

Limes Master Edition: Using Behavioural Data to Refine Game Mechanics in Research

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Abstract: Educational video games are increasingly used in experimental research to examine their effects on learning and motivation. However, many studies focus primarily on outcome measures such as pre–post knowledge tests or self-reported engagement, while paying limited attention to behavioural data generated during gameplay. As a result, it often remains unclear which specific game features contribute to learning outcomes. This paper argues that behavioural logging within educational games can play an important methodological role in experimental research by revealing how learners interact with key game mechanics and by informing the iterative refinement of these mechanics. I illustrate this argument using *Limes*, a Unity-based educational video game designed to teach Roman history, as a methodological case study based on previously conducted research. The paper draws on findings from two previously conducted experimental studies investigating different aspects of the game design. In these studies, behavioural logs captured players' interactions with several gameplay features, including optional Codex entries that provided additional historical information. Analyses indicated that engagement with Codex content was positively associated with knowledge acquisition, highlighting the Codex system as a learning-relevant feature within the game environment. Based on these insights, the Codex system was iteratively redesigned during the continued development of the game, leading to a revised version (*Limes* Master Edition) with more precise behavioural tracking. While earlier versions tracked Codex engagement at a general level, the revised version implemented a logging architecture capable of recording interactions with individual Codex entries. This modification enables future research to analyse detailed patterns of information-seeking behaviour and to better understand how optional learning resources are used during gameplay. Using *Limes* as a case study, this paper discusses challenges that arise when educational games are used as experimental research tools. It illustrates how behavioural evidence from experiments can guide the refinement and instrumentation of game features. Building on this example, the paper proposes guidelines for researchers who develop educational games for experimental studies, outlining how behavioural data can inform the iterative development of game mechanics and logging systems. By linking experimental findings with design refinements, this approach supports a systematic investigation of how specific game features contribute to learning outcomes.

Keywords: Game design, Digital game-based learning, Behavioural data, Experimental research, Experimental methodology

1. Introduction

Digital games have been widely discussed as promising learning environments due to their capacity to combine interactivity, feedback, and goal-directed activity within coherent systems. From a cognitive perspective, such features are assumed to support active processing and the integration of new information, particularly when learners can engage with content through meaningful actions and receive immediate feedback (Mayer, 2014; Plass et al., 2015; Wouters et al., 2013). At the same time, features such as interactivity, feedback, and goal-directed activities have been suggested to foster learners' engagement with instructional material (Plass et al., 2015; Wouters et al., 2013). As a result, educational video games have increasingly been used as tools to promote learning and motivation in experimental settings (Wouters et al., 2013).

Empirical evidence on the impact of educational video games, however, remains inconsistent and difficult to interpret. Meta-analyses and systematic reviews report small to moderate positive effects on learning outcomes but also indicate that results vary depending on design, implementation, and comparison conditions (Clark et al., 2016; Wouters et al., 2013). In some cases, game-based approaches outperform traditional instruction (e.g., classroom lessons or text-based materials), while in others they show no advantage or even lower performance. Meta-analytic findings suggest that digital game-based learning (DGBL) can yield small positive effects on motivational outcomes such as engagement and interest (Barz et al., 2024). However, Wouters *et al.* (2013) report no consistent motivational advantages compared to non-game-based conditions, suggesting mixed findings across studies. This heterogeneity makes it difficult to draw clear conclusions about the conditions under which educational games support learning and motivation.

One important factor contributing to these inconsistent findings lies in the methodological characteristics of existing research. Recent systematic reviews indicate substantial variation in study design, measurement, and reporting practices within the field of DGBL (Aeschbach et al., 2024; Clark et al., 2016). For example, some studies report limitations in how constructs are measured and in the comparability of control conditions, which makes their results difficult to interpret (All et al., 2014). At the same time, systematic reviews point to broader

challenges, including limited data availability, validation issues, and difficulties related to replication (Gomez et al., 2023). In addition, differences in study design and implementation further contribute to heterogeneous findings across studies (Clark et al., 2016). These issues highlight that current evidence is not only mixed, but also shaped by variation in methodological approaches, making it difficult to draw clear conclusions about the effects of educational video games.

Many studies in DGBL rely on outcome measures such as pre-post knowledge tests and self-reported engagement, which provide limited insight into learning processes during gameplay (Gris & Bengtson, 2021). While these approaches capture whether learning occurs, they offer little information about the processes through which learners interact with specific game features. In contrast, research in learning analytics emphasizes the value of data derived from learners' interactions within digital learning environments, such as log data, for examining learning processes in greater detail (Baker & Inventado, 2014; Siemens, 2013). Log data and related behavioural traces can be used to identify patterns of learning behaviour based on learners' interactions with digital environments, providing insights into learning processes beyond traditional outcome measures (Gašević et al., 2015; Nkomo & Nat, 2021). However, these process-oriented approaches remain only loosely integrated into experimental research on educational video games. As a result, it often remains unclear which specific design features contribute to learning outcomes, highlighting the need for methodological approaches that systematically incorporate behavioural data into experimental designs.

To address these limitations, research designs are needed that explicitly connect behavioural processes to learning outcomes within controlled experimental settings. This requires not only capturing fine-grained interaction data, but also systematically manipulating specific game features to examine their effects on learner behaviour and outcomes. Existing work in DGBL has emphasized the importance of focusing on specific design features (Plass et al., 2015), suggesting that differences in design and implementation may account for variation in effects across studies. Bringing these perspectives together requires experimental approaches that integrate behavioural trace data to examine how specific game features relate to learning processes and outcomes. The present study builds on this approach as a methodological case study by drawing on previously conducted controlled experimental comparisons combined with process-level behavioural data, integrating perspectives from learning analytics, which focus on the collection and analysis of data about learners' interactions within digital learning environments (Du et al., 2021), to provide a more precise understanding of how specific design features relate to learning and motivational outcomes. The specific contribution of this paper is to show how behavioural data from educational game studies can be used not only to interpret learning outcomes, but also to guide the iterative refinement of game mechanics and logging systems for future experimental research.

2. How to Refine Game Mechanics Using Behavioural Data: The Case of *Limes*

2.1 *Limes* as an Experimental System

The educational video game *Limes* was developed not only as a learning environment for Roman history but as a controlled system for experimental research (Viccari et al., 2024). In the game, learners progress through a narrative adventure set at the Roman frontier and encounter historical information through gameplay, dialogues, secondary missions, and optional Codex entries. From its initial design, the game was structured to allow systematic investigation of how specific design features relate to learning processes and outcomes. Instead of treating the game as a single intervention, *Limes* was designed so that its key elements could be examined individually.

A central aspect of this approach is the alignment between the game and an equivalent interactive text-based application, which was developed in parallel as a comparison condition in experimental studies (Viccari & Bardach, 2025). Both versions share the same narrative structure, informational content, and progression logic, including the integration of optional learning elements such as Codex entries and secondary missions. This design allows for controlled comparisons between formats while holding content constant, thereby addressing common limitations in DGBL research related to weak comparison conditions (All et al., 2021).

Within the game environment, specific features were implemented to support both learning and analysis. One such feature is the Codex system, which provides optional, content-rich historical background texts on relevant concepts, places, and figures (see Figure 1). Codex entries can be accessed during gameplay and are intended to provide additional information beyond the main storyline. Importantly, these features are not only pedagogically motivated but also analytically tractable, as they can be identified and examined in relation to user behaviour and learning outcomes (e.g., frequency of use, time spent, or interaction patterns).

The experimental use of *Limes* across multiple studies further reinforces its role as a research system. To date, the game has been implemented in two completed experimental studies, examining (a) the effects of content format and instructional framing, and (b) the role of specific design features such as sound within the game environment (Viccari et al., 2025, 2026). In addition, the system has been used in a further experimental study for which behavioural and outcome data will be analysed. Across these studies, *Limes* has been embedded in controlled experimental designs while maintaining its structure as an interactive learning environment. This cumulative use illustrates how the system supports iterative investigation of design features and their relation to learning processes and outcomes.

Taken together, the design and implementation of *Limes* illustrate how educational games can be developed as experimental systems that enable controlled investigation of specific design features. More broadly, this approach provides a methodological basis for integrating behavioural data into experimental research on DGBL, as discussed in the following section.



Figure 1: Example of the *Limes* game interface (left) and Codex entry (right). The Codex system represents an optional informational feature that can be accessed during gameplay, and players' use of the Codex is recorded through measures such as time spent and click interactions

2.2 Behavioural Logging Approach

Behavioural logging refers to the systematic recording of user interactions within a digital system, capturing how learners engage with specific features during task execution. In the context of educational video games, such data provide a process-oriented perspective on learning by documenting actions such as navigation, interaction with content, and engagement with different learning activities (Romero & Ventura, 2020). These behavioural traces complement traditional outcome measures by offering insight into how learning unfolds over time rather than only whether learning has occurred.

Within experimental research, behavioural data provide insights into learning processes that are not captured by self-report measures (Winne, 2022). While pre-post measures can indicate differences in learning or motivation, they do not reveal how participants interacted with specific elements of the intervention. As a result, it often remains unclear which design features contributed to observed effects. Behavioural logging enables the analysis of these interactions, making it possible to link specific in-game behaviours to learning outcomes and to examine how different design features are used during gameplay.

In the *Limes* system, behavioural logging was implemented as an integral component of the game architecture. The system records multiple categories of interaction data, including time spent in different segments of the game (e.g., main storyline, secondary missions, and Codex entries). These variables provide measurable indicators of how learners allocate attention and engage with available resources during gameplay, making it possible to link specific in-game behaviours to learning outcomes and to examine how different design features are used during gameplay.

The use of behavioural data in this context is informed by approaches in learning analytics and educational data mining, which emphasize the analysis of learners' interactions within digital environments as a means of understanding learning processes (Baker & Inventado, 2014; Gašević et al., 2015; Siemens, 2013). The present approach integrates behavioural logging within controlled experimental designs, enabling not only the description of user behaviour but also the systematic investigation of how specific design features relate to behaviour and learning outcomes.

2.3 Empirical Insight: Codex Use and Learning

A central empirical insight emerging from the previously conducted studies with *Limes* concerns the role of the Codex system. As described above, the Codex provides optional historical background information that learners can access voluntarily during gameplay. Because access to these entries is behaviourally logged, the system makes it possible to examine whether engagement with this optional information is meaningfully related to learning outcomes.

Across the experimental studies conducted with *Limes*, behavioural engagement with the Codex consistently emerged as learning-relevant. In the format-comparison study, participants in the text condition accessed Codex entries more frequently and spent more time engaging with them than participants in the game condition, and Codex engagement significantly predicted knowledge outcomes even when controlling for prior knowledge (Viccari et al., 2025). In the sound study, the same pattern reappeared at the level of the game itself: although sound did not significantly alter Codex engagement, both Codex clicks and time spent in the Codex significantly predicted knowledge scores when controlling for relevant covariates (e.g., prior knowledge, interest in history) (Viccari et al., 2026). These findings indicate that interaction with Codex entries was not merely incidental behaviour but systematically related to learners' knowledge acquisition.

To illustrate this previously reported relationship, Figure 2 presents data from a separate study by Viccari et al. (2025), showing the positive association between Codex engagement (time and access frequency) and post-test knowledge performance across conditions.

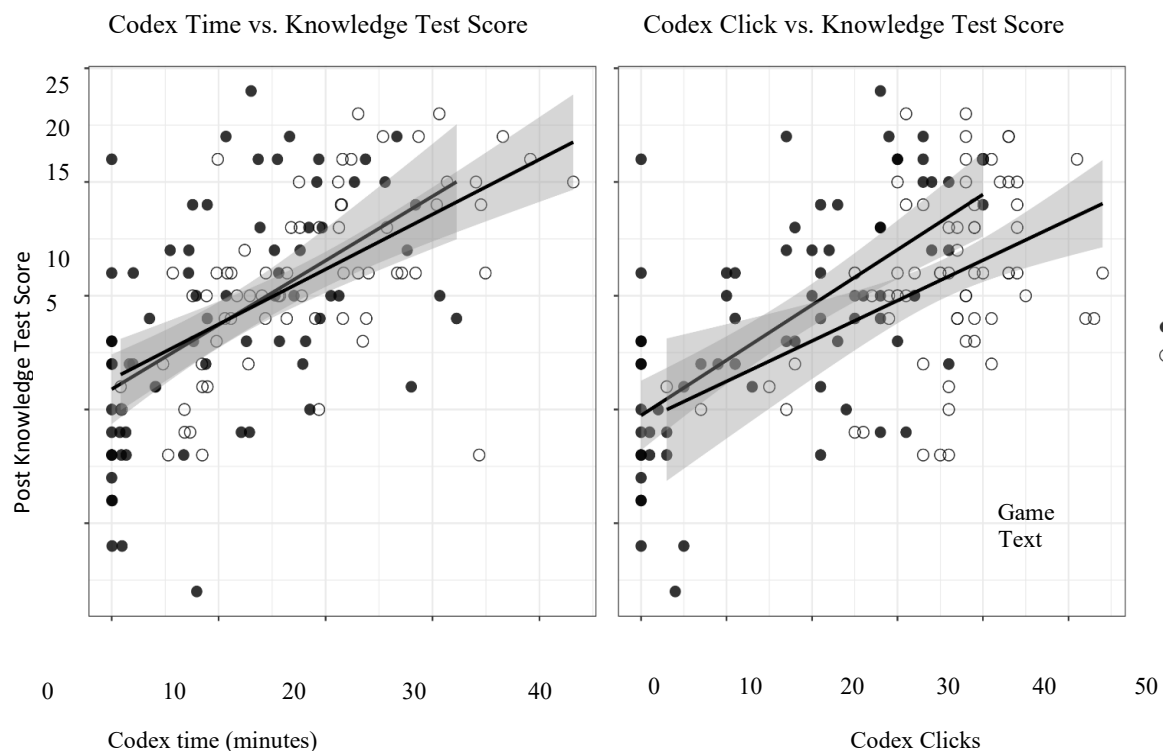


Figure 2: Relationship between Codex engagement (time and clicks) and post-test knowledge performance.
The figure is based on data from a separate study reported in Viccari *et al.* (2025)

This result shows that learning outcomes are linked to a specific design feature within the game (e.g., the Codex system), rather than to overall gameplay. Behavioural data show that the Codex supports information-seeking and learning, which would be difficult to detect using post-test outcomes alone.

At the same time, the two studies suggest that the effectiveness of the Codex depends not only on its presence, but also on how visible, accessible, and integrated it is within the broader task structure. In the format-comparison study, participants engaged more with Codex entries in the text application than in the game version, suggesting that the interface may influence the use of optional learning resources, possibly by guiding attention (Eitel et al., 2025). This point is methodologically important, because it shows that behavioural data

can reveal not only whether a feature matters, but also under which structural conditions it is more likely to be used.

The Codex findings provided a clear empirical example of how behavioural logging can inform the interpretation of learning outcomes in experimental game research. The repeated relation between Codex engagement and knowledge acquisition suggested that this feature deserved closer design attention. These findings led to the redesign of both the logging architecture and the Codex system.

2.4 Design Iteration: From Insight to Redesign

The behavioural findings described above informed subsequent refinements to the Codex system and its associated logging architecture. Although engagement with Codex entries was consistently associated with knowledge acquisition, overall usage of the feature varied, suggesting that its visibility and integration within the game may be linked to whether learners accessed it. To address this, the Codex system was modified to make it more prominent and to more actively guide learners' attention. As shown in Figure 3, the Master Edition introduces an animated notification on the Codex interface element during gameplay, as well as an explicit prompt at the end of each level. This prompt informs players that *"All Codex entries become available in the main menu once you finish the game."* thereby encouraging them to revisit and read Codex content in the main menu, where all entries are accessible after completing that level.

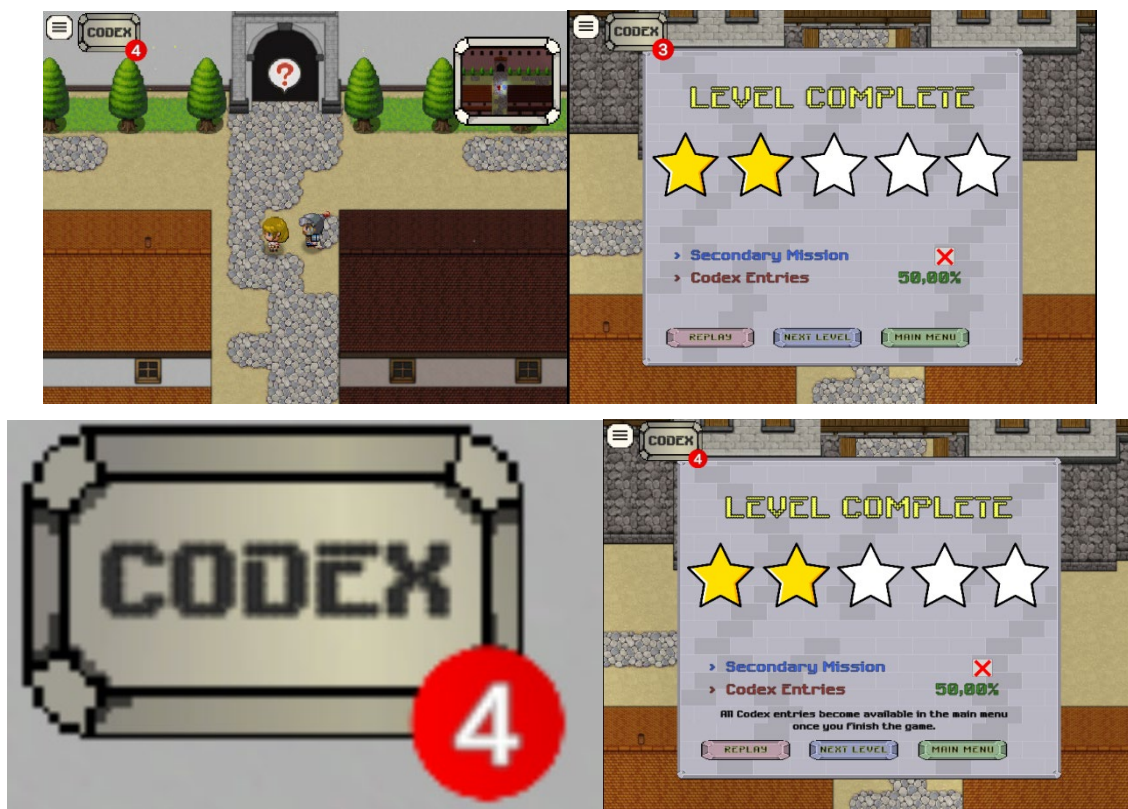


Figure 3: Design modifications to the Codex system in *Limes*. The top row shows the old version, and the bottom row shows the new version. The images illustrate the Codex interface during gameplay (top left) and the end-of-level screen (top right). A zoomed view of the Codex notification is shown (bottom left), which in the new version is animated to attract attention. The end-of-level screen in the new version (bottom right) includes an additional prompt encouraging players to revisit Codex content in the main menu

In addition to these interface changes, the behavioural logging architecture was refined by extending how interaction data are recorded in MongoDB, allowing for more fine-grained analysis of user interactions. As shown in Table 1, earlier versions of the system captured Codex engagement only at an aggregate level (e.g., total time and number of clicks), whereas the Master Edition records interactions at the level of individual Codex entries, including clicks, time spent, and image interactions. This change enables a more precise analysis of information-seeking behaviour and allows for the investigation of how specific content elements relate to learning outcomes.

Table 1: Mongo Database

Mongo Database – Old Edition	Mongo Database – Master Edition
totalTimeCodexMenuOpen: seconds codexButtonClicked: number of clicks	totalTimeCodexMenuOpen: seconds codexButtonClicked: number of clicks CodexEntryStats: [Codex clicks: EntryID]: timeSeconds: number-of-clicks imageClicks: number of clicks seconds

Another reason for making behavioural logging more detailed is the structure of the Codex content itself. The entries were spread across the game and varied in how relevant they were to the main storyline. Core concepts, such as the Roman frontier, military fort structures, or key historical figures (e.g., Julius Caesar, Augustus), were referenced multiple times throughout the main progression, whereas other entries were only mentioned in secondary missions or appeared in more isolated contexts. The selection and emphasis of these core topics were aligned with German school curricula, where such concepts are treated as central learning content (Bayerisches Staatsministerium für Unterricht und Kultus, 2026; Hessisches Kultusministerium, 2002; Ministerium für Kultus, Jugend und Sport Baden-Württemberg, 2016). As a result, looking only at overall Codex use does not adequately capture how learners engage with content of varying importance. With this more detailed logging in the Master Edition, it becomes possible to examine whether learners focus on the most important content, particularly core topics aligned with school curricula, and whether the design of the Codex supports this focus.

2.5 Methodological Implications

The case of *Limes* highlights several methodological implications for the use of educational video games as experimental research tools. First, this case illustrates the value of integrating behavioural trace data with traditional outcome measures in experimental DGBL research. In the present case, the relation between Codex engagement and knowledge acquisition would have been impossible to detect without process-level behavioural data. This suggests that experimental studies in DGBL should integrate process-level measures to better understand how learning unfolds during gameplay. Learning analytics research highlights that process data can provide insights into learners' interactions and help to better understand how learning actually happens (Banihashem et al., 2024). In line with this, game analytics studies show that in-game behavioural data can be linked to learning outcomes, enabling fine-grained analyses of how learner behaviour relates to performance (e.g., Chen, Cui and Chu, 2020).

Second, the identification of the Codex as a learning-relevant component demonstrates how behavioural data can be used to identify specific mechanics that are associated with learning. This approach allows for more precise hypotheses and interpretations than studies that examine the efficacy of educational games and compare their outcomes with other instructional approaches (de Freitas, 2018). In such approaches, games are often evaluated only in terms of overall success or failure, making it difficult to determine whether outcomes are due to specific design choices or omissions (Lameras et al., 2017).

Third, the development of behavioural logging should be considered an integral part of the research design rather than a purely technical addition. In the present case, the transition from aggregate logging to entry-level tracking was directly informed by empirical findings and enabled more detailed analyses of learner behaviour. This highlights that logging architectures need to be aligned with the research questions, as learning analytics involves selecting and structuring data in line with those questions (Romero & Ventura, 2020). In addition, analytics can support iterative refinement over the course of a project by helping to identify design issues and inform improvements to game design (Serrano-Laguna et al., 2014).

Finally, the iterative relationship between design, data collection, and analysis represents a central methodological principle for research using educational games. The redesign of the Codex system illustrates how experimental findings can inform subsequent modifications of both game mechanics and data logging, creating a cycle in which design and research mutually inform each other. Rather than treating development and experimentation as separate phases, this approach integrates them into a continuous process aimed at improving the learning environment, as suggested in iterative, design-based research approaches (e.g., Jong, Dong and Luk, 2017).

2.6 Practical Guidelines

Building on the methodological implications discussed above, several practical guidelines can be derived for researchers who develop and use educational video games in experimental settings.

First, behavioural logging should be planned from the early stages of development rather than added retrospectively. Logging decisions determine which aspects of learner behaviour can be analysed and should therefore be aligned with the research questions and targeted learning processes. In particular, logging can capture detailed process data on learner interactions, providing insights into learners' activities and learning processes during gameplay (Tili et al., 2021).

Second, game mechanics should be designed as analytically tractable units that can be isolated and examined in relation to learning outcomes. Rather than embedding instructional content in ways that are difficult to disentangle, researchers should structure game features so that their use can be measured and, where possible, experimentally manipulated. This enables more precise conclusions about the contribution of specific design elements by linking game mechanics to learning attributes and outcomes (Lameras et al., 2017).

Third, attention should be given to how optional learning resources are integrated and signalled within the game environment. Features such as the Codex may only contribute to learning if learners are aware of them and encouraged to use them. Designers should therefore consider mechanisms that guide attention to relevant content (e.g., textual, visual, or audio information), as signalling techniques can increase learners' selection and processing of important information (Eitel et al., 2025; Spitzer et al., 2025).

Finally, the development of educational games for research should be approached as an iterative process in which design, data collection, and analysis inform one another. Initial implementations can provide insights into learner behaviour, which can guide refinements of game mechanics. This iterative approach supports the progressive improvement of the learning environment (Jong et al., 2017).

3. Conclusion

This paper addressed a central limitation in experimental research on educational video games, namely the limited integration of behavioural data into the analysis of learning processes. While prior research has largely relied on outcome measures such as knowledge tests and self-reported motivation and engagement, such approaches provide only limited insight into how learners interact with specific game features.

Using the development of *Limes* as a methodological case and drawing on evidence from previously conducted experimental studies, the present work demonstrated how behavioural logging can contribute to a more detailed understanding of learning processes within game environments. Across two studies, interaction with the Codex system was associated with knowledge acquisition, highlighting the importance of analysing learner behaviour at the level of specific game mechanics. These findings further informed the iterative redesign of both the Codex system and the underlying logging architecture, resulting in a more fine-grained and interpretable data structure in the *Limes* Master Edition.

More broadly, the paper showed how educational games can be used not only as learning tools, but as experimental systems in which design, data collection, and analysis are closely integrated. By linking behavioural evidence to the refinement of game mechanics, this approach enables a more systematic investigation of how specific design features contribute to learning outcomes.

Future research can extend this approach by using behavioural data to better understand how learners interact with different types of content within game environments, including text, visuals, or audio. In particular, behavioural data (e.g., clicks and time spent on specific content) can help examine how learners select and use relevant information in complex learning environments. Future analyses of data collected with the *Limes* Master Edition will build on this by examining patterns of engagement across individual content elements, allowing for a more detailed understanding of how learners allocate attention to different types of complex information.

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