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ORIGINAL ARTICLE

Gamification in manufacturing: some insights in human–robot collaboration assembly and preliminary results

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Abstract

The application of gamification in manufacturing remains largely unexplored, despite its proven benefits in fields such as education and business. By incorporating game-like elements such as points, challenges and storytelling into real-world tasks, gamification has the potential to improve both performance and user engagement, even in manufacturing environments. This paper explores the feasibility of applying gamification to human–robot collaboration (HRC) assembly processes. Using two different approaches—standard gamification (using points and challenges) and narrative gamification (incorporating storytelling for deeper engagement)—two case studies were conducted to assess the impact of gamification on workers' performance, well-being and emotional engagement. Preliminary results show that (i) narrative gamification significantly reduced frustration and increased immersion, leading to a more engaging experience for participants, and (ii) standard gamification contributed to the development of a well-paced and structured process, without significantly enhancing emotional engagement. By highlighting the feasibility of gamification in HRC assembly, this study lays the groundwork for future research into more immersive and dynamic gamification strategies in manufacturing.

Keywords Human–robot collaboration · Gamification · Manufacturing · Work engagement

Abbreviations

HRC	Human-robot collaboration
MDA	Mechanics, dynamics and aesthetics
SDT	Self-Determination Theory
EDA	Electrodermal activity
PPG	Photoplethysmography
HRV	Heart rate variability
GUI	Graphical user interface
CDA	Continuous Decomposition Analysis
SCL	Skin conductance level
SCR	Skin conductance response
RMSSD	Root mean square of successive differences
NASA-TLX	NASA-Task Load Index
SAM	Self-Assessment Manikin
GEQ	Game Engagement Questionnaire
G	Gamified
NG	Not gamified
VR	Virtual reality
AR	Augmented reality

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1 Introduction

In recent years, the concept of gamification, which involves the application of game design elements in non-game contexts, has emerged as a highly effective strategy for enhancing productivity and engagement across a range of sectors [1, 2]. In manufacturing, this trend has attracted considerable

interest as companies seek novel methods to motivate workers, enhance task efficiency and minimise operational errors [3, 4]. Within the context of repetitive assembly processes, the integration of gamification principles can offer significant benefits by reducing boredom and thus enhancing workers' motivation. Furthermore, enhancing worker engagement is a central pillar of Industry 5.0 [5, 6], which also emphasises human-centred manufacturing. Among the most important technologies enabling Industry 5.0, collaborative robots (cobots) play a crucial role in supporting human workers in shared tasks. Collaborative robots indeed are designed to operate in proximity to humans in a shared workspace. The advent of cobots has further transformed the manufacturing landscape, enabling a new level of synergy between human capabilities and robotic efficiency, leading to what is commonly referred as "Human–Robot Collaboration" (HRC) [7–10]. In this context, the application of gamification to assembly processes performed by humans and robots simultaneously, also known as "collaborative assembly", can offer a promising approach to increase engagement, improve task efficiency and create a more motivating work environment. However, integrating gamification into HRC systems requires careful game design, efficient communication and adaptive feedback mechanisms to ensure real-time responsiveness and operator engagement. Control strategies used in communication-constrained systems [11, 12] provide valuable insights into how to optimise communication of feedback and task adaptation. Such principles can indeed be leveraged for example to design adaptive gamification frameworks.

This paper focuses on the application of gamification in collaborative assembly processes, with the aim of exploring its feasibility in a manufacturing context. Using the MDA (mechanics, dynamics, aesthetics) framework [13], a conceptual basis for integrating gamification into collaborative assembly is provided. Two case studies using two types of gamification were developed: (i) standard gamification, which uses mechanics such as points, badges and levels, and (ii) narrative gamification, which incorporates storytelling elements. Some preliminary findings from these case studies are presented, by offering insights into the practical application of these gamification approaches in the manufacturing environment. The paper is organised as follows: Sect. 2 provides a literature review on gamification, especially in industrial context while Sect. 3 provides some guidelines to apply gamification principles into collaborative assembly processes. Then, Sect. 4 presents two different case studies, Sect. 5 shows the experimental setting and Sect. 6 provides the related preliminary results. Finally, Sects. 7 and 8 summarise and discuss the main findings, limitations and future developments.

2 Literature review

This section provides a review of the existing literature on the two core aspects of this study: gamification and human–robot collaboration. First, the concept of gamification is explored, focusing then on its application in industrial contexts. A brief overview of HRC is then presented, particularly in a manufacturing scenario.

2.1 Gamification

The concept of gamification, initially gained popularity in digital entertainment and education, has recently expanded its influence into areas such as business, healthcare and learning environments. A major contribution to the field was made by Chou [14], who proposed comprehensive guidelines for implementing well-designed gamification in various domains. Another widely used framework in gamification, known as MDA framework, was proposed by Hunicke et al. [13]. This framework identifies three crucial elements for the design of games: (i) mechanics that include fundamental components of games, encompassing the rules, actions, algorithms and data structures that govern its functionality; (ii) dynamics that refer to the dynamic interactions between mechanics and player input, as well as the manner in which these mechanics collaborate with one another, and (iii) aesthetics that encompass all the emotional responses that players experience in response to the game's visuals, sounds and overall presentation. Conceptually, gamification is rooted in three core psychological theories: Self-Determination Theory (SDT), Motivation Theory and Flow Theory. Self-Determination Theory, developed by Ryan and Deci [15], emphasises the importance of satisfying three innate psychological needs: competence, autonomy and relatedness. Competence refers to an individual's ability to interact effectively with their environment, autonomy refers to the freedom to make independent choices and relatedness involves a sense of belonging and acceptance within a group. These needs, when satisfied, drive intrinsic motivation and lead individuals to engage in tasks where they feel empowered, competent and connected to others. Motivation theory further distinguishes between intrinsic and extrinsic motivation, where intrinsic motivation is driven by enjoyment and satisfaction from the activity itself, whereas extrinsic motivation is driven by external rewards such as money or recognition [16]. Flow Theory, introduced by Csikszentmihalyi [17], describes an optimal state of consciousness in which individuals are fully immersed in an activity, experiencing goal

orientation and satisfaction. In this state of flow, tasks are enjoyable when there is a balance between the challenge of the task and the individual's ability to complete it. Well-designed gamification can induce this state of flow, providing motivation and optimal performance by matching the difficulty of the task to the user's skill level.

Although gamification has been used extensively in various sectors, its adoption in manufacturing is relatively recent. A systematic literature review by Leite et al. [18] highlighted the limited application of gamification in the manufacturing sector, noting gaps in long-term studies and ethical considerations. However, their review highlighted the potential of gamification to motivate workers in repetitive tasks and highlighted emerging trends, such as the integration of gamified collaborative platforms. There have been few attempts to adapt the principles of gamification to industrial contexts. Deterding et al. [19] explored the historical origins of gamification and proposed its definition as the use of game design elements in non-game contexts. While these ideas laid the foundation for its use in industry, the implementation of gamification in manufacturing environments is still evolving. Keepers et al. [4] highlighted the limited scope of current research in industrial gamification and suggested directions for future studies. Empirical evidence from Liu et al. [20] showed that gamified work design, particularly the use of smartphones to implement game mechanics, significantly improved work motivation, satisfaction and operational performance. Ohlig et al. [21] provided further evidence by demonstrating how gamified performance management systems—using visualisations of process metrics in a gamified way—increased employee motivation. Sochor et al. [22] developed a framework to guide the selection and implementation of gamified elements in manufacturing and logistics, while Klevers et al. [23] introduced the GameLog model, which integrates game mechanics into existing business processes to increase engagement and efficiency. Lee et al. [24] presented a five-step design framework for gamification in manufacturing, which they tested in an automotive assembly line and showed promising results in improving worker performance and engagement. In a related study, Roh et al. [25] examined how gamification affected operators' flow states and emotional experiences, and linked these experiences to intrinsic motivation. In addition, Dolly et al. [3] examined the impact of gamification on industrial assembly tasks and showed that it not only improved productivity, but also reduced cognitive load and contributed to worker's well-being. Korn et al. [26] also found that gamified interfaces could be used to train workers on advanced technologies in smart factories, revealing improvements in both productivity and user satisfaction through real-time feedback and interactive systems. Ulmer et al. [27] focused on the development of an assistive system designed to improve human performance in manufacturing tasks, by combining gamification principles with hardware modularisation to create a more interactive and motivating environment for workers.

2.2 Human–robot collaboration

Within manufacturing activities, the use of gamification in the context of human–robot collaboration (HRC) is an emerging and almost still unexplored area of research. Collaborative robotics, also known as cobotics, were developed to work alongside with humans, sharing spaces and goals [7, 10, 28–30]. The integration of cobots in manufacturing requires the removal of physical barriers that have traditionally separated human workers from robotic systems. As a result, ensuring safety in HRC environments remains a fundamental concern as established by the introduction of ISO 10218–1 and ISO 10218–2 and later with ISO/TS 15066. In this regard, to assess safety levels in collaborative manufacturing, Zanchettin et al. [31] proposed a metric that evaluates critical factors such as the distance between humans and robots, the type of robotic system used and its operating speed, all of which play a crucial role in mitigating risks in HRC environments. Beyond safety, human factors play a critical role in determining the success and efficiency of HRC systems. Emotional and cognitive aspects significantly influence how operators interact with robotic collaborators, affecting both performance and well-being. Khamaisi et al. [32, 33] introduced a framework for evaluating user experience in manufacturing environments, combining questionnaires and non-invasive physiological sensors to identify tasks that are highly stressful and may negatively impact performance. Similarly, Kühnlenz et al. [34] investigated how different robot trajectory patterns affect human responses using physiological signals thus providing insights into physiological stress levels during interaction. Another crucial issue to ensure effective HRC is to enable fluent and natural interaction and communication between human and robot. In this regard, Wang et al. [35] highlighted the need to develop effective human–robot communication interfaces. Unlike conventional automation, HRC requires seamless interaction, coordination and communication between human operators and robots in shared workspaces. While this paradigm shift increases flexibility and productivity, it also poses key challenges such as task synchronisation,

effective interaction, cognitive load and trust building [7, 36]. Effective human–robot interaction depends on real-time communication and feedback mechanisms, which are often limited to visual cues or predefined task sequences [28]. This lack of intuitive engagement can lead to operator stress, uncertainty and reduced efficiency. Furthermore, the cognitive demands of monitoring and adapting to robot behaviour can impact worker performance and well-being, necessitating novel approaches to support human engagement and task fluency. Therefore, they offer unique opportunities for gamification due to their ability to interact dynamically with human operators. In this regard, Venås et al. [37] investigated the use of gamification as a training tool in human–robot collaboration (HRC), specifically in a cooperative lifting. The findings highlighted the potential of gamification as a promising methodology for improving HRC, making complex tasks easier to learn and improving user interaction with cobots in industrial settings. In general, gamification has been extensively studied in fields such as education, healthcare and business, and has shown significant potential for improving engagement and productivity. However, its application in manufacturing remains relatively underexplored, with few studies investigating its impact on worker performance in industrial contexts. Even less attention has been paid to the use of gamification in collaborative assembly tasks. While some research began to explore gamified systems in manufacturing, there is a clear gap in understanding how gamification can affect human–robot collaboration in terms of cognitive load, stress reduction and performance.

3 Applying gamification to collaborative assembly processes

Gamification offers a promising strategy to enhance human–robot collaboration by using game design elements to improve interaction, motivation and performance [2, 19]. Through structured feedback systems, progress indicators and real-time performance tracking, gamification can facilitate clearer communication between humans and robots, reducing uncertainty and decision fatigue. In addition, narrative-driven gamification introduces immersive elements that promote operator engagement, transforming the collaborative process into a goal-oriented experience rather than a repetitive task. While gamification has been explored in training and industrial performance management [21, 26], its application to HRC processes in manufacturing remains underexplored.

To apply gamification principles in collaborative assembly, the well-known MDA framework developed by Hunicke et al. [13] was used. In detail, this framework identifies three crucial aspects in game design that can also be applied in HRC assembly:

- Mechanics, that refer to the rules, algorithms and structures that govern gameplay. These are the fundamental systems and processes that define how the game works—everything from scoring systems to the logic behind challenges or rewards. Mechanics define how information is processed and presented to human workers to facilitate effective collaboration with cobots.
- Dynamics come from how the mechanics are executed and evolve during gameplay. These are the interactions between the player and the system, and between players, based on the established mechanics. For example, the strategic choices or behaviours that arise as players interact with the rules form the dynamics. In HRC assembly, dynamics influence how operators interact with cobots, promoting strategic decision-making, collaboration and engagement.
- Aesthetics represent the emotional responses and experiences evoked in the player. It refers to how players feel when they engage with the game, such as a sense of accomplishment, challenge or immersion. Aesthetics influence the emotional experience of workers during HRC, affecting motivation, engagement and trust. Gamification increases the perceived fun and immersion of assembly tasks, making collaboration less repetitive and more rewarding.

Figure 1 summarises how the MDA framework can be adapted to collaborative assembly processes. Using a combination of mechanics, dynamics and aesthetics, various strategies can be integrated into the assembly process to enhance performance and engagement. In this regard, for each of the three of the MDA framework, this work presents some details on strategies and tools useful to implement gamification in collaborative assembly tasks, as provided in Table 1.

4 Case-study description

Based on the guidelines outlined in Table 1, two case studies were developed focusing on the dichotomy already presented in the scientific literature [38] between narrative and standard gamification. In their study on gamification among manufacturing workers, Seo et al. [38] conceptualised two different types of gamification: conventional and

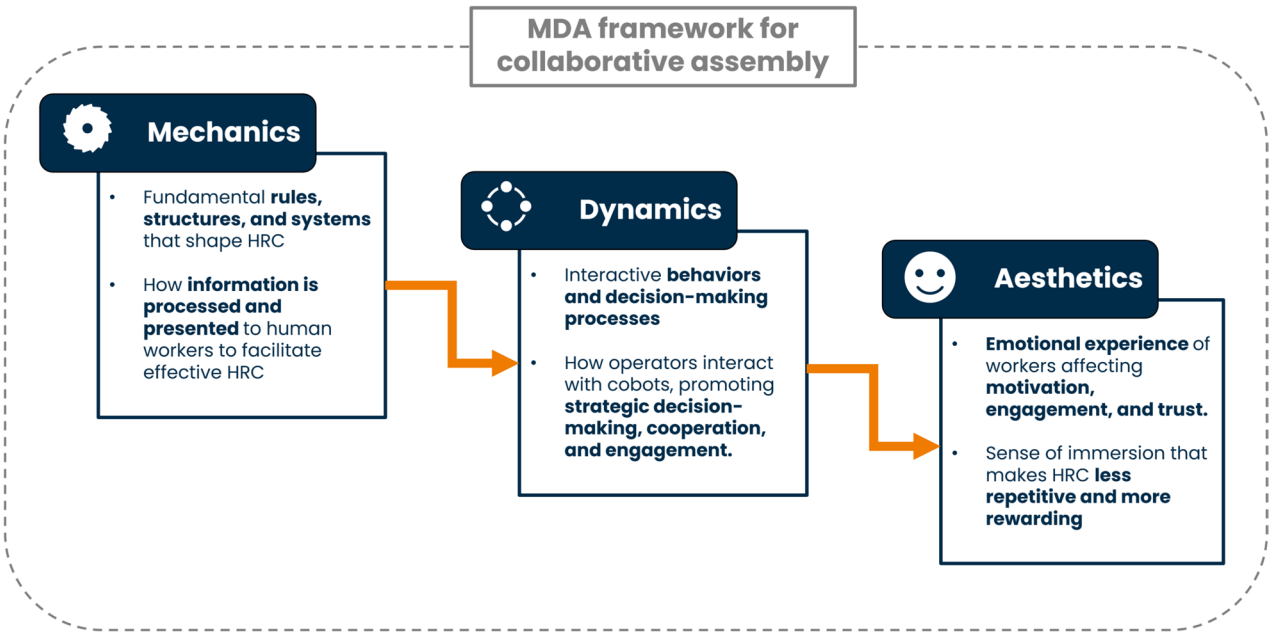


Fig. 1 The MDA framework applied in collaborative assembly (adapted from [13])

narrative gamification. Conventional gamification is based on the use of badges, points and rewards and is linked to the "extrinsic motivation" (i.e. derived from externally dictated goals). Narrative gamification, instead, provides storytelling to create immersive experiences that increase intrinsic motivation, i.e. derived from self-directed goals. By analogy, in this paper, such dichotomy was exploited to create two different gamification case studies: standard and narrative. The first approach, standard gamification, used traditional game mechanics such as points, badges and leaderboards, which are commonly used to motivate and reward performance. This method focuses on increasing productivity and efficiency through tangible metrics and feedback, encouraging participants to improve their performance based on quantifiable achievements. The second approach, narrative gamification, aimed to provide a more immersive and contextually rich experience by embedding the assembly process within a story-driven framework. Generally, standard and narrative gamification cannot be seen as completely different approaches, as they share common elements. The case study of this work concerns the collaborative assembly of a tile cutter (see Fig. 2a and b). The elementary tasks and the related allocation between human and cobot are provided in Table 2. The assembly process is divided into 4 main phases: (i) the assembly of the two lateral supports, namely C1a and C1b on the base; (ii) the assembly of the cutting mechanism; (iii) the assembly of the cutting mechanism and the rail rods with the base and (iv) the picking of the final product.

The work area (see Fig. 2c) consisted of a table on which a collaborative robot Universal robot UR3e [39] is positioned to support the human operator who performed manual tasks in the human's work area. The human operator controlled the robot via a button located on the table in the work area. In addition, a monitor with graphical interface was provided to display performance metrics. This interface was developed and connected to the cobot using Node-RED [40].

4.1 Standard gamification

In order to apply standard gamification to the collaborative assembly processes, elements such as points, progress bars, multimedia feedback and suggestions were selected. The use of progress bars and points in the assembly process is directly linked to conventional productivity metrics (e.g. Performance Measurement Systems) such as cycle time, process failures and product defects. In addition, suggestions for improvement, such as optimised assembly instructions, help to minimise errors and improve product quality [41, 42]. Figure 3 shows the graphical user interface (GUI) implemented.

This interface, developed and connected to the cobot using Node-RED [32], allowed live calculation of performance metrics using direct communication with the robotic system. A screen was placed on the workstation to ensure that the operator could continuously monitor his progress throughout the task. Each time the operator pressed the

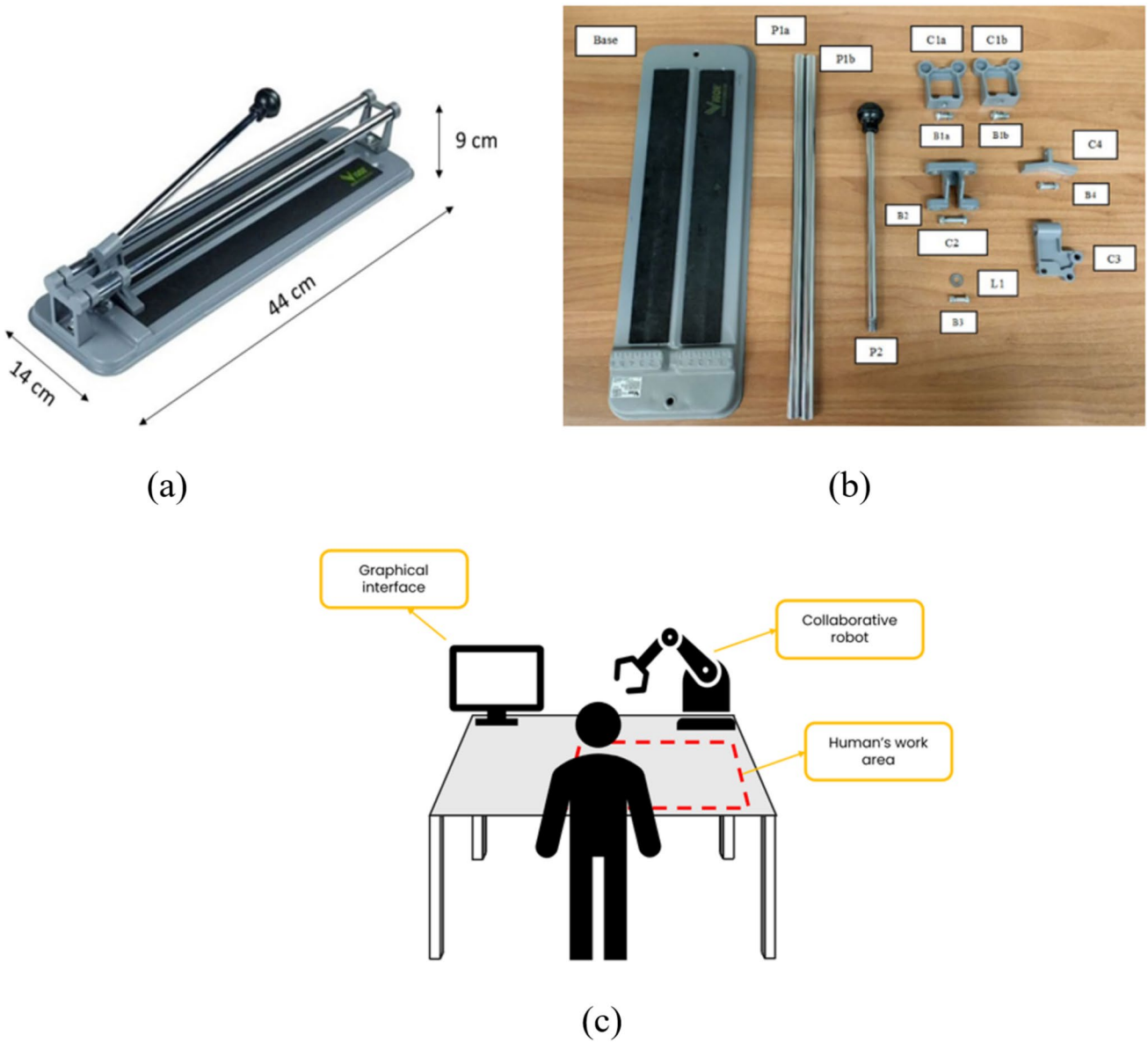


Fig. 2 **a** The tile cutter, **b** its components and **c** the scheme of the experimental collaborative assembly work area set up at the Mind4Lab at Polito (c)

button to instruct the cobot to perform the next task, this input was also registered as a timestamp to calculate the duration of the most recently completed phase. Once the button is pressed, signalling the completion of an assembly phase, the graphical interface updates the corresponding data in real time, while the system simultaneously begins recording performance metrics for the ongoing phase. This approach ensured seamless tracking of task execution times and provided immediate feedback to the operator, enhancing situational awareness. Specifically, the main gamification elements were:

- Scoring system: The scoring system is based on comparing the time taken by the operator to complete the assembly with the expected times from Table 3, which represent average execution times derived from previous experience and thus define the time taken by an "average user". Offering points for tasks provides an immediate reward, reinforces positive behaviour and encourages continued engagement. The assembly of the tile cutter can be divided into four main phases: phase 1, which involves joining the two supports to the base; phase 2, during which the cutting mechanism is assembled; phase

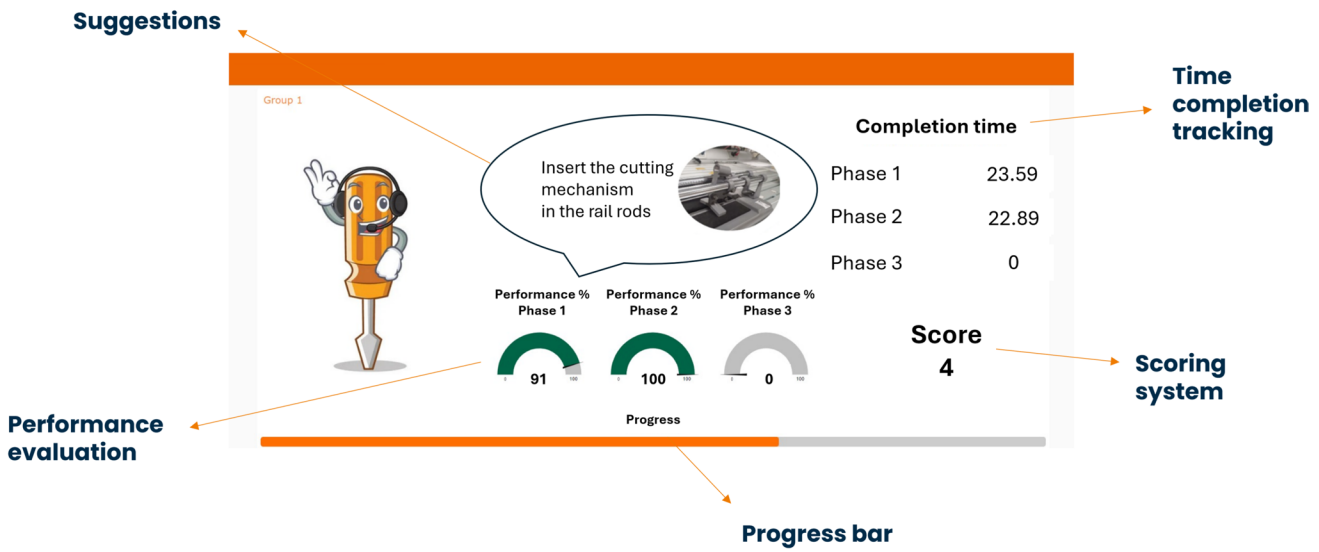


Fig. 3 Graphical user interface for standard gamification

3, which is the final assembly of the cutting mechanism, rail rods and base to form the final product; and phase 4, which involves picking and placing the final product, where the operator does not intervene. Each of the first three phases includes some activities performed by the operator and others performed by the cobot. The time taken by the operator during the three assembly phases is used to provide the scoring system, by comparing the observed time, denoted as T_j(where j refers to the specific assembly phase), with benchmark values shown in Table 3. The observed time T_j is defined as the period between two successive digital outputs recorded by the system, which includes both the cobot's movement time and the operator's assembly time. This can be represented by the formula:

$$T_j = C_j + O_j \tag{1}$$

where C_j is the time associated with tasks completed by the cobot, and O_j represents the time taken by the operator. For each phase, T_j is compared with the corresponding reference value T_j^* from Table 3, which combines the cobot and operator times ($T_j^* = C_j^* + O_j^*$).

The scoring system assigns a score p_j based on this comparison. If the observed time T_j is less than or equal to the benchmark T_j^*, the operator receives 2 points ($p_j = 2$); otherwise, 1 point is awarded ($p_j = 1$). The final score for the assembly process is the sum of the points earned in the first three phases, represented by the formula: $p_i = \sum_{j=1}^{3} p_j$. The scoring system chosen was designed to balance simplicity and effectiveness in assessing operator performance. The simplicity of the scoring system ensures clear and immediate communication, without overwhelming the operator with difficult information.

- Progress bar: A dynamic progress bar is displayed on the dashboard and fills up visually as each task is completed. The progression of the bar reflects the percentage of the assembly process that has been completed, providing a real-time indicator of the worker's progress. When the entire product assembly is complete, the bar reaches full completion. This visual representation helps users monitor both completed and remaining tasks, providing a clear and intuitive sense of progress and achievement.
- Multimedia feedback: It was decided to display the completion times for each assembly phase, providing the operator with real-time feedback on his performance. As shown by Ohlig et al. [21], gamified information systems can significantly increase operators' motivation. Real-time feedback allows operators to immediately assess their performance, helping them to identify both strengths and areas for improvement. By measuring and visualising completion times, a performance indicator is generated as a second layer of feedback. This indicator is based on the assumption that the assembly times for each phase are normally distributed, allowing a performance indicator (TPI_j) to be calculated for each stage of the assembly process.

$$TPI_j = (1 - \Phi(T_j)) \times 100 = \left(1 - \Phi\left(\frac{T_j - T_j^*}{\sigma_j}\right)\right) \times 100 = (1 - \Phi(Z_j)) \times 100 \tag{2}$$

The anti-cumulative distribution of T_j was chosen because it increases as T_j decreases, making it a more appropriate

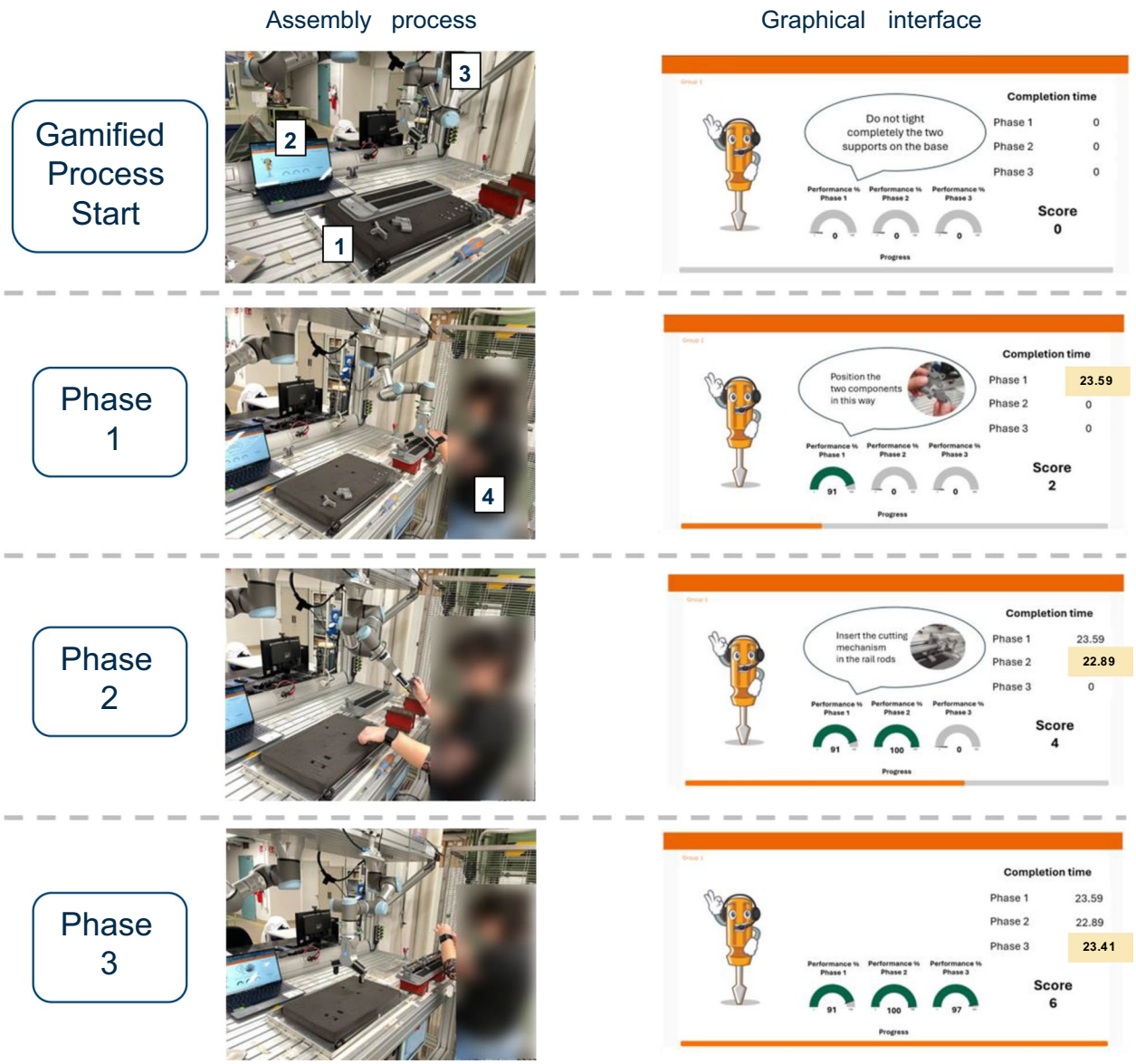


Fig. 4 Game phases of the collaborative assembly process (where (1) represents the feeding tray where all the components of the tile cutter are placed, (2) is the graphical interface, (3) is the collaborative robotUR3 and (4) is the human operator) and the related graphical dashboard for standard gamification where all the performance metrics are step-by-step updated in each phase of the assembly process (Mind4Lab at Polito)

representation of operational performance. This approach ensures that faster completion times are clearly reflected as better performance in the system's feedback mechanism.

- Suggestions: A virtual avatar is displayed during the assembly process to provide guidance and advice to help the operator perform tasks correctly. The avatar also provides illustrative images to enhance understanding and facilitate the assembly.

Figure 4 shows the four phases of the gamified collaborative assembly process. For each phase, the participant gets a score representing the performance of that specific phase.

4.2 Narrative gamification

The second gamification type is defined as "narrative gamification" since it is based on the integration of narrative and storytelling aspects in the gamified collaborative

assembly process. To this aim, both graphical and audio interface were developed to create an immersive environment. The objective of the gamified process, introduced by an audio clip, is to successfully complete a mission to fulfil an order for tile cutters that requires the assistance of skilled operators. To achieve this, players must complete all three levels, working together with UR3e cobot. This gamified activity aims to reduce operator stress and feelings of alienation, while increasing efficiency and precision. The rules of the game, also explained in the introductory audio clip, require players to complete the assembly by progressing through all the levels. Each level must be completed before moving on to the next one. The player's goal is to complete all three levels within the given time limits, while ensuring the quality of the assembly. Upon completion of the levels and mission, players are awarded a trophy based on their performance. Level difficulty and standards could be updated over time to maintain long-term engagement. At the end of the process, operators can earn virtual trophies based on the number of levels they successfully complete within the time limits:

- Gold Trophy: Awarded for excellence, when all three levels are successfully completed within the time limit.
- Silver Trophy: Awarded for high skill, when two levels are completed within the time limit.
- Bronze Trophy: Awarded for completing one or fewer levels within the time limit, representing determination and encouragement to improve.

Each trophy is associated with virtual rewards, which can include experience points that help you climb an internal leaderboard, as well as specific recognition such as training bonuses or small incentives. The gamified process is divided into four main phases, each with a specific reference time according to Table 3. The assembly process is initiated by pressing a button connected to the cobot, which performs pre-programmed movements to complete the task. As the levels progress, the operators are challenged to complete each phase within the specified time limits, receiving real-time feedback through the Node-RED dashboard. The feedback is displayed with a specific colour—green for success, red for failure—along with specific messages indicating the outcome of each level. A novel aspect of this process is the inclusion of audio clips that narrate the different stages of the process and guide the operator through the gamification. The aim of these audio prompts is to align the operator's objectives with those of the company. These clips, modified with specific audio effects to match the gamified context, help to create an engaging and dynamic atmosphere. The graphical user interface for narrative gamification is provided in Fig. 5. The graphical interface in the narrative gamification condition was deliberately designed to be more minimalist than the standard version. Specifically, the display provided only live feedback and a trophy icon as an indicator of performance. This design choice was made to prioritise immersion through auditory feedback, which the operator received through headphones. In this setup, the storytelling was primarily conveyed through the audio feedback, increasing engagement and guiding the user through the assembly process without relying on extensive on-display elements. The time calculation mechanism remained the same as in the standard condition: each time the operator pressed the button to instruct the cobot to perform the next task, this input was also used to register the completion time of the previous phase. The game phases and the related graphical interface are shown in Fig. 6. For each phase, participant heard narrative feedback through the

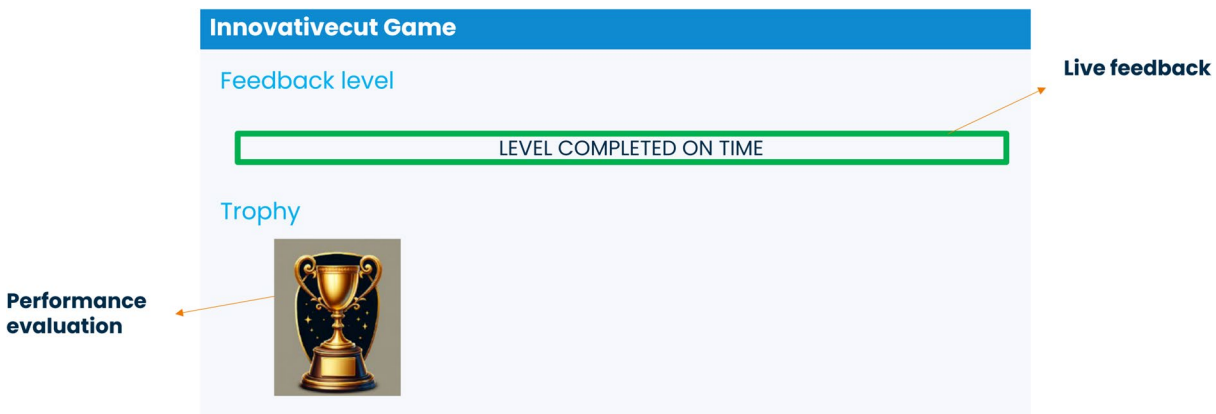


Fig. 5 Graphical user interface for narrative gamification

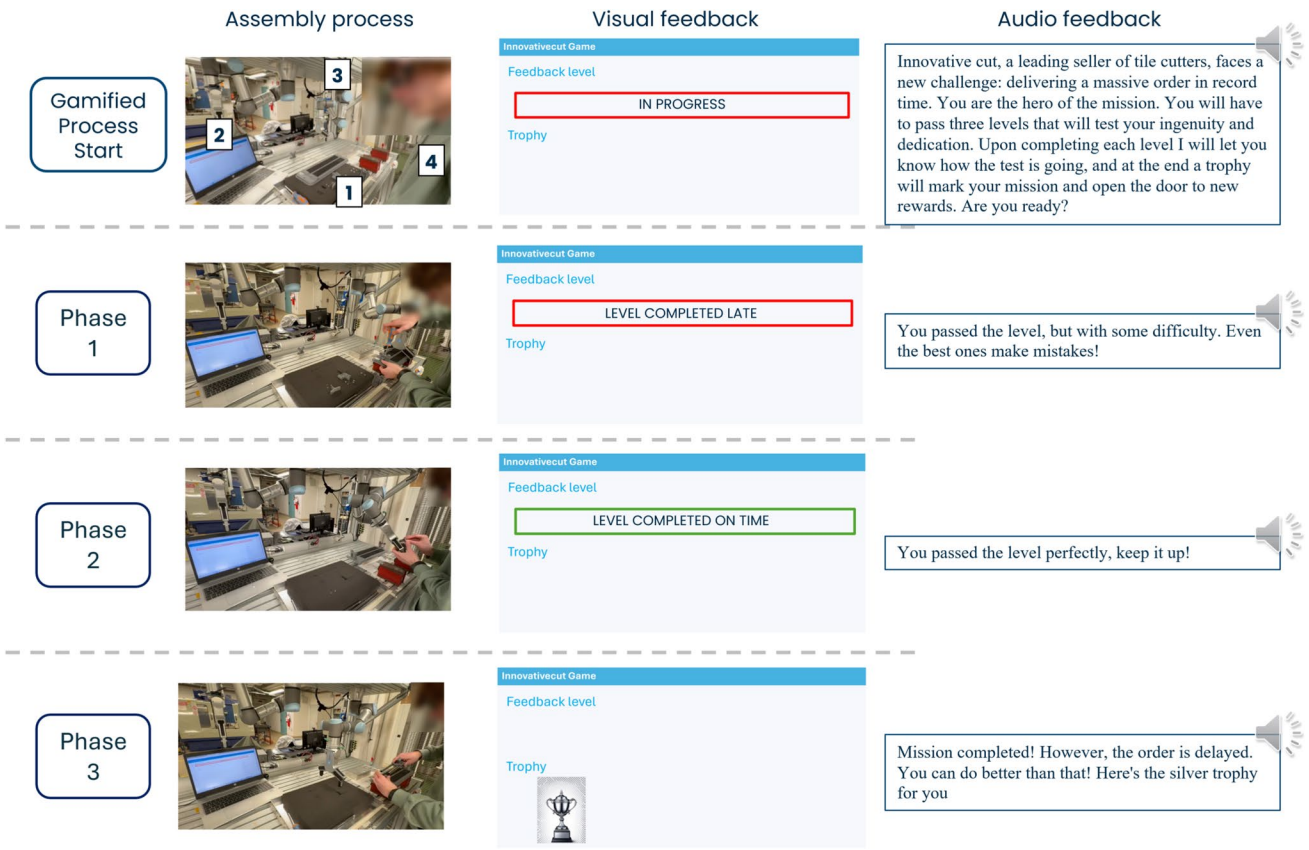


Fig. 6 Gamified phases of the collaborative assembly process (where (1) represents the feeding tray where all the components of the tile cutter are placed, (2) is the graphical interface, (3) is the collaborative robotUR3 and (4) is the human operator); the graphical dashboard for narrative gamification updated step-by-step and the related audio feedback (Mind4Lab at Polito)

earphones. The transcript of the audio files is provided in Fig. 6.

5 Experimental setting

The experiment was carried out in the laboratories of Mind-4Lab at Politecnico di Torino and involved a total of 30 participants. All participants were engineering students of Politecnico di Torino. The use of students as participants was intended to avoid the biases that experienced workers might bring, ensuring that the focus remained on testing the feasibility of applying gamification to assembly processes without the influence of pre-existing knowledge or habits. Participants were divided equally into two groups, each corresponding to a specific gamification type (standard or narrative). The details on the two gamification types and on the assembly process of the tile cutter are provided in Sect. 4. Each participant completed the same collaborative assembly (see Table 2) in two modalities:

- Not gamified (NG): in this modality, participants performed the tile cutter collaborative assembly without the introduction of any gamification elements
- Gamified (G): in this modality, participants performed the collaborative assembly tasks experiencing either the standard or narrative gamification, depending on their assigned group. Hence, each participant tried only one of the two gamification types.

Consequently, the aims of the experiment were two-fold: firstly, testing whether the introduction of gamification (either standard or narrative) could produce measurable

improvements in performance, quality and operator well-being compared to the non-gamified modality; and secondly, determining whether narrative or standard gamification produced better results. Therefore, each group followed a different experimental protocol:

- The first group of 15 participants performed 5 repetitions of a non-gamified collaborative assembly task and 5 repetitions using standard gamification. The order of the two modalities was randomised. In this gamification type, standard game elements such as points, badges and levels were incorporated into the process to motivate participants and improve performance (see Fig. 4).
- The second group of 15 participants also completed 5 repetitions of the non-gamified collaborative assembly tasks and 5 repetitions using narrative gamification. In this narrative type, storytelling and thematic progression were used to create a more immersive experience, aiming to engage participants on an emotional level in addition to the functional aspects of the task (see Fig. 6).

5.1 Data collected

The following objective and subjective data regarding performance, process quality and operators' well-being were collected throughout the whole experiment:

- Completion time: it refers to the time taken by an operator to perform an entire collaborative assembly. It was computed as the time interval between the start of the first elementary task and the end of last elementary task of the assembly process (see second column of Table 2).
- Process failures: these are defined as all those errors made by humans or robots that slow down the assembly process and thus generate inefficiencies. Since the aim of the experiment was to evaluate the impact of gamification on the human operator, only human-caused process failures were considered, as shown in Table 4.
- Physiological signals: to assess participants' well-being and cognitive effort during the tasks, physiological signals were recorded using the non-invasive biosensor Empatica E4 device, collecting electrodermal activity (EDA) at 4 Hz, heart rate data via photoplethysmography (PPG) at 64 Hz and 3-axis accelerometer data at 32 Hz. Stress indicators such as heart rate variability (HRV) and skin conductance response (SCR) can be derived from the EDA and PPG data. Heart rate variability (HRV) derived from PPG data provides a robust measure of cognitive load, with lower HRV values typically indicating increased mental effort and stress levels [43]. Similarly, electrodermal activity, particularly through skin conductance level (SCL), reflects overall arousal and cognitive engagement, with elevated SCL levels generally corresponding to higher emotional arousal and increased cognitive effort during task performance [44]. Thus, the combination of HRV and SCL data provided a comprehensive insight into the participants' well-being during the collaborative assembly tasks. The MATLAB package "Ledalab" was used to process the EDA data. Continuous Decomposition Analysis (CDA) [45] was used to decompose the EDA signal into continuous phasic and tonic activity. Tonic activity, measured by changes in skin conductance level (SCL), reflects long-term fluctuations not directly related to external stimuli. In contrast, phasic activity represents short-term changes in response to specific stimuli and it can be described by skin conductance responses (SCRs) which indicate changes in amplitude from the SCL to the peak of the response. The difference between SCL and SCR is shown in Fig. 7.

In addition, HRV data derived from heart rate measurements were also used as an indicator of stress and arousal to provide a more comprehensive understanding of physiological stress. In this study, the root mean square of successive

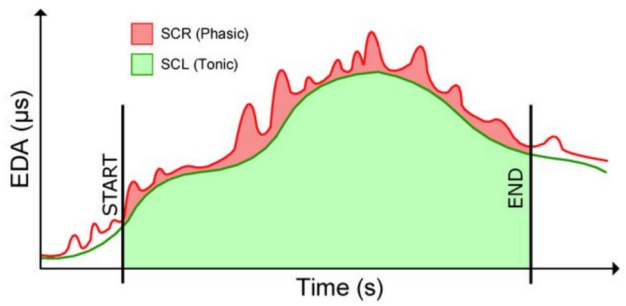


Fig. 7 Example of SCR and SCL in an EDA signal [46]

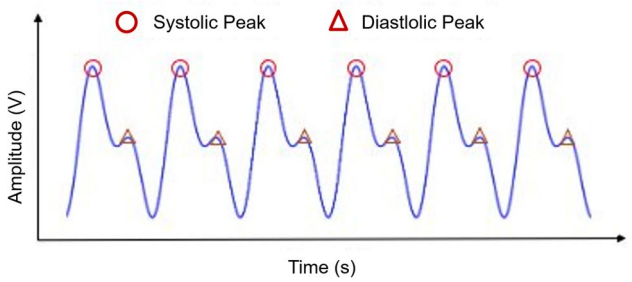


Fig. 8 Typical PPG signal [48]

differences between adjacent NN intervals (RMSSD) was used as a measure of heart rate variability (HRV), following its widespread use in previous research [43, 47]. RMSSD is calculated using the formula:

$$RMSSD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}(NN_{i+1} - NN_i)^2} \quad (3)$$

where N is the number of systolic peaks within the given time window and NN_i is the time interval between two consecutive systolic peaks (i and $i+1$). Figure 8 shows a typical PPG signal.

RMSSD is commonly used because of its reliability in capturing short-term variations in heart rate that are indicative of parasympathetic nervous system activity [10].

- Questionnaires: participants were also asked to fill in the following three questionnaires respectively provided in Appendixes 1, 2 and 3: (i) NASA-TLX [49]; (ii) Self-Assessment-Manikin [50] and (iii) Game Engagement Questionnaire [51]. Nasa-TLX is a common tool in the evaluation of perceived workload that is organised in 6 dimensions to evaluate on a scale from low to high: mental demand, physical demand, temporal demand, effort, performance and frustration. Each dimension is rated individually by participants on a scale ranging from "low" (0) to "high" (100). These ratings are then combined through a weighting procedure in which participants make pairwise comparisons between dimensions to indicate their relative importance. This produces an overall weighted workload score that reflects the participant's overall perceived workload during task performance. Self-Assessment-Manikin (SAM) [50] is used to assess emotional response and it is based on the evaluation of three dimension: arousal, dominance and valence on a scale from 1 to 9. Each dimension is represented by a set of manikin figures, allowing participants to intuitively express their emotional state without relying on verbal or numerical descriptions. The scale for each dimension ranges from 1 to 9, where valence measures the pleasantness of the emotion, ranging from extremely unpleasant (1) to extremely pleasant (9). Arousal measures emotional intensity, from very calm or inactive (1) to highly activated or excited (9). Then, dominance assesses the participant's perceived sense of control over the situation, ranging from feeling completely controlled or powerless (1) to feeling completely in control and dominant (9). Finally, the Game Engagement Questionnaire (GEQ) is a validated self-report instrument designed to assess the level of engagement experienced by participants in a gamified task [51]. The version used in this study consists of 19 items, each addressing different aspects of engagement. Participants answer to each statement on

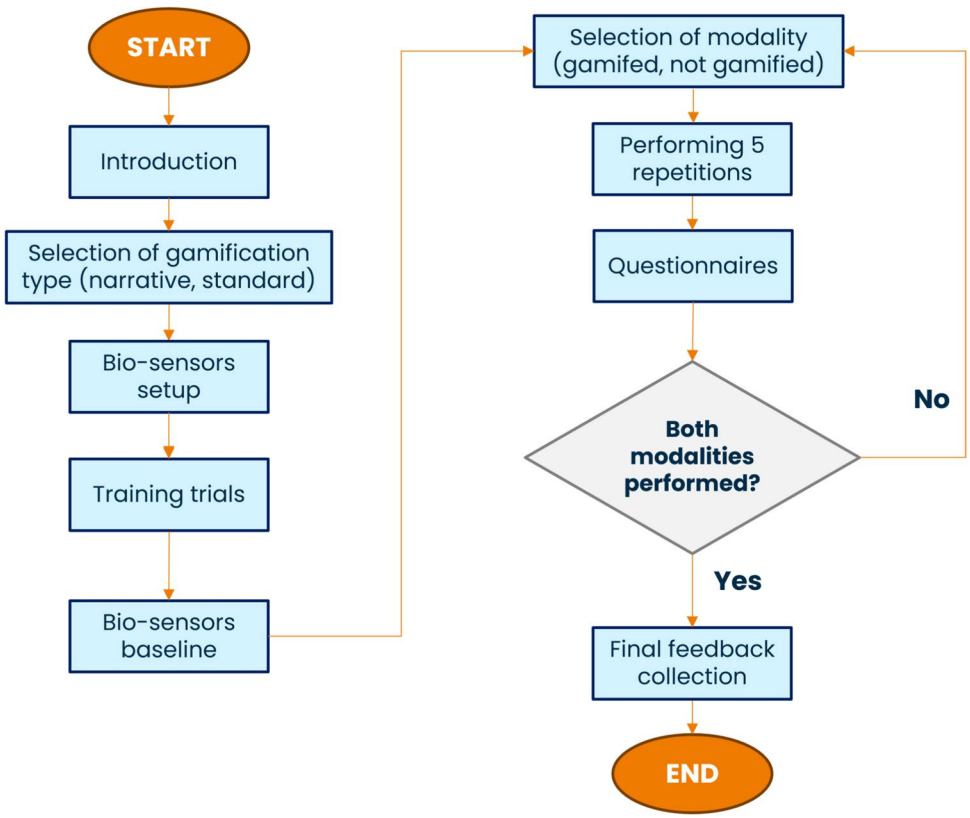


Fig. 9 Flowchart of the experimental procedure

a three-point scale: "yes", "maybe" or "no". The GEQ assesses engagement across a number of key dimensions: (i) *immersion* which is the extent to which participants feel absorbed in the experience, (ii) *presence* that refers to the feeling of being mentally and emotionally present in the game-like environment, (iii) *flow* that indicates the feeling of effortless involvement, where the challenge of the task is well matched to the participant's abilities, and (iv) *absorption* that refers to the degree of emotional and cognitive involvement, reflecting the extent to which the experience captures attention and reduces awareness of time. The overall engagement score is obtained by analysing the frequency of "yes", "maybe" and "no" responses, with a higher proportion of "yes" responses indicating greater overall engagement.

5.2 Experimental procedure

The experimental procedure included the following steps, as shown in Fig. 9:

- Introduction: Each participant was introduced to the activities and the gamification type they would be undertaking during the experiment.
- Empatica E4 setup: Participants were equipped with the non-invasive biosensor Empatica E4 wristband, which measures physiological signals such as electrodermal activity (EDA) and heart rate variability (HRV). This device collected continuous data throughout the experiment.
- Training phase: Participants underwent a brief training session in which they were instructed on how to perform the collaborative assembly task correctly.
- Baseline measurement: A 2-min baseline period was conducted to establish a reference for physiological measures.
- First modality assembly: Participants began the experiment by completing five repetitions of the collaborative assembly process in one of the two modalities randomly selected (gamified or not gamified). The first group of 15 participants performed standard gamification, while the second group narrative gamification.
- Questionnaires: After completing the first modality, participants were asked to fill in a series of questionnaires, including the NASA-TLX, the Self-Assessment Manikin (SAM) and the Game Engagement Questionnaire.
- Second modality assembly: Participants performed the 5 repetitions of the assembly in the second modality. At the end participants completed the same set of questionnaires.
- Final feedback: After completing both trials and giving their feedback of the two processes, the experiment was completed.

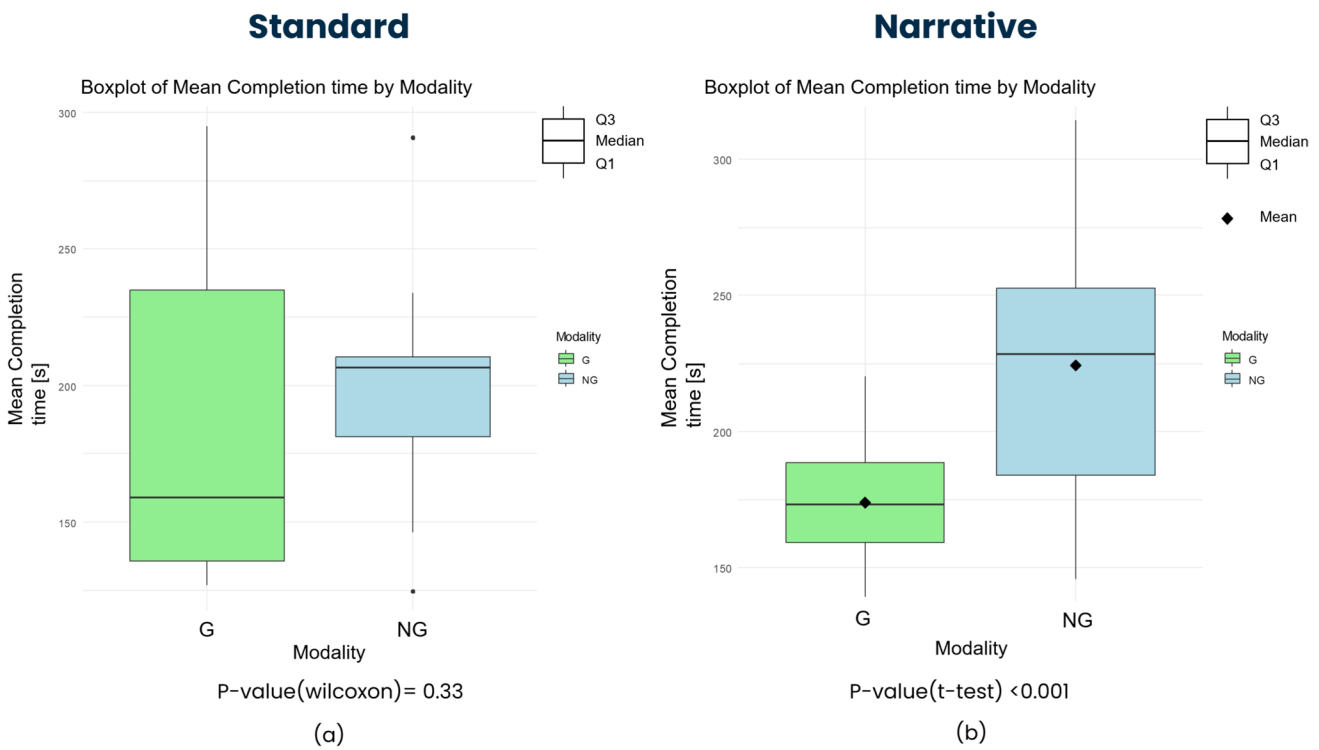


Fig. 10 Boxplot of completion times for both types **a** standard and **b** narrative in gamified (G) and not gamified (NG) modality

6 Results

The analysis of the experiment focused on several key metrics to assess the impact of gamification on the collaborative assembly process, including completion time, process errors, physiological stress indicators and perception questionnaires. Each of these metric was collected in both the standard gamification and narrative gamification types, as well as the not gamified baseline. For each gamification type (standard and narrative), the normal distribution of the data in both the gamified (G) and non-gamified (NG) modality was first checked using the Shapiro test [52]. Appendix 4 shows the histogram plots of the main data collected. Based on the results of this normality test, appropriate hypothesis tests were then conducted to determine statistical significance:

- Paired *t*-tests were used if the data followed a normal distribution.
- Paired samples Wilcoxon signed rank test was used when the normality assumption was rejected [53].

As the same participants performed both gamified and non-gamified modality, paired tests were performed to highlight differences between the two gamification approaches. Statistical significance was set at a *p*-value of less than 0.05.

6.1 Completion time

Completion time can be considered a measure of the efficiency of the process, and it is computed as the overall time necessary to assemble the product. For each gamification type, the mean completion time is calculated as the average of the 5 repetitions for each participant in each of the two modalities (i.e. gamified or not gamified). The related histogram plots of these data are shown in Appendix 4 – Fig. 18. The box plots for completion time in both the standard gamification and narrative gamification show clear differences in performance compared to the non-gamified (NG) modality (see Fig. 10).

In the standard gamification (a), the mean completion time for the gamified (G) modality is lower than for the non-gamified (NG) modality. However, the *p*-value from the Wilcoxon test ($p = 0.33$) indicates that this reduction in completion time is not statistically significant, suggesting that while there may be some improvement in efficiency with standard gamification, it is not enough to confirm a significant effect. In the narrative gamification (b), the mean completion time in the gamified (G) modality is significantly lower than in the non-gamified (NG) modality. The *p*-value from the paired *t*-test ($p < 0.001$) indicates that this reduction is statistically significant, showing that in this preliminary

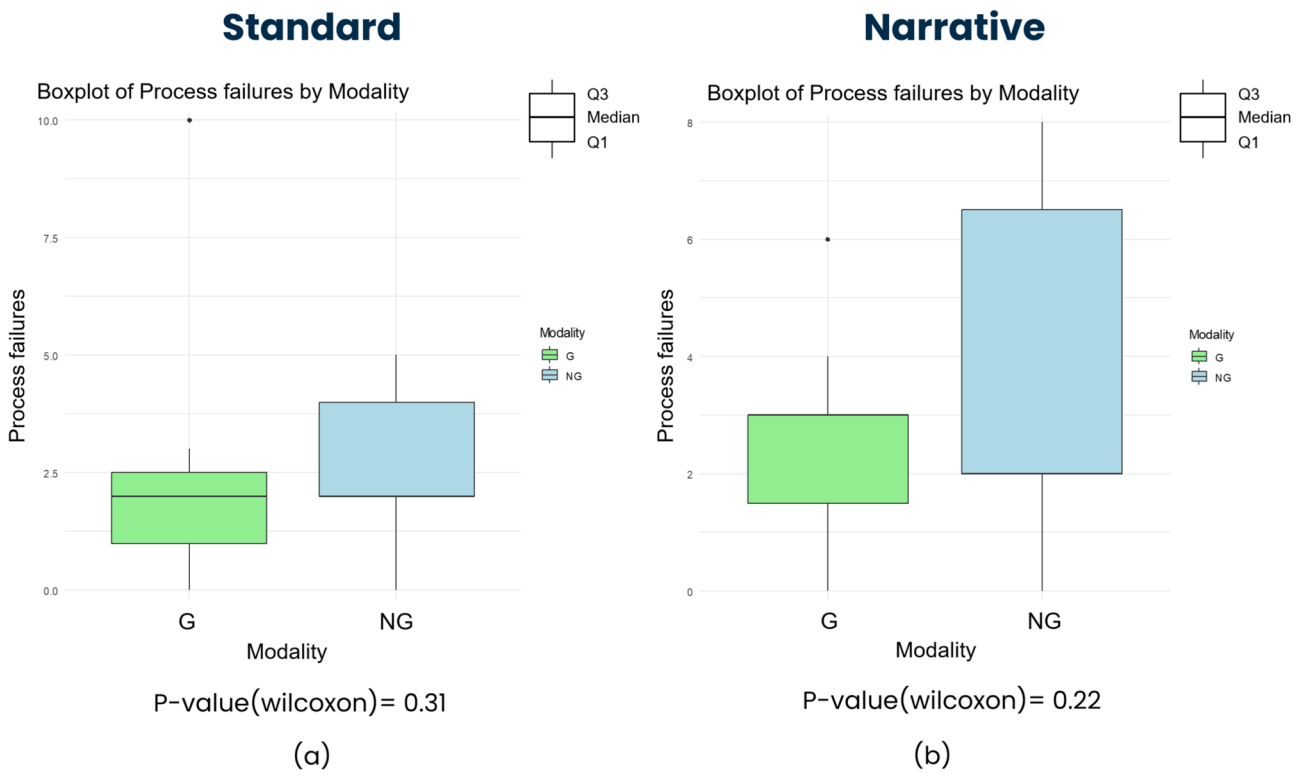


Fig. 11 Boxplot of human-caused process failures for both types **a** standard and **b** narrative in gamified (G) and not gamified (NG) modality

experiment narrative gamification led to a significant improvement in task completion time.

6.2 Process failures

Process failures were computed as the total number of failures found in the 5 repetitions of each modality. The histogram plots of process failures are shown in Appendix 4 – Fig. 19. The analysis of process failures in both the standard and narrative gamification did not provide significant results (see Fig. 11). In the standard gamification, the median number of process errors for the gamified (G) modality is slightly lower than the non-gamified (NG). However, the p-value from the Wilcoxon test ($p = 0.31$) indicates that this difference is not statistically significant. Similarly, in the narrative gamification type, the p-value from the Wilcoxon test ($p = 0.22$) still indicates that the difference is not statistically significant.

6.3 Physiological signals

Electrodermal activity (EDA) and heart rate variability (HRV) were analysed to assess physiological responses related to stress and engagement during the collaborative assembly tasks. For EDA, Skin Conductance Level (SCL) was chosen as the primary measure since it is considered more suitable to analyse sweat production over time intervals [54], and for HRV, RMSSD was used. These measures were chosen because of their relevance to the monitoring of stress and autonomic nervous system activity. For both metrics, individual scores were standardised to account for individual differences by calculating z-scores using the formula:

$$z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \tag{4}$$

where z_{ij} is the z-score i for participant j, x_{ij} the observation i for participant j, $\bar{x}_j$ the sample mean for participant j, and s_j the sample standard deviation for participant j, with $i = 1, \ldots, 5$ and $j = 1, \ldots, 30$. Hence, the mean SCL scaled value was obtained by averaging all the SCL scaled values within a single repetition. The histogram plots for Mean SCL scaled values are shown in Appendix 4 – Fig. 20. The box plots in Fig. 12 show the mean SCL for both gamified (G) and non-gamified (NG) modalities for standard and narrative gamification.

In the standard gamification type, the mean SCL for the gamified modality is slightly lower than for the non-gamified modality. However, the p-value from the Wilcoxon test ($p = 0.14$) indicates that this difference is not statistically significant. This suggests that while there may be

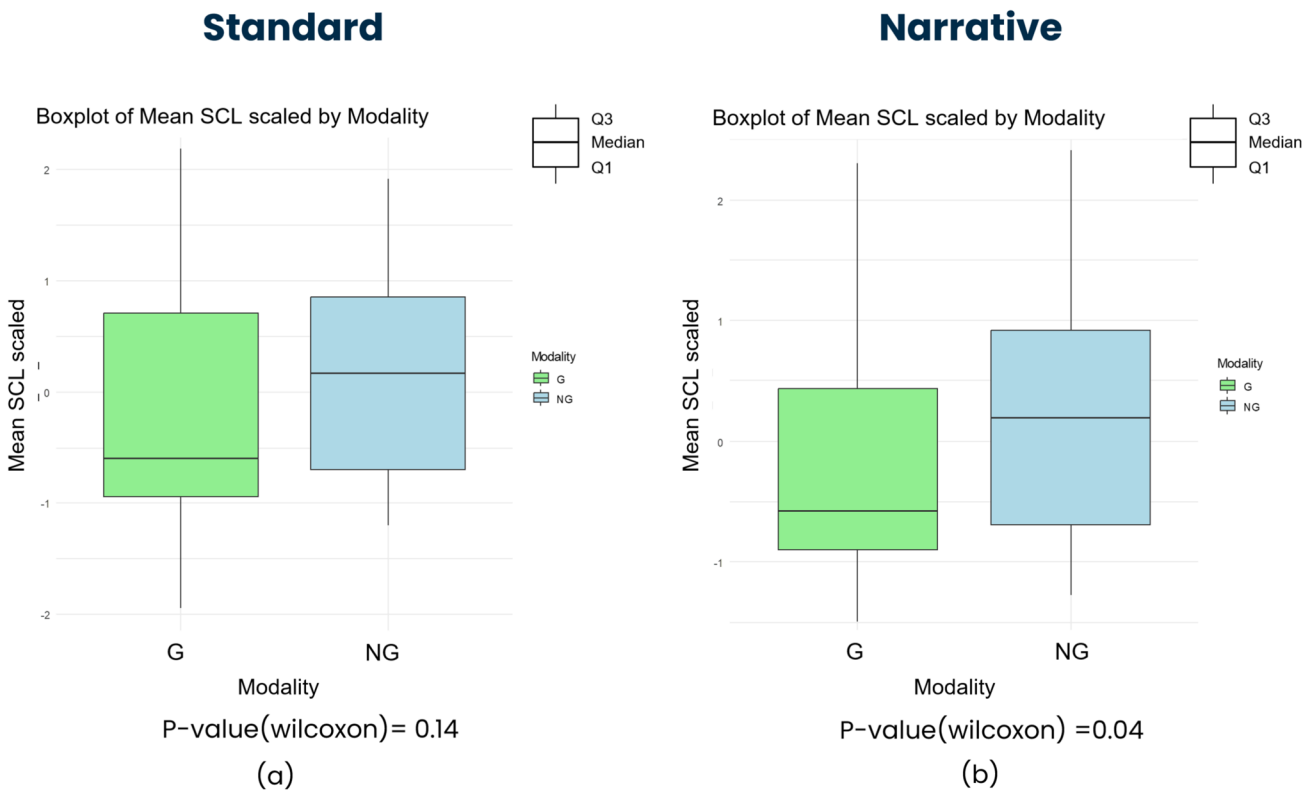


Fig. 12 Boxplot of Mean SCL for both types **a** standard and **b** narrative in gamified (G) and not gamified (NG) modality

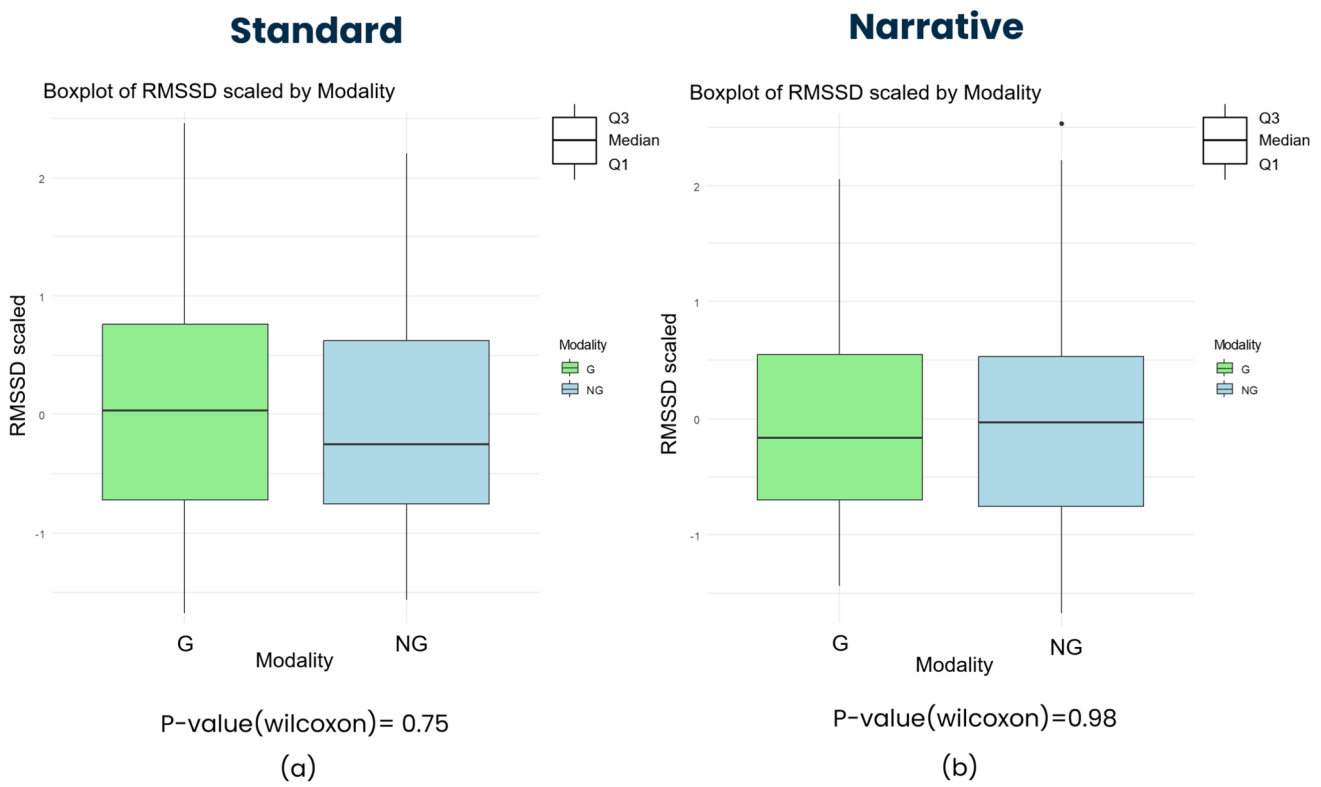


Fig. 13 Boxplot of RMSSD for both types **a** standard and **b** narrative in gamified (G) and not gamified (NG) modality

some effect on stress reduction in the gamified modality, the effect of standard gamification on physiological stress is not strong enough to be statistically significant. In the narrative gamification, the median SCL for the gamified modality is significantly lower than in the non-gamified modality, with a p-value of 0.04, indicating statistical significance. This suggests that narrative gamification had a more pronounced effect on reducing physiological stress, as reflected in lower SCLs during the gamified tasks. For RMSSD (see Appendix D – Figs. 21 and 13), no statistical significance emerged.

6.4 Questionnaires

The questionnaires analysed were NASA-TLX, SAM and GEQ. Regarding NASA-TLX, in the standard gamification type, no significant differences were found between the gamified and non-gamified modalities on any of the 6 dimensions (see Fig. 14a).

In standard gamification indeed, some participants reported that they did not feel immersed in the game, with many stating that they did not even engage with the interface, which likely explains the lack of significant findings for perceived workload and performance. However, several significant differences emerged in the narrative gamification (see Fig. 14b):

- Frustration was significantly higher in the non-gamified modality, suggesting that the narrative elements in the gamified version helped to reduce participants' frustration by providing engagement during the task.
- Physical demand was also significantly higher in the non-gamified modality, suggesting that participants found the gamified task less tiring. This may be due to the immersive and guided nature of the narrative, which made the task feel more fluid and manageable.
- Performance was rated higher in the gamified modality, which is a negative finding in this context. The NASA-TLX scale for performance is inverted, meaning that lower scores indicate better performance perceived. Participants in the gamified modality felt less successful in completing the task, possibly due to the immediate audio and graphical feedback they received during the task. This real-time feedback likely made them more aware of their mistakes or inefficiencies, thus reducing their perceived performance success.

The contrast between the standard and narrative gamification results suggests that narrative elements may play a role in user engagement and workload perception. In the standard gamification, participants were not as engaged with the gamified elements, whereas in the narrative type, the feedback mechanisms significantly influenced their experience.

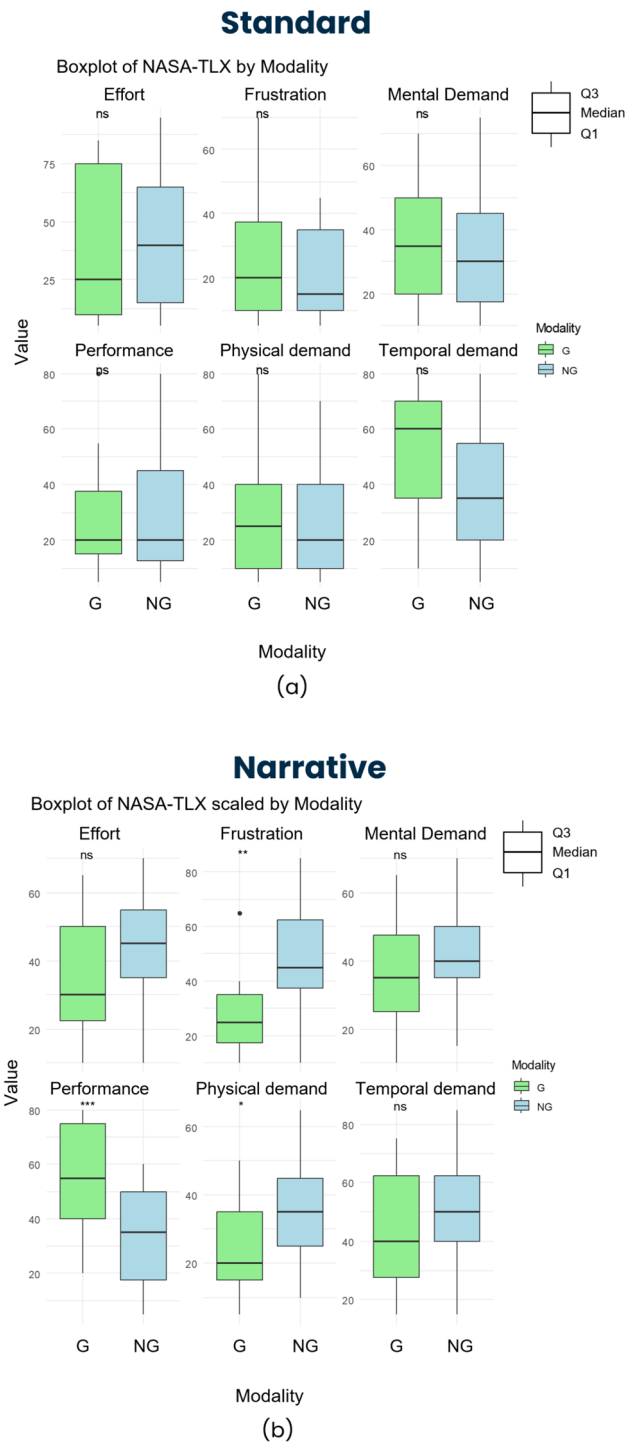


Fig. 14 Boxplot of NASA-TLX dimensions for both types **a** standard and **b** narrative in gamified (G) and not gamified (NG) modality

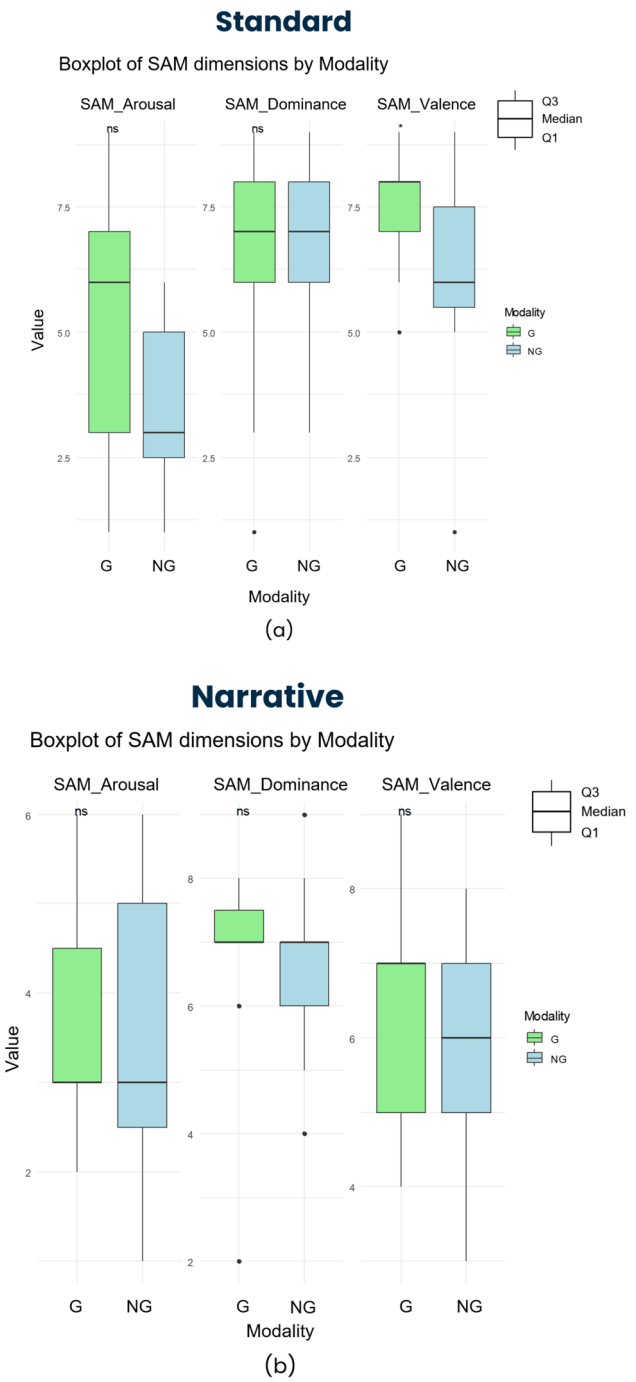


Fig. 15 Boxplot of SAM dimensions for both types **a** standard and **b** narrative in Gamified (G) and not gamified (NG) modality

The Self-Assessment Manikin (SAM) questionnaire was used to measure participants' emotional responses across three dimensions: arousal, dominance and valence. Results for each dimension were compared between the gamified (G) and non-gamified (NG) modalities (see Fig. 15). In both the standard and narrative gamification, no statistically significant differences in arousal were observed between the gamified and non-gamified modality. This suggests that neither type of gamification had a noticeable effect on how participants felt during the task. Similarly, no significant differences were found in the dominance dimension for either modality. Finally, in the standard gamification, there was

Table 1 Application of the MDA framework in collaborative assembly

Dimension	Definition	Practical tools	Examples in collaborative assembly
Mechanics	The rules, structures and systems that form the foundation of the game	Point systems: Rewarding workers for task completion or performance milestones	Workers earn points for completing tasks with accuracy, speed or efficiency. Cobots provide real-time feedback on progress
		Levels/progression: Unlocking new tasks or capabilities as users progress through stages	Unlock advanced features of cobots (e.g. faster response times) as workers improve their performance in assembly tasks
		Challenges/quests: Assigning specific tasks or challenges to users to encourage engagement	Workers are given daily or weekly challenges (e.g. assemble a certain number of parts within a time limit)
		Timers and time limits: Adding time constraints to tasks to increase urgency or encourage efficiency	Timed assembly challenges, where workers must complete tasks within a certain period to receive rewards
		Feedback systems: Providing continuous feedback (scores, progress bars) to reflect performance	Cobots display real-time metrics (e.g. speed, accuracy) through screens or AR tools to keep workers informed
Dynamics	The behaviours and interactions that emerge because of the mechanics in place	Cooperative interaction: Encouraging teamwork between human workers and robots through shared goals or tasks	Workers and cobots must complete tasks together, optimising coordination and efficiency
		Competition: Encouraging friendly competition among workers to achieve better performance	Workers can compete in team-based challenges, comparing scores with each other
		Strategic choices: Offering different paths or methods to complete tasks, encouraging experimentation	Workers can choose different tools or techniques to collaborate with cobots in assembly tasks for optimal performance
		Resource scarcity: Introducing limited resources (time, tools) that need to be managed to achieve goals	Workers must allocate their time or use specific tools efficiently while collaborating with cobots
Aesthetics	The emotional responses or experiences evoked in users, influenced by the mechanics and dynamics	Narrative/storytelling: Using stories to frame tasks or create context for the collaboration	Framing assembly tasks within a narrative where workers and cobots are part of a mission (e.g. assembling critical parts for an urgent project)
		Achievement/satisfaction: Creating moments of success through progress tracking, badges or awards	Workers receive visual rewards (badges, trophies) when completing tasks efficiently, displayed on graphical dashboards
		Immersion/flow: Designing the experience to create deep focus, where tasks are optimally challenging but achievable	The gamified system adapts task difficulty based on performance, ensuring workers and cobots are always challenged, but not overwhelmed
		Sense of progress: Showcasing improvement over time, through level-ups, ranking systems or skill development indicators	Workers see their progress (e.g. improving assembly speed or reducing defects), contributing to a sense of personal improvement
		Social interaction: Promoting engagement through leaderboards, team rankings or shared achievements	Workers can compare performance and progress through team rankings, encouraging friendly competition in assembly processes

Table 2 List of product's parts, codes and quantities, list of the elementary task of the assembly process (divided in the 4 main phases) and the related allocation between human and robot

Product characteristics			*Assembly process*	*HRC Task allocation*	
Parts and fasteners	Code	Quantities	Elementary task (same in manual and HRC)	Human	Cobot
Base	Base	1	1.1 Pick and place Base		X
Lateral support	C1a/C1b	2	1.2 Pick and place C1a and C1b on Base	X	
Joint component	C2	1	1.3 Preliminary screwing C1a and C1b on Base	X	
Cutting component	C3	1	2.1 Placing the subassembly (Base + C1a + C1b) out of the assembly area		X
Blade	L1	1	2.2 Pick and place C2		X
Tile blocker	C4	1	2.3 Pick and place C3 in C2	X	
Rail rod	P1a/P1b	2	2.4 Screwing C3 and C2	X	
Handle	P2	1	2.5 Pick and place L1	X	
Bolt type 1	B1	2	2.6 Screwing L1 and C3	X	
Bolt type 2	B2	1	2.7 Pick and place C4 in C3	X	
Bolt type 3	B3	2	2.8 Screwing C4 and C3	X	
Nuts type 1	N1	2	3.1 Placing the subassembly (C2 + C3 + C4 + L1) out of the assembly area		X
Nuts type 2	N2	1	3.2 Pick and place subassembly (Base + C1a + C1b) back in the assembly area		X
Nuts type 3	N3	2	3.3 Insert subassembly (C2 + C3 + C4 + L1) in both P1a/P1b	X	
			3.4 Insert P1a/P1b in C1a/C1b	X	
			3.5 Final screwing C1a/C1b on Base	X	
			3.6 Pick and place P2	X	
			3.7 Screwing P2	X	
			4.1 Pick the final product and place out of the assembly area		X

Table 3 Completion times of the four phases of the tile cutter assembly process

Phase	C_j^*[s]	O_j^*[s]	T_j^*[s]
1	13	57	70
2	16	103	119
3	20	80	100
4	11	0	11

a statistically significant difference in valence ($p < 0.05$). Participants in the gamified modality reported lower valence scores, indicating less positive emotions, compared to the non-gamified modality. This could be due to participants being more aware of their performance and feeling less satisfied with their achievements, as previously noted in their NASA-TLX performance ratings.

Table 4 Human-caused process failures considered in the experiment (adopted from [10])

Process failures	Description
Wrong part selection	The operator picks up the wrong part according to the correct assembly sequence
Dropping of parts	Operator drops a part/subassembly/final product involved in the assembly process
Wrong part positioning	Operator places a part/subassembly incorrectly with respect to what the task requires
Incorrect assembly	Operator assembles a part/subassembly incorrectly
Part damage	Operator causes structural damage to a part/subassembly/final product
Dropping of screws	Operator drops a screw
Dropping of nuts/washers	Operator drops nuts/washers
Wrong input to cobot	the operator gives input to the cobot at the wrong time according to the assembly sequence
Wrong screws/nuts/washers selection	The operator picks up the wrong screw/nut/washer according to the correct assembly sequence
Wrong screws/nuts/washers positioning	Operator places a screw/nut/washer incorrectly with respect to what the task requires
Incorrect assembly of screws/nuts/washers	Operator uses screws/nuts/washers incorrectly
Dropping of tools	Operator drops tools (e.g. screwdrivers)

Table 5 Results of GEQ

GEQ	YES		MAYBE		NO	
Item	Standard	Narrative	Standard	Narrative	Standard	Narrative
I lose track of time	6	6	3	3	6	6
Things seem to happen automatically	9	10	1	4	5	1
I feel different	5	4	5	4	5	7
I feel scared	0	0	0	0	15	15
The game feels real	6	7	2	8	7	0
If someone talks to me, I don't hear them	1	3	5	5	9	7
I get wound up	5	1	5	5	5	8
Time seems to kind of stand still or stop	2	5	4	4	9	6
I feel spaced out	3	3	1	4	11	8
I don't answer when someone talks to me	0	1	3	4	12	10
I can't tell that I'm getting tired	6	5	4	3	5	7
Playing seems automatic	9	10	4	3	2	2
My thoughts go fast	6	5	7	5	2	5
I lose track of where I am	3	1	2	4	10	10
I play without thinking about how to play	5	7	4	4	6	4
Playing makes me feel calm	3	4	5	8	7	3
I play longer that I meant to	1	4	7	2	7	9
I really get into the game	12	13	0	2	3	0
I feel like I just can't stop playing	2	2	3	3	10	10

Table 6 Standard and narrative gamification assessed through the MDA framework

Dimensions	Practical tools	Standard gamification	Narrative gamification
Mechanics	Points	X	
	Levels		
	Challenges	X	X
	Time limits	X	X
	Feedback systems	X	X
Dynamics	Cooperative	X	X
	Competition		
	Strategic choices		
	Resource scarcity		
Aesthetics	Story telling		X
	Achievements	X	X
	Immersion		X
	Sense of progress	X	X
	Social interaction		

The results of the Game Engagement Questionnaire (GEQ) are shown in Table 5. In the narrative gamification type, more participants reported that the game felt real (7 "Yes" in narrative with 8 "maybe" vs 6 "yes" in standard with 2 "maybe"), and a higher number of participants reported that they "really got into the game" (13 "Yes" in narrative with 2 "maybe" vs. 12 "yes" in standard). This suggests that the narrative elements increased the sense of immersion. Participants in the narrative type were more likely to lose track of time, with 6 "yes" responses in both cases, but a greater number in the narrative type felt that "time seemed to stand still" (5 "yes" in narrative vs. 2 in standard), that may suggest greater absorption in the task. In both types, a high number of participants felt that the task became automatic, with 10 "Yes" in narrative and 9 in standard, indicating a similar level of fluency in task performance. Finally, participants in the narrative gamification type reported feeling calmer (4 "Yes" with 8 "maybe" for narrative vs. 3 "yes" with 5 "maybe" for standard), consistent with findings that narrative gamification reduced frustration and increased emotional engagement. Hence, narrative gamification led to slightly greater immersion and absorption, while standard gamification showed slightly lower engagement in these areas. The other items did not show any interesting results.

7 Discussion

This study investigated the feasibility of applying gamification to collaborative assembly by providing preliminary insights into its potential impact. Referring to the MDA framework introduced in Sect. 3, Table 6 outlines how the two types of gamification meets the key dimensions of mechanics, dynamics and aesthetics [13] and the related practical tools provided in Table 1. Standard gamification primarily covers the dimensions of mechanics and dynamics,

Table 7 Summary of the main results obtained

Family	Variable/tool	Main results
Performances	Completion time	Narrative gamification significantly reduced completion time
	Process failures	Less failures in gamified modalities (although not statistically significant)
Physiological signals	EDA – Mean SCL	Narrative gamification significantly reduced stress in operators
	HRV-RMSSD	Not clear differences
Questionnaires	NASA-TLX	In narrative gamification participants reported less frustration and physical demand with respect to the not gamified modality
	SAM	Not clear differences
	GEQ	Greater immersion and absorption in narrative gamification

incorporating challenges, scoring and feedback systems, but lacking enough aesthetic elements. In contrast, narrative gamification excels in the aesthetic dimension, using storytelling to enhance immersion and emotional engagement.

From a mechanics perspective, standard gamification showed its strength in structuring tasks with elements such as points, time limits and feedback systems. These elements helped to create a structured environment, but participants in this gamification type reported a lack of immersion, which may explain the limited emotional engagement and awareness of performance feedback. This suggests that standard gamification, while functional, may not fully exploit the motivational potential of gamification, particularly in tasks that require deeper emotional and cognitive engagement. In contrast, narrative gamification excelled in the aesthetic dimension by embedding storytelling, which enhanced immersion and emotional engagement. The results showed that narrative elements reduced frustration and physical demands, creating a smoother and less stressful experience. However, the real-time audio and graphical feedback in narrative gamification, while improving participants' awareness of their performance, paradoxically led to lower perceived success as participants were more aware of their mistakes. This highlights the delicate balance required in gamified systems: while feedback can improve performance, it can also negatively impact if not carefully managed. Table 7 summarises the main findings of this study.

In general, narrative gamification significantly reduced physiological stress indicators (Electrodermal Activity-EDA) and operator frustration, likely due to the immersive, audio-based storytelling that intuitively guided operators through collaborative tasks. Standard gamification also showed positive effects, although not significant, by providing clear visual feedback, structured task guidance and immediate performance metrics. However, the clear advantage of narrative gamification observed in this study can be attributed to its greater ability to improve emotional engagement and reduce operator stress by increasing a deeper sense of immersion and flow [17]. The findings of this preliminary study are consistent with the few existing studies in the literature on gamification in manufacturing contexts. Similar to Dolly et al. [3], the present findings suggest that gamification can positively influence operator performance and reduce frustration during assembly tasks. However, this paper also shows that narrative gamification has the potentials to specifically improve operator well-being. This is in line with Seo et al. [38] who also found that narrative gamification promotes intrinsic motivation. Furthermore, the current findings are consistent with those reported by Lee et al. [24], who found that a carefully designed gamification framework applied to an automotive bolt-tightening assembly task effectively increased worker motivation and led to better performance.

8 Conclusions

Gamification has been shown to be effective in increasing engagement, motivation and performance in various domains; however, its application in manufacturing remains underexplored. The primary contribution of this study is to develop practical guidelines and show how gamification can be strategically implemented in collaborative assembly processes. By empirically comparing two different gamification modalities, namely standard and narrative, the study revealed unique benefits associated with narrative gamification in particular. Specifically, narrative gamification significantly reduced physiological stress indicators and operator frustration, primarily due to the increased immersion and sense of flow facilitated by audio-driven storytelling. Standard gamification, although less emotionally impactful, demonstrated potential by providing clear visual feedback, structured task guidance and immediate performance metrics. In addition, the integration of objective physiological measures (such as EDA) alongside subjective self-report measures strengthened the robustness of the findings, providing insights into the operator experience beyond traditional performance metrics.

Despite these promising findings, this study presents some limitations:

- The relatively small sample size and the participation of students rather than experienced industrial workers limit the generalisability of these findings to real industrial contexts.
- The assembly task chosen for this study was relatively simple and may underestimate the challenges inherent in typical manufacturing operations. In addition, the results are inevitably influenced by the way the robot was specifically programmed.
- The short-term nature of the experiment leaves unanswered questions about sustained operator motivation and potential boredom or disengagement that may occur with prolonged exposure to gamified tasks.
- The simplicity of the gamification technology used, which relied on basic visual and audio feedback systems, may limit the depth of operator immersion and long-term engagement.

To address these limitations and increase the generalisability and robustness of these findings, future research will be addressed to:

- Expanding the sample size and include professional operators to better reflect industrial realities and validate the practical utility of gamification.
- Evaluating gamification in more complex assembly scenarios to explore the scalability and effectiveness of gamification under realistic manufacturing conditions. Further research could also explore how different gamification design can affect operator engagement and performance, potentially leading to more adaptable and personalised gamification strategies. Moreover, it is also worth exploring if the usage of different evaluation variables or tool would affect results in terms of the effectiveness of gamification strategies.
- Conducting longitudinal studies to assess operator engagement, motivation and potential boredom or disengagement over time.
- Exploring adaptive gamification mechanisms tailored to operator characteristics, preferences and real-time responses, potentially integrating advanced immersive technologies such as augmented reality (AR) or virtual reality (VR) to maximise engagement.

In conclusion, the results of this exploring study suggest that gamification, particularly narrative-based approaches, can significantly improve worker engagement, reduce stress and enhance process quality in collaborative assembly processes, providing tangible benefits to the manufacturing sector. In highly variable and human skill–dependent assembly tasks, where operators must frequently interact with cobots and adjust their actions based on real-time feedback, gamification can serve as a tool to ensure smoother collaboration. In particular, industries such as electronics assembly, automotive manufacturing and precision engineering, where human dexterity and cognitive decision-making are essential, could benefit from increased engagement and motivation through well-designed gamification strategies. In addition, training processes for new operators could use gamification to accelerate skill acquisition and retention. By integrating real-time performance feedback and immersive storytelling elements, manufacturing companies can create a more stimulating and efficient working environment, in line with Industry 5.0 principles that emphasise both productivity and worker well-being.

Appendix 1. NASA-TLX [49]

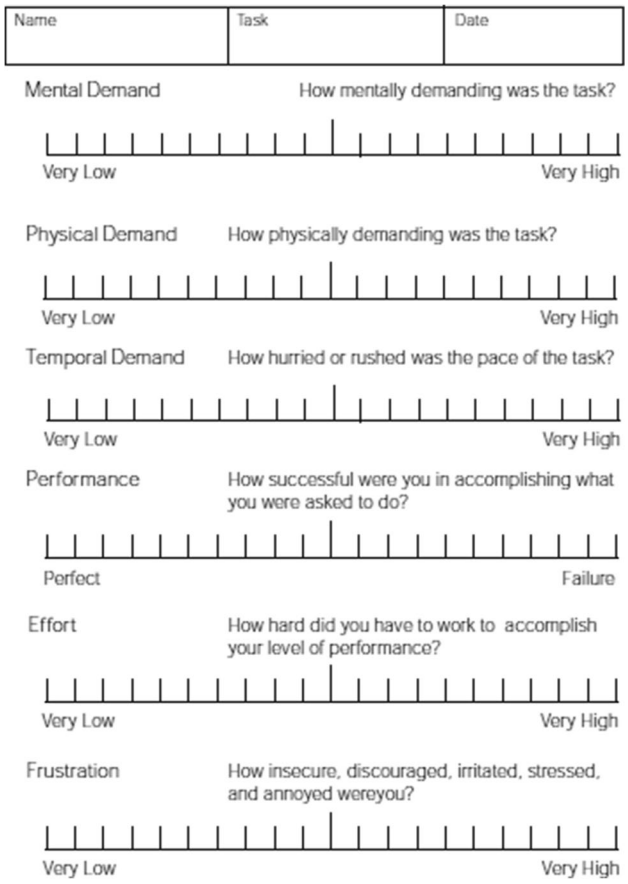


Fig. 16 NASA-TLX [49]

Appendix 2. Self - Assessment Manikin [50]

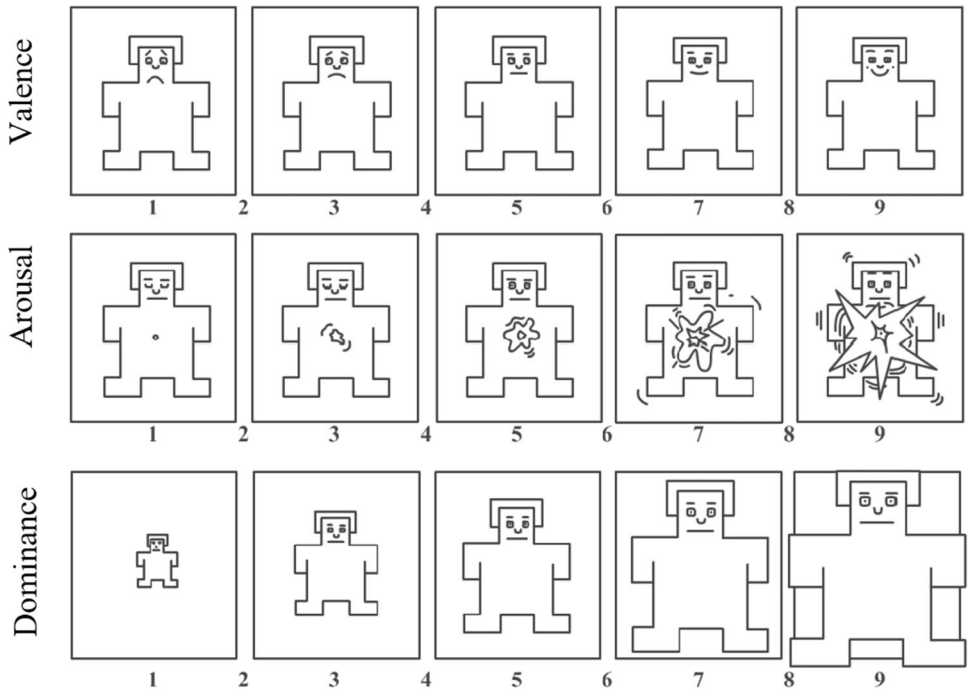


Fig. 17 Self-Assessment Manikin [50]

Appendix 3. Game Engagement Questionnaire [51]

Table 8 Game Engagement Questionnaire [51]

Item n.	Item
1	I lose track of time
2	Things seem to happen automatically
3	I feel different
4	I feel scared
5	The game feels real
6	If someone talks to me, I don't hear them
7	I get wound up
8	Time seems to kind of stand still or stop
9	I feel spaced out
10	I don't answer when someone talks to me
11	I can't tell that I'm getting tired
12	Playing seems automatic
13	My thoughts go fast
14	I lose track of where I am
15	I play without thinking about how to play
16	Playing makes me feel calm
17	I play longer than I meant to
18	I really get into the game
19	I feel like I just can't stop playing

Appendix 4. Histogram plot of the data collected

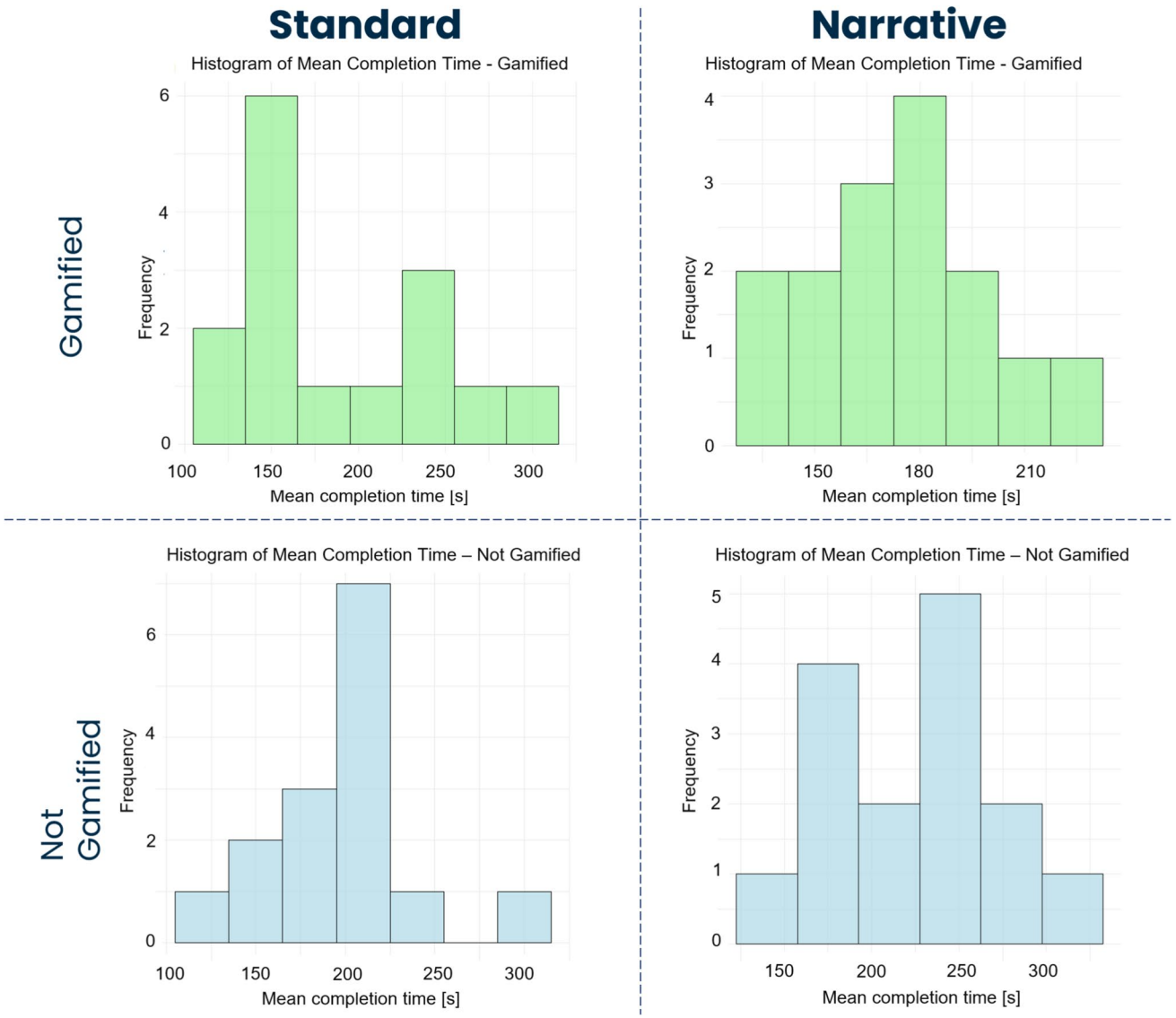


Fig. 18 Histogram plots of the mean completion times

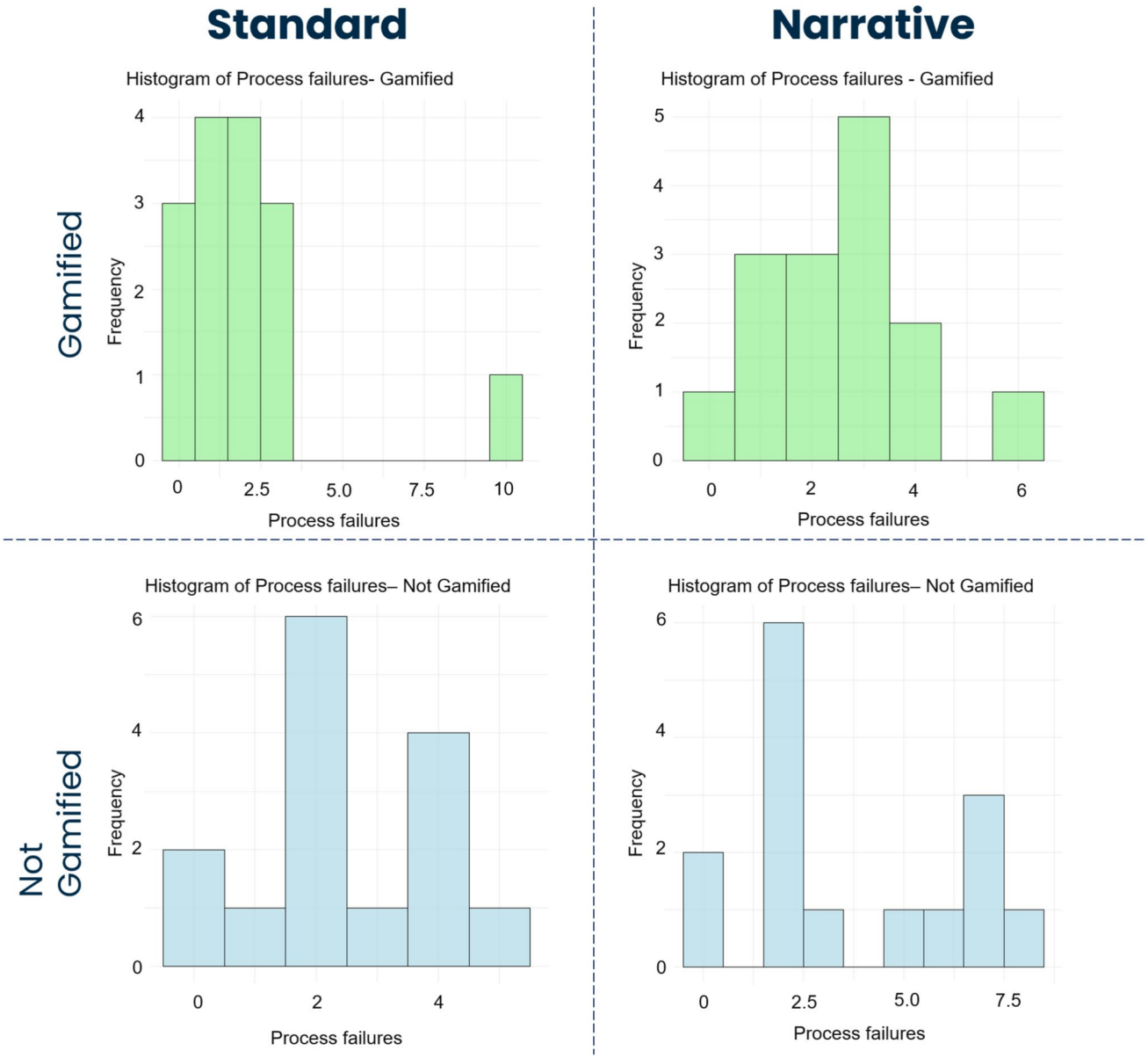


Fig. 19 Histogram plots of the process failures

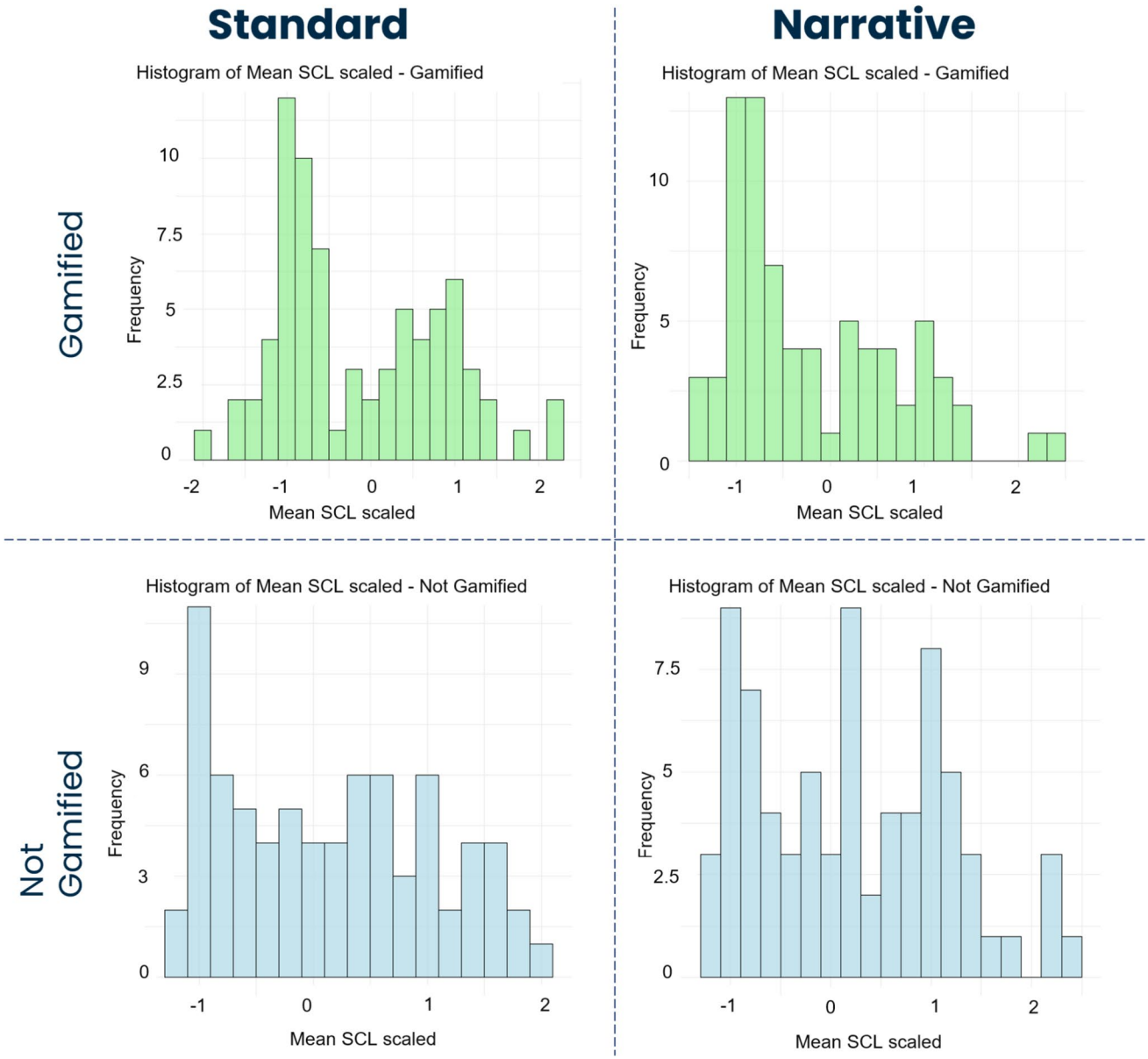


Fig. 20 Histogram plots of mean SCL scaled

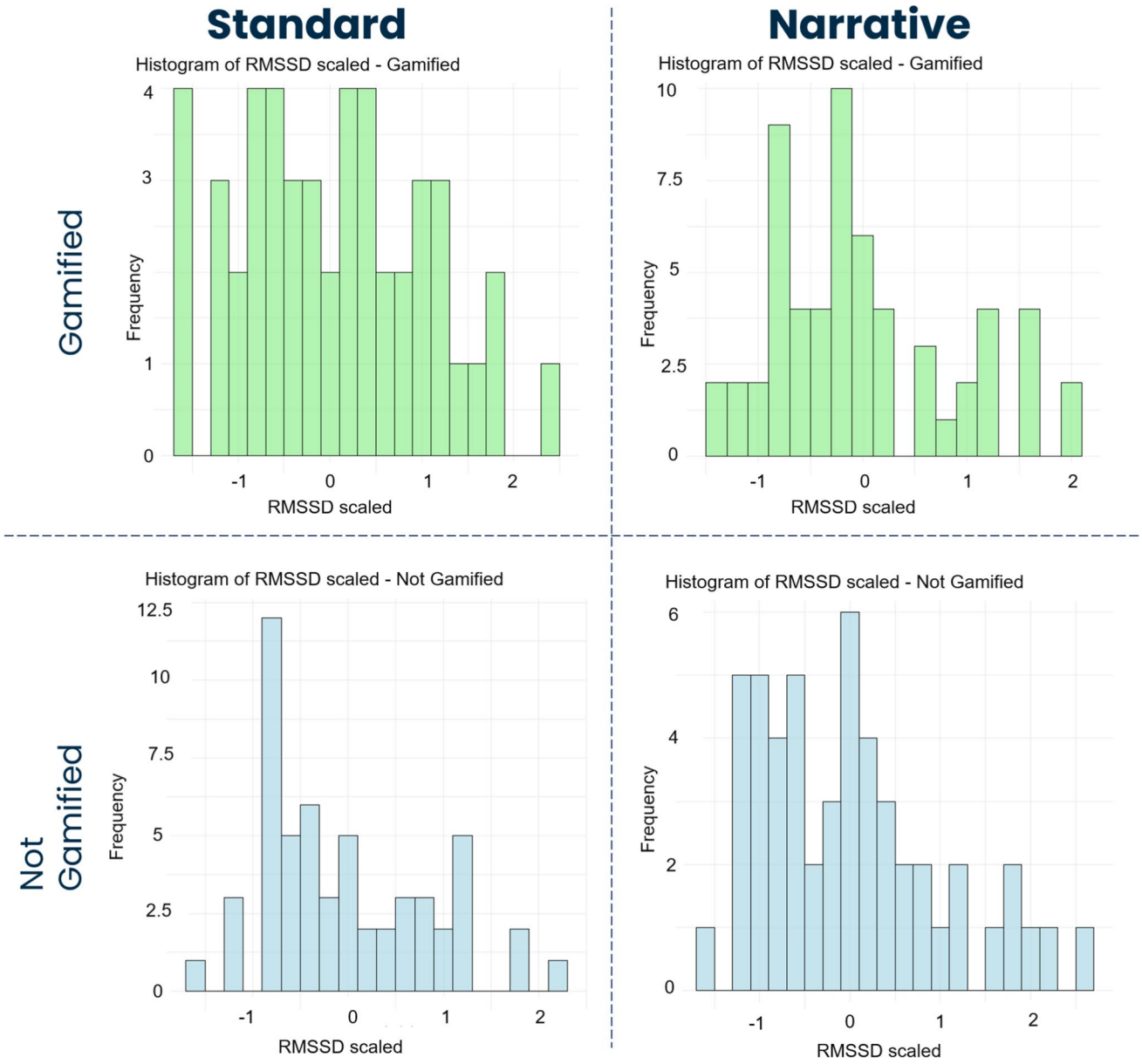


Fig. 21 Histogram plots of the RMSSD scaled

Author contribution All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by M. Capponi and R. Gervasi. The first draft of the manuscript was written by M. Capponi and R. Gervasi under the supervision of L. Mastrogiacomo and F. Franceschini. All authors read and approved the final manuscript.

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Data availability Datasets generated and analysed during this study are not currently publicly available. Videos of the gamified assembly processes are available at https://drive.google.com/drive/folders/1GlXTFgPCXnk_iNzNtOwOfq0jMmzl5u_k?usp=drive_link.

Declarations

Ethics approval The authors respect the ethical guidelines of the journal.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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