Technological modalities for collaboration learning

As the second step of our research design (see STEP 2 in Fig. 2) and building on the theoretical foundations and empirical evidence reviewed earlier, we synthesized how each modality is likely to make O'Leary et al.'s (2020) categories of factors visible in a learning context. The following anticipations are therefore grounded in prior studies on LEGO® in education, digital learning environments such as ME, and immersive simulations in VR (see Fig. 3).

2.3.1. Physical–LEGO®

LEGO® bricks provide a tangible, playful, and accessible environment through which students can experience collaboration. Their ease of use and familiarity, since many participants played with LEGO® in childhood, make them an immediately useable tool, requiring little preparation (Bonneau & Bourdeau, 2019). As a tangible medium, they foster immersion and are frequently used to make abstract theoretical concepts visible (Liang et al., 2021). Manipulating LEGO® bricks also stimulates creativity and imagination by offering challenges that can be easily adapted: from simple to complex constructions (Bonneau & Bourdeau, 2019). This engagement encourages curiosity, supports reflection, and helps reduce stress while promoting new ideas (Wheeler et al., 2020). LEGO® has also been shown to provide a shared language and to foster empathy and cohesion (Warburton et al., 2022; Wheeler et al., 2020). Yet, participants may initially perceive LEGO® as a children's toy, leading to skepticism or reluctance to engage fully (Warburton et al., 2022). Moreover, benefits are often recognized only once participants immerse themselves in the activity (Warburton et al., 2022; Zenk et al., 2018).

Therefore, based on these insights from the literature, our premise is that LEGO® highlights several collaborative factors within O'Leary et al.'s framework:

At the *endemic-social level*, LEGO® activities tend to elicit **intrinsic motivation** and **empathy**. The playful nature of the medium stimulates engagement and enjoyment, encouraging participants to take part actively and persist in the task (Bonneau & Bourdeau, 2019; Wheeler et al., 2020). At the same time, its tangible and collective dimension often triggers empathic responses, as individuals become more attentive to others' actions and emotions within the shared construction process (Warburton et al., 2022).

At the *endemic-material* level, LEGO® offers high **ease of use**, as emphasized in prior work, since participants can manipulate the bricks directly and observe the evolving construction. We anticipated that this usability would, in turn, facilitate mutual adjustment and collective control over the task. LEGO® may also raise **issues of acceptance**, as some participants initially perceive it as a children's toy (Warburton et al., 2022). We anticipated that such skepticism could result in reluctance to engage fully.

At the *relational-social* level, the literature highlights the role of LEGO® in creating **a shared language** that facilitates mutual understanding within teams. We also anticipated that the tangible and visible nature of the constructions would support more **natural coordination** among participants (Bonneau & Bourdeau, 2019). Taken together, these interaction-level factors were expected to reduce stress, strengthen trust, and foster cohesion within the group (Wheeler et al., 2020).

At the *relational-material* level, even if this aspect is not explicitly emphasized in the literature, we considered that, in our case, LEGO® bricks provide a strong task–technology fit. Participants collaborate through **physical co-presence** and **synchronous**

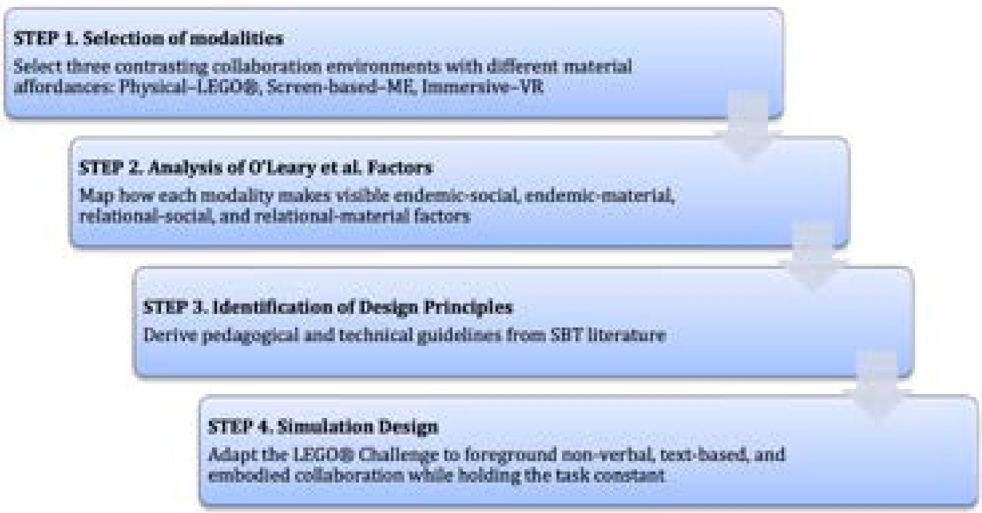

Fig. 2. Research design for developing collaboration simulations.

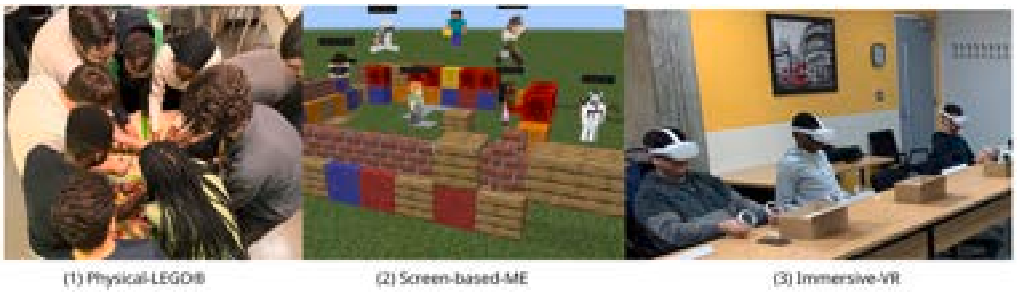

Fig. 3. A threefold simulation to enhance collaborative skills.

interaction, manipulating shared materials in real time, which offers immediate feedback and facilitates coordination. We anticipated that this alignment would make task management more straightforward than in digitally mediated settings.

2.3.2. Screen-based–ME

Minecraft Education (ME) is an education-oriented version of one of the most popular video games worldwide. It provides a structured yet flexible environment where participants use avatars to construct and interact with structures, making it a valuable tool for developing digital training activities at lower cost than proprietary solutions (Coulon et al., 2025). ME's flexibility and accessibility enable instructors to design activities that reflect real-world demands such as negotiation, role distribution, and coordination (García-Álvarez & Acevedo-Borrega, 2025; Jiménez-Puerto & Gallello, 2025). Its relatively low complexity and modest technical requirements reduce entry barriers, allowing students to focus on group dynamics rather than technical mastery (Bourdeau, Coulon, & Petit, 2021). The multiplayer environment fosters authentic teamwork, as participants synchronize actions and manage shared resources, while sandbox features make contributions visible and support accountability and interdependence (Callaghan, 2016; García-Álvarez & Acevedo-Borrega, 2025). The playful design of ME also encourages persistence and reflection, as trial and error is normalized and students can critically engage with collective decision-making (Coulon et al., 2025).

Yet, for learners, maintaining focus can be problematic in open-ended environments, particularly in remote learning contexts (Coulon et al., 2025; Hébert & Jenson, 2020). Multiplayer modes, while supporting collaboration, may also enable disruptive behaviors such as resource hoarding or “griefing” (Hébert & Jenson, 2020). Technical issues, such as software bugs or unstable internet connections, may further disrupt learning activities (García-Álvarez & Acevedo-Borrega, 2025). Finally, differences in player experience may create imbalances, as expert players dominate or fall back on habitual strategies while novices struggle with basic mechanics, leading to frustration and unequal participation (Nebel et al., 2016).

Based on these insights from the literature, our premise is that ME highlights several collaborative factors within O'Leary et al.’s framework.

At the *endemic-social* level, we anticipated that differences in **player experience**, with some participants arriving as expert gamers and others as novices, would influence individual confidence and willingness to contribute (Nebel et al., 2016). In turn, we expected **differential motivation**, fostered by the playful design of ME, sustaining persistence and collective engagement for some students while proving more challenging for others.

At the *endemic-material* level, we anticipated that the **ease of use** of ME would enable students to focus directly on collaborative tasks rather than on learning how to handle the tool (Bourdeau, Coulon, & Petit, 2021). Conversely, issues of **technical reliability**, such as connection problems or bugs, if occurring, were expected to generate frustration and hinder effective collaboration (García-Álvarez & Acevedo-Borrega, 2025).

At the *relational-social level*, we anticipated that **online teamwork in a shared virtual space** in ME, where all participants are present simultaneously and can observe one another's actions while using the same resources (blocks, items), would foster coordination and a sense of working toward a shared objective, making the teamwork feel authentic despite the lack of physical co-presence. At the same time, the possibility of **disruptive behaviors**, such as griefing, was expected to challenge cohesion and create tensions within the group (Hébert & Jenson, 2020). Finally, **difficulties of maintaining attention** in open-ended environments were anticipated to weaken group cohesion and collaboration (Coulon et al., 2025).

At the *relational-material level*, we anticipated that the shared virtual space of ME would provide **digital co-presence**, allowing participants to collaborate in real time within the same environment (Callaghan, 2016; García-Álvarez & Acevedo-Borrega, 2025). We considered this setting to enhance task–technology fit by enabling synchronous interaction and collective alignment.

2.3.3. Immersive-VR

VR places learners in three-dimensional, computer-generated environments (Chen & Syu, 2024) that foster a strong sense of presence (Krassmann et al., 2024) and enable more natural interactions such as gaze, gesture, or handshakes (Moon et al., 2024). Research highlights that VR supports experiential learning (Crogman et al., 2025) and has been shown to increase motivation and engagement (Crogman et al., 2025; Yu & Duan, 2024). Its immersive qualities strengthen social presence (Oh et al., 2018) and have been shown to foster empathy and social skills (Alazmi & Alemtairy, 2024). VR also provides a safe and risk-free environment in which learners can practice complex tasks (Buchner & Hofmann, 2022; Crogman et al., 2025). Moreover, by allowing geographically dispersed participants to collaborate in the same virtual space, it broadens access to teamwork opportunities (Crogman et al., 2025).

Applications of VR already extend to leadership, human resources, and entrepreneurship (Alcañiz et al., 2018; Haber et al., 2022; Ronaghi & Forouharfar, 2024) confirming its potential for developing complex interpersonal competencies. Studies show that VR can foster trust (Pidel & Ackermann, 2020), shape coordination through avatars and shared objects (Schäfer et al., 2022) and make visible the dynamics of shifting between loosely and tightly coupled teamwork (Bimberg et al., 2025).

At the same time, using VR in education entails significant challenges. Technically, high costs, hardware maintenance, and connectivity issues can interrupt group activities, while latency and desynchronization directly undermine collaborative flow (Crogman et al., 2025; Köroğlu, 2025; Zielke et al., 2025). Pedagogically, designing tasks that align immersive features with learning objectives is difficult; poor design risks overwhelming students with excessive cognitive load (Sakr & Abdullah, 2024). Finally, learner experience adds further constraints: many participants have no prior exposure to VR (Noble et al., 2022), and platforms often involve a steep learning curve (Balalle, 2025). Moreover, physical discomforts such as motion sickness (Sakr & Abdullah, 2024) can reduce participation and limit the effectiveness of the simulation.

Based on these insights from the literature, our premise is that Immersive–VR highlights several collaborative factors within O'Leary et al.'s framework.

At the *endemic-social* level, the literature has highlighted motivation as a recurring outcome of VR. Building on this, we anticipated **heightened motivation**, as the immersive and playful nature of VR was expected to sustain persistence and active participation, further reinforced by the initial "wow factor" of immersion. The literature has also underlined the role of VR in fostering **empathy** (Alazmi & Alemtairy, 2024), as embodied interactions were expected to strengthen perspective-taking and social sensitivity, creating a more supportive collaborative climate. At the same time, differences in **player experience**, with some participants entirely new to VR and others more familiar, were anticipated to influence confidence and willingness to contribute (Noble et al., 2022).

At the *endemic-material* level, limitations in **technological reliability**, such as latency, desynchronization, or connectivity issues, were expected to disrupt collaborative flow, as highlighted in prior work. In addition, **usability challenges**, given the steep learning curve and lack of prior experience for many participants (Balalle, 2025), were anticipated to slow down effective collaboration.

At the *relational-social* level, we anticipated that VR would enable more **quasi-natural coordination**, as participants could rely on gestures and gaze to align their actions more easily (Moon et al., 2024). We also anticipated that these affordances would foster trust, reinforcing cohesion and openness within the team despite the lack of physical co-presence (Pidel & Ackermann, 2020).

At the *relational-material* level, we anticipated that VR would make **distributed collaboration** feel more immediate, as its immersive qualities foster **immersive co-presence** and allow interactions to appear more natural (Moon et al., 2024). At the same time, we expected that risks of **latency and desynchronization** could undermine this alignment, disrupting the fluidity of group work.

3. Simulation design

To design our simulations, we combined the three technological modalities while carefully considering both their reported benefits and challenges. We first analyzed the literature on simulation-based training in general, followed by studies on SBT in digital environments and SBT in VR, to identify a set of guiding principles. From this broader set, we retained the principles that were directly applicable to our context, ensuring that our design choices were pedagogically grounded, technically feasible, and supportive of meaningful learning.

3.1. Guiding principles

In the third step of our design process (see STEP 3 in Fig. 2), we derived a set of pedagogical and technical principles from the simulation-based training literature to ensure comparability and engagement across modalities. Table 2 presents the guiding principles retained to support the design of our simulations.

Building on these principles, the next section presents the three simulations developed and tested in our study.

3.2. The study

To ensure comparability across modalities, we implemented the same collaborative task, the "LEGO® Challenge",[1] in three distinct forms: with Physical–LEGO®, Screen-based–ME, and Immersive–VR. This design allowed us to simulate scenarios requiring synchronous collaboration in different technological and spatial setups, thereby examining how varying environments shape teamwork and collaboration.

Originally designed to let participants experience the challenges of non-verbal communication, leadership dynamics, and teamwork, the "LEGO® Challenge" is a collaborative exercise where 10 to 12 participants work together to build, in silence, a structure from LEGO® bricks under specific constraints, such as limited time or communication restrictions, and included individual secret instructions to enhance complexity (e.g., You have to make sure that there are only red bricks in the 2nd and 5th layers of the building; You have to make sure that the first layer (layer 1) of the building consists of exactly 10 bricks). All three simulations used the same set

[1] https://www.sessionlab.com/methods/lego-challenge.

of secret assignments, but the assignments were randomly distributed for each simulation, and we made sure that no student had the same assignment twice. For our study, we adapted the communication-related rules to fit each simulation modality but kept all other task elements identical.

Across the study, all students participated in the three modalities. Teams of ten rotated through the three settings, and the order was randomized. At any given time, the three simulations ran in parallel, with one team assigned to each modality and supported by two facilitators. Each simulation lasted 20 min, followed immediately by a structured debriefing before the team moved on to the next setting.

3.2.1. Physical–LEGO®

In the first modality, participants engaged in the original "LEGO® Challenge", a collaborative construction task completed in total silence. Ten students formed a single team, each receiving their own secret personal instructions. They were given a large bin of assorted LEGO® bricks with the instruction to build a structure within 20 min. Verbal communication was not permitted, requiring participants to rely exclusively on gestures, facial expressions, and non-verbal coordination to organize their work. Two facilitators observed and supported the activity logistically. This setup emphasized the importance of physical presence and non-verbal cues in team collaboration, illustrating how coordination and trust can emerge—or break down—in the absence of speech. A debriefing session followed to encourage reflection on the role of implicit communication in shaping teamwork.

3.2.2. Screen-based–ME

The second modality transferred the same construction task into a digital environment using ME on a computer. Ten participants worked together for 20 min in a blank Minecraft world with unlimited resources. Communication was limited to text-based chat, with no time or message constraints other than the task deadline. They were instructed not to share their secret mission with their teammates. As with the LEGO® simulation, two facilitators were present for oversight and support. This setting was designed to investigate the effects of asynchronous, written communication on collaboration, particularly in terms of role distribution, coordination of actions, and the challenges of interpreting meaning without visual or vocal cues. The simulation foregrounded the material constraints of digital platforms, highlighting both the opportunities (record of interactions, equal visibility of written contributions) and the challenges (delays, misinterpretation, uneven participation). A structured debriefing followed, focusing on the advantages and limitations of text-only collaboration.

3.2.3. Immersive–VR

The third modality employed Minecraft in virtual reality headsets, immersing ten participants in a shared 3D world. Teams were placed in a different blank map, with unlimited resources, and asked to construct collaboratively within a 20-min timeframe. Unlike the screen-based version, participants communicated freely through voice chat, but without the possibility of seeing one another's physical faces or gestures outside the virtual space. Here too, they were instructed not to share their secret mission with their teammates. This design allowed learners to experience whether the affordances of immersion, presence, and embodied interaction could foster stronger cohesion and more effective teamwork compared to traditional digital platforms. Two facilitators supported the simulation, and a debriefing session followed, inviting participants to reflect on how immersion and voice-based communication influenced trust, coordination, and the sense of "being together."

Demonstration capsules were provided, prior to class, for the digital tools (VR and screen-based versions of Minecraft) to facilitate ease of use. For the screen-based version, a mandatory tutorial session prior to the main activity ensured that students were well-prepared to navigate the software, effectively minimizing potential technological hurdles.

Beyond the factors anticipated from the literature and summarized in Table 1, our empirical design introduced additional features intended to make specific aspects of O'Leary et al.'s (2020) framework more salient to students. This stage corresponds to the fourth step of our research design (see STEP 4 in Fig. 2), which involved translating theoretical expectations into concrete simulation design choices.

Table 1
Anticipated collaboration factors across simulation modalities derived from the literature and organized according to O'Leary et al.'s (2020) framework.

Collaboration Factors	Simulation Modalities		
	Physical–LEGO®	Screen-based–ME	Immersive-VR
Endemic-Social	Intrinsic motivation Empathy	Differential motivation Player experience	Heightened motivation Empathy Player experience
Endemic-Material	Ease of use Issues of acceptance (skepticism)	Ease of use Technological reliability	Usability challenges Technological reliability
Relational-Social	Natural coordination Shared language	Online coordination in a shared virtual space Disruptive behaviors Difficulties of maintaining attention	Quasi-natural coordination in VR
Relational-Material	Physical co-presence Synchronous interactions	Digital co-presence	Immersive co-presence Distributed collaboration Latency and desynchronization

Table 2
Design principles for simulation-based training in collaboration learning.

Description	Modalities	Sources
Pedagogical and Learning Design		
Align simulation with learning objectives: Simulations should be explicitly designed so that collaboration is central to the task, requiring interdependence among participants and directly connected to the intended learning outcomes. ⇒ In our case, this means designing tasks in a way that integrates O'Leary et al.'s (2020) four categories.	**ALL**	Lin and Wang (2024); Peney and Skarratt (2024); Solmaz et al. (2024); Wehrmann and Zender (2024); Hébert and Jenson (2020); Vlachopoulos and Makri (2017); Salas et al. (2009)
Foster immersion and psychological safety: This principle is expected to foster student engagement across all forms of SBT. ⇒ In our case, it also serves to make visible the role of endemic-social factors (e.g., motivation, empathy) and relational-social factors (e.g., trust, group norms).	**ALL**	Coulon et al. (2025); Lin et al. (2024); Lin and Wang (2024); Matute-Vallejo and Melero-Polo (2019); Silva et al. (2019); Sinha (2023)
Provide feedback and reflection: Opportunities for feedback and debriefing should be integrated to promote iterative learning. ⇒ In our case, these debriefings also ensure that students explicitly recognize and articulate the factors highlighted in O'Leary et al.'s (2020) framework.	**ALL**	Faisal et al. (2022); Köroğlu (2025); Matto et al. (2024); Udeozor et al. (2023)
Ensure authenticity: Simulations should reproduce meaningful and realistic scenarios. ⇒ In our case, authenticity helps students connect the task with real-world collaboration, making visible how O'Leary et al.'s (2020) factors play out in practice.	**ALL**	Alcañiz et al. (2018); Ketron et al. (2025); Wehrmann and Zender (2024)
Technical Design		
Design engaging environments: Simulation environments should balance realism and creativity, combining authentic representations with imaginative elements. ⇒ In our case, this principle ensures that students experience both the affordances and constraints of the medium.	**Screen-based–ME and Immersive–VR**	Wehrmann and Zender (2024)
Leverage readymade platforms: Instead of developing proprietary solutions, accessible "readymade" platforms should be used to reduce technological complexity and costs while ensuring adaptability and scalability. ⇒ In our case, this means relying on the tools already available at our university.	**Screen-based–ME and Immersive–VR**	Bourdeau, Coulon, and Petit (2021)
Manage cognitive load: VR should be designed to balance sensory input and cognitive processing, with clear objectives, structured tasks, and in-app guidance to prevent overload ⇒ In our case, this means structuring the activity so that students can focus on collaboration itself, making visible both relational-social factors and endemic-material constraints (usability, technical stability).	**Immersive-VR**	Elaish et al. (2024); Lin et al. (2024); Wehrmann and Zender (2024)
Implementation and Support		
Manage expectations: Simulations should include demonstrations and tutorials to set realistic expectations and reduce frustration. ⇒ In our case, tutorials for ME and VR help students engage effectively, while still making visible how varying levels of familiarity with the tool (an endemic-material factor) influence collaboration dynamics.	**Screen-based–ME and Immersive–VR**	Netland et al. (2020); Solmaz et al. (2024)
Provide technical support: Dedicated assistance should be available to provide troubleshooting and guidance, particularly for challenges related to hardware, connectivity, or unfamiliar platforms. ⇒ In our case, this means providing support to students during the workshops to address technical difficulties; at the same time, these difficulties were deliberately kept visible, illustrating how endemic-material constraints (usability, stability) can disrupt or shape collaboration.	**Screen-based–ME and Immersive–VR**	Köroğlu (2025); McGovern et al. (2020)

In the LEGO® condition, the restriction to silence foregrounded **non-verbal communication**, highlighting how gestures, facial expressions, and bodily coordination serve as substitutes for verbal interaction. In the screen-based simulation, **the reliance on text-based chat** required participants to communicate exclusively through written messages, a design choice detailed in the methods. We anticipated that this restriction would slow coordination, increase misunderstandings, and ultimately reduce synchronicity across participants. In the VR simulation, by contrast, we incorporated voice chat to approximate face-to-face communication, allowing participants to coordinate more fluidly but also revealing how issues of turn-taking, overlapping speech, and audio quality shape collaboration.

Table 3 therefore consolidates the initial theoretical expectations (Table 1) with these additional design-specific elements, illustrating how our pedagogical choices deliberately emphasized certain collaborative dynamics that were not explicitly discussed in prior studies.

4. Methods

This study follows a comparative mixed-method research design aimed at examining how different technological modalities shape collaboration learning. The same collaborative task was implemented across three modalities—Physical–LEGO®, Screen-based–ME, and Immersive–VR—allowing within-participant comparisons of learning experiences. Participants completed the task in each modality through a rotating sequence of simulations, ensuring that all students experienced the three conditions under comparable time and task constraints. Quantitative survey data and qualitative feedback were collected after each simulation to capture students' perceptions and experiences across modalities. This approach allows us to identify measurable differences in engagement and perceived learning while also capturing how students interpret and experience collaboration in each technological setting.

The simulation was conducted with 60 undergraduate students enrolled in a hybrid work collaboration course within a business and management program at a North American university. All students in the course participated in the simulation activities as part of the course, but participation in the research component (survey and data collection) was voluntary. Students were familiar with digital collaboration tools commonly used in academic settings, including messaging platforms, online meetings, shared documents, and a wiki that functioned as both a learning platform and a space for collaborative writing; by contrast, prior exposure to immersive technologies such as virtual reality was limited and, when present, was mostly confined to recreational uses such as gaming.

The study took place across two sessions held in Fall 2023 and Winter 2024. The first iteration involving 20 students served as a pretest to refine the study's design and tools. This paper analyzes data collected exclusively during the second iteration conducted with 40 students. Since the number of VR headsets was limited (10), we designed each of the three simulations for a group of 10 students and adapted the "LEGO® Challenge" accordingly.

Following each simulation activity, i.e., Physical–LEGO®, Screen-based–ME, and Immersive–VR, participants completed a survey using a 7-point Likert scale to evaluate constructs related to collaborative work: Flow, Perceived Learning, Enjoyment, Satisfaction, and Behavioral Engagement (adapted from Barzilai & Blau, 2014; Buil et al., 2020; Opdecam et al., 2014). These constructs measure the depth of engagement, perceived educational value, emotional response, overall satisfaction, and level of active participation. The survey was enriched with open-ended questions to capture students' perceptions and experiences, aiming to delineate the pros and cons of each collaborative modality and their optimal contexts.

Participation in the survey was voluntary, dissociated from academic evaluation, with all 40 students providing responses for each simulation modality. The six facilitators documented the activities through field notes, while two PhD students served as independent observers, providing additional qualitative insights into the collaborative dynamics.

To ensure the reliability and validity of our scales, we computed Cronbach's alpha, descriptive statistics for each construct, and employed comparative analyses to highlight experiential differences across the Physical–LEGO®, Screen-based–ME, and Immersive–VR simulations. To examine mean differences between conditions, we used mixed-effects (multilevel) models with random intercepts that vary across participants to account for repeated measures. This approach, more flexible than traditional repeated-measures ANOVA, accommodates uneven observation counts and offers robust estimates for randomly missing data (Enders, 2022). We used the restricted form of maximum likelihood estimation, which yields more valid and less biased results in smaller samples (Hox et al., 2018). All analyses were conducted using R v4.5.1 (R Core Team, 2025). Mixed-effects models are implemented in the library lme4 (Bates et al., 2015), and pairwise mean comparisons are performed using the library emmeans (Lenth, 2025).

In our qualitative analysis, we meticulously categorized 311 brief responses extracted from three open-ended questions in the

Table 3
Anticipated collaboration factors across modalities, integrating literature-based expectations (Table 1) with additional design elements introduced in the simulations.

Collaboration Factors	Simulation Modalities		
	Physical–LEGO®	Screen-based–ME	Immersive-VR
Endemic-Social	Intrinsic motivation Empathy	Differential Motivation Player experience	Heightened motivation Empathy Player experience
Endemic-Material	Ease of use Issues of acceptance (skepticism)	Ease of use Technological reliability	Usability challenges Technological reliability
Relational-Social	Natural coordination ***Nonverbal communication*** Shared language	Online coordination in a shared virtual space ***using text-based chat*** Disruptive behaviors Difficulties of maintaining attention	Quasi-natural coordination in VR
Relational-Material	Physical co-presence Synchronous interactions	Digital co-presence ***Reliance on text-based chat***	Immersive co-presence Distributed collaboration Latency and desynchronization ***Voice chat***

survey, employing O'Leary et al.'s (2020) framework as an initial coding structure. The four main categories—Endemic-Social, Endemic-Material, Relational-Social, and Relational-Material—served as deductive dimensions guiding the organization of the data. Within each of these overarching categories, we identified sub-dimensions that combined theoretical and empirical origins. Some sub-dimensions were drawn directly from our conceptual framework (see Table 3), while others emerged inductively from participants' responses during the coding process.

The analysis was conducted in NVivo by two researchers who independently coded a subset of responses to ensure interpretive consistency before applying the final coding scheme to the full dataset. Coding differences were discussed between the researchers until consensus was reached. This hybrid approach—deductive for the main categories and inductive for the emergent sub-themes—allowed us to preserve theoretical coherence while remaining open to new insights from the data. Finally, the coded material was triangulated with our observational notes taken during the simulations, which provided contextual validation and enriched the interpretation of participants' experiences.

5. Results

5.1. Quantitative findings

Table 5 presents the descriptive statistics and the results of the comparative analysis. All Cronbach's alpha values were above 0.9, indicating a high level of internal consistency among the items within each scale.

Overall, the scores across all simulations were positive, with averages exceeding 5 on a 7-point scale, indicating a generally favorable response from participants. The analysis reveals notable differences in participant experiences with the Physical–LEGO®, Screen-based–ME, and Immersive–VR simulations. Specifically, the Physical–LEGO® simulation consistently resulted in higher scores across Flow, Perceived Learning, Enjoyment, Satisfaction, and Engagement. In contrast, the Immersive–VR simulation scored significantly lower across these dimensions.

The effect sizes reported in Table 6 further clarify these differences. The largest differences are observed between Physical–LEGO® and Immersive–VR for perceived learning ($d = 0.79$) and engagement ($d = 0.63$), suggesting substantial experiential differences between these two conditions. By contrast, the smallest difference appears between Physical–LEGO® and Screen-based–ME for enjoyment ($d = -0.03$), indicating that students reported very similar levels of enjoyment in these two modalities.

5.2. Qualitative findings

This study explores how various environments influence collaborative dynamics, allowing participants to experience firsthand the complexities of collaborative work across different contexts. Analyzing student feedback, guided by O'Leary et al.'s (2020) framework, revealed that participants could identify and articulate how these settings influenced their collaborative experiences.

5.2.1. Endemic-social factors

Participants pinpointed specific inherent characteristics of individuals, such as leadership abilities, empathy, personality, motivation, or skills, that they observed to affect collaboration distinctly across different settings.

Introversion and personality traits were mentioned repeatedly. Some introverted individuals found it challenging to engage in direct interactions, such as those involving LEGO® bricks: "*For an introvert, making big gestures without speaking can be difficult.*" In contrast, anonymity in ME provided a safer space: "*The chat allows for anonymity that introverts may appreciate.*" VR presented a more nuanced case: immersion encouraged some to participate more actively, but others still noted discomfort with being fully present in a shared digital environment.

Leadership behaviors also emerged as critical. In LEGO®, students explicitly noted how some participants "*imposed their way of doing things*" or naturally guided the group. In VR, leadership was linked to communication, with participants highlighting that explaining tasks or proposing strategies became central to moving the group forward.

Engagement and disengagement varied across modalities. Physical presence with LEGO® often heightened involvement, since participants could directly observe one another's actions and feel social pressure to contribute. By contrast, in ME, the absence of facial expressions and body language, combined with the difficulty of accessing a global view of the construction, made disengagement easier. To see the overall structure, participants had to step back from the immediate task, which reduced their control over the

Table 5
Descriptive statistics and comparative analysis.

Construct	Physical–LEGO®	Screen-based–ME	Immersive–VR	Comparative Analysis
	Mean (SD)	Mean (SD)	Mean (SD)	
Flow (Barzilai & Blau, 2014)	5.75 (1.23)[a]	5.27 (1.44)[a,b]	4.90 (1.51)[b]	LEGO > VR
Perceived learning (Barzilai & Blau, 2014)	5.72 (1.11)[a]	5.19 (1.50)[b]	4.48 (1.78)[c]	LEGO > ME > VR
Enjoyment (Barzilai & Blau, 2014)	6.17 (1.27)[a]	6.18 (1.01)[a]	5.36 (1.81)[b]	LEGO, ME > VR
Satisfaction (Opdecam et al., 2014)	6.16 (1.04)[a]	5.87 (1.22)[a,b]	5.53 (1.66)[b]	LEGO > VR
Engagement (Buil et al., 2020)	6.39 (0.72)[a]	6.03 (1.07)[a,b]	5.66 (1.28)[b]	LEGO > VR

Note. Means sharing the same letter do not differ significantly; means with different letters differ significantly.

Table 6
Cohen's *d* effect sizes for mean comparisons between conditions.

Construct	LEGO® vs ME	LEGO® vs VR	ME vs VR
Flow	0.30	0.46	0.33
Perceived learning	0.51	0.79	0.53
Enjoyment	−0.03	0.43	0.51
Satisfaction	0.20	0.47	0.28
Engagement	0.34	0.63	0.36

Note. Cohen's d values can be interpreted as small (≈0.20), medium (≈0.50), and large (≈0.80) effects (Cohen, 1988).

building process and allowed some students to withdraw more easily, as their limited participation was less noticeable. In both the screen-based and VR versions of Minecraft, disengagement was also observed when some participants used TNT to blow up parts of the terrain, disrupting group progress and creating frustration within teams. Conversely, VR's immersive qualities increased motivation and concentration: "*Immersion in a problem made our sense of involvement much greater*." Observers also noted that in VR, gamers tended to dominate, while less experienced participants risked withdrawing.

Related to this, *motivation and enjoyment* played a strong role. Several students described the activities as "*amusing and captivating*" (ME) or "*hyper interesting to learn that way*" (VR). Observers likewise noted a high level of enthusiasm among participants, with students generally showing excitement and energy during the simulations. However, they also reported moments of frustration, particularly in ME, where communication and visualization were more demanding, and in VR, where technical difficulties occasionally disrupted the experience. These affective responses were closely linked to how easily students engaged with the tools, with enthusiasm prevailing when the interaction felt smooth, and frustration arising when communication or technical issues created barriers.

A further aspect concerned *technology proficiency and adaptation time*. Students with gaming backgrounds engaged more easily: "*Our group had many gamers and their abilities made us faster*." For novices, however, adaptation was slower despite tutorials. Observers emphasized that familiarity with tools directly shaped the speed and quality of collaboration. LEGO® required little adaptation, ME demanded some digital literacy, while VR posed the steepest curve.

5.2.2. Endemic-material factors

Participants emphasized how the physical and technological infrastructures shaped collaboration across the three modalities. Students pointed to differences in usability, control, immersion, and technical stability, all of which directly influenced how effectively they could engage in collaborative tasks.

Perceived control over the environment was central in LEGO®. Several participants underlined that being able to directly manipulate the bricks and intervene in others' constructions enhanced both coordination and accountability: "*With LEGO we had more control over the blocks*." This sense of immediacy contrasted with digital environments, where interaction was mediated by interfaces and therefore less tangible. Observers similarly noted that physical presence allowed participants to regulate one another's actions, for instance, stopping someone from building in the wrong place or undoing a mistake before it spread. This contrasted sharply with both ME and VR, where the inability to physically intervene meant that individuals could add or destroy blocks without the others having time to react. In screen-based and VR alike, this often created moments of chaos, as entire sections of the construction had to be redone after unintended actions.

Ease of use and accessibility distinguished ME. Students described the screen-based version as "*easy to understand and simple to use*" and appreciated that it required only a laptop, making it more accessible than VR. They also noted that the environment allowed them to focus on their tasks and, in some cases, to multitask: "*It was easier to take my place and manage multiple things at once*." At the same time, limitations quickly became apparent. Gaining an overview of the construction required moving away from the building site and looking from above, which meant losing direct control over the task in progress. This difficulty in maintaining situational awareness, combined with the reliance on text chat, often disrupted the flow of activity. Messages were frequently overlooked, leading to chaotic coordination compared to the direct visibility afforded by LEGO®.

Immersion and presence were most pronounced in Immersive–VR compared to Screen-based–ME. Students praised the environment as "*very immersive, with no distractions*" and valued being able to communicate with gestures and speech, which fostered a stronger sense of presence. Observers also noted that VR helped sustain concentration, as participants felt less tempted by external distractions. Yet these strengths came at a cost. Several participants struggled with discomfort such as *motion sickness or vertigo*, while others experienced *technical problems*, unstable connections, or short battery life.

Discovering new technologies also emerged as a theme in Immersive–VR. For many students, the activity was their first exposure to immersive environments, making the experience simultaneously an exercise in collaboration and an initiation into a novel technological medium: "*It was my first time doing VR and Minecraft—it allowed me to discover a new technology*." While this novelty sparked excitement, it also contributed to uneven participation, as some students were still learning to operate the interface while others advanced more quickly.

5.2.3. Relational-social factors

According to participants, the dynamics and quality of relationships within teams varied considerably across modalities. Students emphasized that the ability to align individual efforts toward a collective objective depended strongly on communication practices, trust, and the establishment of group norms.

Communication quality was repeatedly highlighted as a central factor. With LEGO®, students underlined how non-verbal communication, such as gestures, facial expressions, and direct observation, helped them understand one another more easily: "*The fact that we could see faces and gestures made it easier to reach the common objective.*" In contrast, ME introduced significant barriers: participants had to interrupt their building to read the chat, many messages went unnoticed, and misunderstandings accumulated, sometimes leading to frustration and duplicated work. Observers, who were able to follow the chat and the construction process simultaneously, also reported a certain level of confusion in the exchanges, as participants struggled to coordinate written communication with task execution. VR offered a middle ground: voice and gestures facilitated richer exchanges than the screen-based version, yet some students noted that "*when you don't see people in real life, you lose quality in communication.*"

Trust and mutual support also varied across settings. LEGO® often fostered stronger interpersonal ties, as students directly experienced others' involvement and felt accountable to the group. Several noted that the activity "*helped break the ice and develop team spirit*" or allowed them to learn to trust their teammates' decisions. In VR, pseudonyms and avatars sometimes encouraged withdrawal or "passive collaboration," while in ME, the reduced visibility of participation made it harder to know whether teammates were contributing consistently.

Decision-making and coordination presented another layer of complexity. With LEGO®, groups often managed to take collective decisions, though some participants found it hard to impose their point of view or felt that decisions came too late. In VR, participants described difficulties in dividing tasks or agreeing on details such as the color or order of construction, pointing to the need for clearer coordination structures. In ME, students stressed the importance of clarifying instructions and structuring teamwork through chat; without this, collaboration easily descended into chaos.

Social norms and behaviors influenced collaboration as well. In screen-based and VR simulations, anonymity sometimes facilitated constructive participation for introverts, but it also created opportunities for disengagement or even disruptive behaviors, such as sabotage in the VR environment: "*Someone kept blowing everything up with TNT.*"

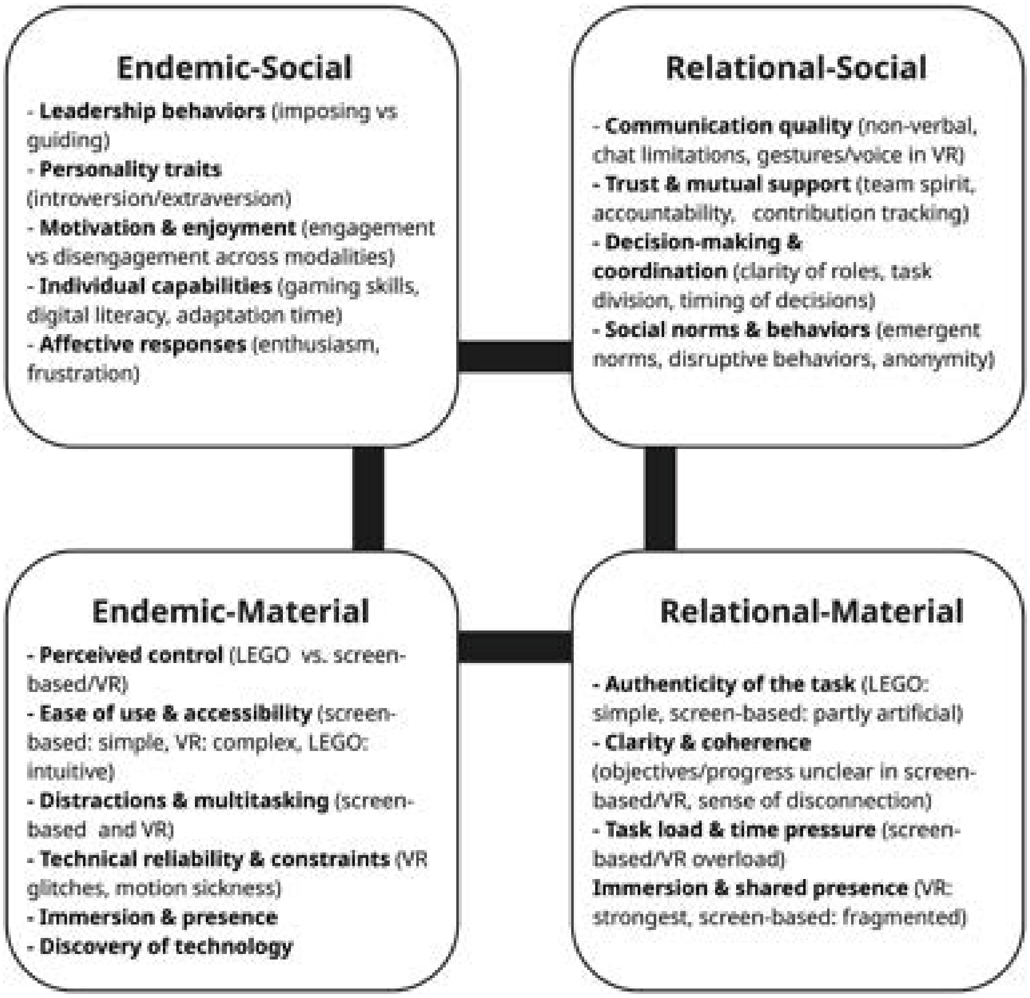

Fig. 4. Empirical extension of O'Leary et al.'s (2020) framework for teaching collaboration across physical and digital modalities.

5.2.4. Relational-material factors

Students frequently emphasized how the interplay between task requirements and technological mediation shaped their collaborative experience. While face-to-face interaction with LEGO® made coordination intuitive, technology-mediated contexts introduced both affordances and constraints that directly influenced group dynamics.

Perceived authenticity of the task varied across modalities. With LEGO®, some participants found the activity too simple or unrealistic, making it difficult to see its relevance for real-world teamwork: "*The limits of the activity are quickly reached given its simplicity*." Similarly, in ME, students noted that while the activity was stimulating and relevant for remote collaboration, it sometimes lacked authenticity, as the simplified tasks did not mirror real professional challenges.

Clarity of objectives and task coherence emerged as another key factor. Several LEGO® participants remarked that the objectives felt unclear at times, complicating collective alignment. In ME, the lack of coherence among team members was frequently noted, particularly in the early stages of the simulation when the construction remained abstract: "*The beginning was much more chaotic than with LEGO, as it took longer before something tangible took shape*."

Task load and time pressure further shaped experiences. LEGO® teams often mentioned the feeling of pressure, as non-verbal constraints and limited time intensified the challenge: "*The pressure builds up because there isn't much time, and sometimes we don't really understand each other with the gestures*." Students also described moments of overload when managing the interdependent nature of the team's building tasks.

Immersion and shared presence in VR provided a contrasting experience. Unlike Screen-based–ME, where participants often felt disconnected, VR fostered a sense of proximity and simultaneity: "*Everyone connected sees the same thing.*" Students emphasized how immersion helped reduce the typical fragmentation of distributed collaboration, although technical disruptions occasionally undermined this potential. With the handheld controllers, participants could exchange simple signals or point directly to a block, making interactions more tangible. VR also conveyed a stronger sense of shared presence, appearing less solitary than the screen-based version, while offering a clearer overview of the collaborative workspace.

The qualitative analysis thus revealed how the four categories of O'Leary et al.'s (2020) framework manifested differently across modalities, while also uncovering new interconnections between social and material dimensions. Building on these insights, Fig. 4 synthesizes our empirical extension of O'Leary et al.'s framework, illustrating how the identified factors interact across Physical–LEGO®, Screen-based–ME, and Immersive–VR settings in the context of collaboration learning.

6. Discussion

The consistently high satisfaction scores across all three simulations, supported by convergent qualitative feedback, indicate that the simulation-based design successfully fostered immersion and engagement—two core mechanisms of experiential learning (Kolb, 2014). Beyond enjoyment, these reactions reflect how students were cognitively and emotionally involved in the process of learning collaboration. The overall positive evaluations confirm that, irrespective of the technological medium, students perceived the activities as meaningful opportunities to experience, reflect on, and conceptualize collaborative work. Yet, comparing the three modalities reveals distinct learning mechanisms and trade-offs that nuance this general pattern.

Convergence: Physical–LEGO® yielded the most coherent alignment between quantitative and qualitative results. Students' sense of flow, engagement, and perceived learning was reinforced by the tangible, co-located nature of the task. The visibility of others' actions created an immediate form of mutual awareness, where coordination relied on observation and anticipation rather than verbal negotiation. This direct, embodied interaction exemplifies O'Leary et al.'s endemic-social factors such as empathy and shared attention. At the same time, the difficulties reported by more introverted participants highlight that physical immediacy can also amplify social pressure, reminding educators that not all learners thrive equally in high-exposure settings.

Divergence: The Immersive–VR environment produced a notable divergence between students' subjective enthusiasm for immersion and their lower quantitative satisfaction scores. This tension reveals a pedagogical paradox: immersive technologies heighten the sense of presence and engagement, yet they can also impose a cognitive and physical load that hinders reflection. Technical instability, discomfort, and unequal familiarity with gaming interfaces constrained collaborative flow, illustrating how endemic-material factors can override relational benefits. Nevertheless, qualitative accounts suggest that students still internalized key lessons about trust, co-presence, and the management of complexity, showing that even imperfect immersive experiences can serve as powerful catalysts for reflection.

Nuance: The Screen-based–ME condition provided an intermediate experience. Text-based coordination slowed down the pace, creating moments of confusion but also opportunities for deliberate articulation and clarification. Students had to externalize their intentions in writing, transforming tacit teamwork processes into explicit communication acts. This slower rhythm supported awareness of coordination, even if engagement felt less vivid. In O'Leary et al.'s terms, this environment exposed relational-material constraints while encouraging reflective learning about the importance of structure and communication clarity in distributed collaboration.

Taken together, the three modalities reveal that collaboration learning emerges from the dynamic interplay of social and material dimensions. Physical tangibility supports intuitive coordination and empathy, immersive environments enhance presence but can introduce sensory and cognitive strain, and screen-based settings, though less engaging, make communication processes more explicit. These findings broadly confirm the patterns anticipated in Table 3, yet they also show that these categories interact more fluidly than initially expected. Rather than functioning as distinct domains, the endemic and relational dimensions, both social and material, shift according to the level of physical and sensory involvement afforded by each modality.

Overall, the results suggest that Table 3 should not be seen as a fixed typology but as a flexible framework whose dimensions vary in salience across different learning environments. The relative weight of social and material factors appears to depend on how each medium shapes learners' interactions and engagement. This reinterpretation refines O'Leary et al.'s framework by showing that the relative influence of social and material factors varies with the technological environment. Collaboration learning appears to emerge from the interplay between these dimensions as learners adapt their coordination strategies across the three technological modalities examined in this study. At the same time, the results point to important practical boundary conditions for immersive environments. In contexts involving large cohorts or limited techno-pedagogical infrastructure, including the resources required to maintain and facilitate the technology, implementing VR-based simulations may be difficult, making physical or screen-based modalities more scalable alternatives for teaching collaboration.

7. Theoretical contributions

From a theoretical standpoint, this study refines O'Leary et al.'s (2020) framework by illustrating how endemic-social, endemic-material, relational-social, and relational-material dimensions interact differently across contrasting modalities of collaboration. The findings show that these categories, while conceptually distinct, often overlap in simulation-based learning contexts where social and material factors co-evolve. For instance, Physical–LEGO® foregrounded visibility and immediacy as social drivers of engagement, Screen-based–ME highlighted how material constraints shape communication and coordination, and Immersive–VR revealed an unanticipated tension between relational affordances such as presence and material limitations such as technical instability and fatigue.

While O'Leary et al.'s (2020) model acknowledges the complementarity of these factors, our results provide empirical illustrations of how their salience varies across physical, digital, and immersive settings. Rather than treating these dimensions as discrete, the study demonstrates that their interplay depends on the technological and sensory conditions through which collaboration unfolds. In doing so, it contributes to a contextual refinement of the framework, showing how it operates as a flexible lens for analyzing teamwork in educational environments.

Beyond refining O'Leary et al.'s framework, the study also advances theorization on collaboration as a learnable practice. The simulations exposed learners to the ambiguities, asymmetries, and interdependencies that characterize real-world teamwork, allowing them to experience—not just observe—the complexities of collaboration. This suggests that collaboration can be taught through the structured experience of its tensions, fostering a more situated understanding of teamwork.

More broadly, the study contributes to theorization on the pedagogy of collaboration by positioning physical, screen-based, and immersive simulations not as interchangeable tools but as complementary environments that activate distinct mechanisms of teamwork. This comparative perspective advances understanding of how transversal competencies such as collaboration can be intentionally cultivated and assessed through simulation-based training.

8. Practical contributions

From a practical perspective, this study offers concrete guidance for educators and institutions seeking to teach collaboration more effectively. First, it provides both a set of design principles (Table 2) and a structured four-step process for developing collaboration simulations, from selecting modalities to deliberately foregrounding specific collaborative factors (Fig. 2). This systematic approach serves as a transferable design framework that instructors can adapt to their own pedagogical contexts.

Second, by systematically comparing Physical–LEGO®, Screen-based–ME, and Immersive–VR, the study offers a framework to help educators identify the strengths, limitations, and complementarities of different modalities for teaching collaboration. Rather than promoting a one-size-fits-all solution, our design demonstrates how these tools can be integrated into a multimodal learning pathway: Physical–LEGO® to make visible the social and embodied aspects of collaboration, Screen-based–ME to highlight the coordination constraints of text-based communication, and Immersive–VR to immerse learners in distributed teamwork. Experiencing these environments sequentially encouraged students to compare modalities critically and to challenge the assumption that technological sophistication automatically enhances collaboration.

Third, the findings emphasize the critical role of facilitation and debriefing. The pedagogical value of simulations lies not only in the activity itself but in the guided reflection that connects experience to theoretical understanding. Effective implementation therefore requires that instructors allocate sufficient time and support for debriefing sessions to help students articulate insights about teamwork dynamics and link them to O'Leary et al.'s (2020) framework.

Fourth, while the study's design is context-specific, it provides a useful evidence base for institutional reflection on investments in simulation-based learning. Physical–LEGO® exemplifies how low-cost, tangible tools can surface collaborative processes; Screen-based–ME illustrates the scalability and accessibility of digital collaboration; and Immersive–VR highlights both the promise and the challenges of immersive environments. As summarized in Table 7, the strongest pedagogical impact arises when these modalities are combined, enabling students to compare, challenge, and integrate learning across contexts.

Finally, this study reinforces the broader institutional objective of preparing graduates with transversal collaboration skills relevant to contemporary professional realities. Collaboration—often assumed but rarely taught explicitly—can be cultivated through structured, theory-driven simulations that mirror the ambiguities and interdependencies of real teamwork. Integrating such experiences into curricula can help learners build adaptive, reflective, and digitally literate collaboration practices suited to increasingly hybrid and immersive work environments.

Table 7
Learning affordances and challenges of each modality and their combined pedagogical value.

Learning dimension	Physical–LEGO®	Screen-based–ME	Immersive–VR	Combined value
Learning objectives made visible	Awareness of non-verbal communication, leadership emergence, empathy, and trust building	Recognition of coordination challenges and role distribution through written communication	Experience of presence, co-presence, and distributed collaboration in immersive teamwork	Encourages comparative reflection on how collaboration mechanisms differ across modalities
Learning affordances	High engagement and immediate visibility of contributions foster active participation and shared attention	Accessibility and persistence of text-based exchanges support explicit expression and coordination efforts	Immersive environment enhances motivation, presence, and naturalistic interaction through gestures and voice	Comparing modalities encourages awareness that technological sophistication does not necessarily enhance collaboration
Learning challenges	Social exposure and implicit participation pressure may create discomfort for introverted learners	Reliance on text-based communication can lead to delays, misunderstandings, and reduced situational awareness	Technical instability, motion discomfort, and uneven familiarity with gaming tools can disrupt coordination and inclusion	Experiencing diverse challenges across modalities encourages reflection on teamwork conditions and the use of collaboration tools
Pedagogical contribution	Embodied interaction and tangibility make social dynamics visible and concrete	Digital collaboration highlights the need for structure, clarity, and patience in coordination	Immersive simulation enables reflection on presence, coordination, and the complexity of virtual teamwork	Integrating the three modalities strengthens students' capacity to compare and reflect on collaboration strategies across contexts

9. Limitations and avenues for future research

As with any exploratory study, this research presents several limitations that invite further investigation. First, the study involved a relatively small sample (40 students and 120 questionnaires) from a single North American university course, which constrains the transferability of the findings. Replication in larger, more diverse, and cross-cultural educational settings would strengthen confidence in the observed patterns and help determine whether contextual factors influence collaboration learning in simulation-based environments.

Second, while the three simulations were designed to keep the task constant, variations in group composition, prior experience with technology, and facilitation style may have influenced learning processes and outcomes. Future research could employ mixed-method or quasi-experimental designs to disentangle these effects and explore how individual characteristics such as technological proficiency, personality, or previous exposure to teamwork moderate engagement and learning. Future studies could also develop instruments to better capture the experiential and reflective dimensions of collaborative learning.

Third, the study relied on Minecraft for both screen-based and VR modalities, ensuring comparability but also limiting generalization to a single technological ecosystem and a specific collaborative task, the "LEGO® Challenge". Future work could extend this research to alternative platforms, hybrid setups combining physical and virtual elements, or tasks involving different forms of interdependence. Longitudinal studies would also be valuable to examine whether the awareness and insights gained through such simulations are sustained and applied in authentic professional collaborations over time.

More broadly, future research could investigate how simulation-based pedagogies can be integrated into curricula to foster the development of collaborative competence and to examine how institutional conditions such as class size, instructor expertise, or technological infrastructure affect their implementation and impact.

10. Conclusion

This study demonstrated how simulation-based training can render collaboration both visible and teachable by comparing three distinct modalities: Physical–LEGO®, Screen-based–ME, and Immersive–VR. Each environment illuminated different strengths and challenges, while the combined design enabled students to reflect critically on the mechanisms of teamwork across physical, screen-based, and immersive settings. Building on O'Leary et al.'s (2020) framework, the findings reveal how social and material factors intersect in context-specific ways that alternately enable or constrain collaboration.

For educators, the study underscores that pedagogical value does not reside in any single tool but in the deliberate sequencing and integration of modalities, supported by guided facilitation and reflective debriefing. Designing learning environments that contrast these experiences helps students surface the invisible dynamics of teamwork and develop a more situated understanding of collaboration.

At an institutional level, incorporating such multimodal simulations into curricula can foster adaptive and transferable collaboration skills, preparing learners to navigate increasingly hybrid and technologically mediated professional environments. Future research could further explore how these experiential designs influence the long-term development of collaborative competence across educational and organizational contexts.

CRediT authorship contribution statement

Thibaut Coulon: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Régis Barondeau:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Simon Bourdeau:** Validation, Methodology, Investigation, Conceptualization. **Yannick Hémond:** Validation, Investigation, Conceptualization.

Data availability

Data will be made available on request.

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