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Article

Museum Games and Personal Epistemology: A Study on Students' Critical Thinking with a Mixed Reality Game

Simon Morard[1], Eric Sanchez[1] and Catherine Bonnat[2]

[1]*LIP/TECFA, Faculty of psychology and educational sciences, University of Geneva, Geneva, Switzerland;* [2]*UER MI, HEP VD, Lausanne, Switzerland*
simon.morard@unige.ch ; eric.sanchez@unige.ch ; catherine.bonnat@hepl.ch

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Abstract

This study examines how 12-15-year-old students use information while playing Geome, a mixed reality game intended for museum school visits. Geome presents environmental issues, prompting students and asking them to discern and dismiss misinformation and rumors. The study aims to analyze the students' playful learning experience and their perspective on the game. It focuses on the students' critical thinking, interactions and beliefs about knowledge and knowing, referred to as personal epistemology. Adopting a qualitative approach, the research was conducted across three classes in a museum. A combination of audio, video, and in-game interactions was collected from specific moments during gameplay and analyzed according to epistemological dimensions (Certainty, Simplicity, Source, Justification). Video analysis suggests that when faced with ill-structured problems within a playful scenario, some students are spurred to actively process information and develop critical thinking skills. Meanwhile others remain entrenched in their initial conceptions about the nature of knowledge and the act of knowing. The study discusses how the game's characteristics shape students' personal epistemology. Overall, this research demonstrates that games in museum contexts have the potential to promote active learning and critical thinking in some students, when confronted with complex or ill-structured problems.

1. Introduction

Incorporating digital-game-based-learning in science museums should not only foster players' motivation and engagement through immersive gameplay and engaging scenery, but also facilitate reflective exploration and hypotheses testing [1,2]. We use frameworks from game-based-learning (GBL), critical thinking, and epistemology to understand the player's subjective learning experience [2].

Our research focuses on a nature museum, for which we developed Geome, a mixed reality learning game for middle school students aged 12 to 15 years. Students are exposed to the complex and intricate interconnexions between humans, animals and their environment. The game presents open-ended and complex environmental problems requiring the students to exercise curiosity, critical thinking, and independent judgment. Our approach stands out as both original and innovative, as none of the games identified in academic literature seem to focus on critical thinking not for its own sake, but in a contextualized manner.

Our research is based on the framework of personal epistemology which refers to the beliefs and theories that individuals develop regarding knowledge and how it is acquired [4,5]. Using this framework we are able to examine the players' ability to process information. Student's personal epistemology shapes their perceptions of a task and influences how they approach it [6]. We hypothesize that, when faced with a complex problem, students should evaluate information, using argumentation, critical thinking, and an understanding of the underlying arguments [5]. Our goal is to develop a methodology dedicated to characterizing epistemology using audio and video recordings and to reflect the different patterns of player experience based on key moments in gameplay identified in a previous study [7].

In the following we introduce our research subject, the game Geome, highlighting its epistemic potential and its capacity to encourage students to question their own understanding of knowledge, fake news or rumors. Then we discuss the relation between critical thinking and GBL environments.We further develop into the theoretical foundation, drawing from play design, personal epistemology and critical thinking. We also address our research problem and question. Next, we detail our research methodology, data collection and results obtained from a thematic analysis which provide valuable insights for our research questions.

2. Geome, a Game to Foster Critical Thinking

2.1 Game-based-learning and Critical Thinking

GBL is defined as a learning method which integrates digital games into the learning environment [8]. A recent meta-analysis on GBL's effects on critical thinking [9] showed its alignment with problem-based learning and social-conflict theories [10, 11]. Critical thinking involves evaluating information relevance and making informed decisions [10]. GBL challenges students with intricate problems encouraging various solution strategies. Game feedback adds in refining players critical thinking [11,12]. The inclusion of storylines, rewards, and other game components enhance students' engagement and support positive effects on critical thinking [13,14]. Notably, GBL does hinder critical thinking due to cognitive biases or distractions even in high load cognitive settings [9,15-18].

The positive effect of GBL on critical thinking varies depending on specific factors, such as game type, critical thinking construct and cultural context [9]. Games with conflicting views or complex problems enhance critical thinking with role-playing games excelling over genres like adventures, strategy, simulation and game construction according to a meta-analysis of 21 GBL studies [9]). This aligns with Vygotsky's theory which suggests that role-playing promotes adults-like thinking and critical thinking skills development through peer interactions and resolution [9].

GBL more significantly impacts critical thinking disposition (i.e open-mindedness) than specific skills like analysis, interpretation, evaluation and inference [9,19]. Finally, the effect of GBL on critical thinking may also depend on cultural aspects. Students from collectivistic cultures, emphasizing group objectives and self-assessment, are more influenced by GBL [9,20].

While many studies focus on GBL's effects on critical thinking, few examine its relationship with players' personal epistemology. In the realm of epistemic curiosity defined as the drive to gain knowledge [21] it pushes individuals to fill information gaps and tackle intellectual challenges [22]. This pursuit is crucial for mastering complex skills [23,24] and students with heightened epistemic curiosity are often driven by complexity, fueling their learning engagement [21,25].

2.2 Geome and its Epistemic Potential

Geome, a mixed reality game co-designed by researchers, teachers, museum mediators, anthropocene experts and computer scientists blends virtual and real-world elements for an immersive experience. Mixed reality games provide players with structured and purposeful play experiences that integrate virtual and real-world elements. They have the potential to extend game mechanics into physical activities such as sport or culture [25,26]. In Geome players interact with the museum exhibition via a tablet to explore the Anthropocene era, characterized by biodiversity loss and climate shifts. The game also encourages students to introspect about knowledge and its creation [3,4,5]. After an introductory setup, players, in teams of 2-3, find themselves in a valley, gathering resources by interacting with stuffed animals. Choices, like hunting or domesticating animals, yield resources, which can later be traded. Yet, excessive resource hunting depletes the "Tree of Life", symbolizing limited natural assets, making abstract environmental concepts tangible through metaphors [27].

Figure 1. Classmates playing Geome in dedicated spaces of a nature museum

In the game's intiale 10-15 minutes part, players are set up to fail. In the next stage, they take on wildlife expert roles solving puzzles while navigating fake news and controversies about the environment. Progressing through the museum, they uncover clues, learn about natural ecosystems, and build an ecosystem map detailing animal interdependencies (see Figure 2). To succeed, players must critically assess information and recognize animal relationships demanding curiosity, critical thinking and museum knowledge acquisition.

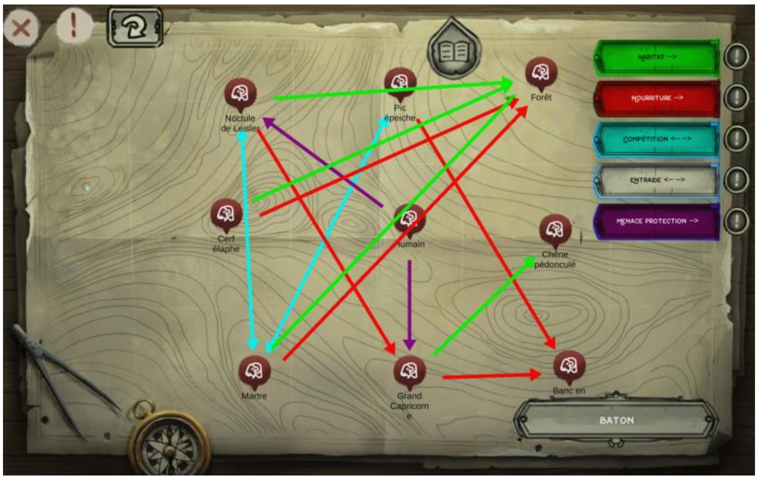

Figure 2. Geome eco-systemic map

Geome's puzzles address media education, socio-scientific and Anthropocene related issues such as climate change and biodiversity loss (see table 1). These enigmas are ill-structured lacking clear solutions due to ambiguous goals and limited data. Typically real-world problems are ill-structured [28] and their solutions hinge on accessible information, and the player's ability to understand ecosystem complexity [7].

Table 1. Enigma about the suspicious death of trees

Excerpt of an enigma from Geome	Thematic / Subject
A scientific paper has recently been published in a journal. but we are unable to access it. However, the information was taken up by several newspapers and websites in Valais. Here is the summary that was made and spread:	Media education and critical thinking
The trees are perishing due to the destructive effect of the Great Capricorn beetle. This insect has a preference for young oak forests and inflicts damages by excavating galleries that cause the tree to become ill.	Anthropocene and environmental issues
The foresters, who operate within the forest, find this story astonishing and decide to inspect the young oak trees. Upon examination, they discovered markings on oaks that were slated for removal.	Anthropocene and environmental issues
Go to the location and report your observations. Can we trust what has been published by the media?	Media education and critical thinking

The game's developers aimed to help students grasp complex topics like ecology and the Anthropocene, promoting critical thinking and challenging their knowledge accuracy. Media education emphasizes understanding media production, distribution, and honing analytical skills for content evaluation [29]. Uniquely, the game integrates media education within scientific problem-solving. Through an *a priori* analysis we were able to pinpoint connection between the game design, the students critical thinking and their reactions to potentially misleading or incomplete data.

Certain game moments may trigger specific aspects of a student's personal epistemology. Indeed, the game clues can make the player doubt their reliability. As they integrate information from the exhibition to form an ecosystemic understanding, players realize the interdependence of knowledge. As the players gather information and propose solutions, they are expected to identify themselves as meaning makers, all while facing authority figures such as the media and scientific information from the museum. The mission's success depends on discerning information quality and resisting authoritative influence. We expect the game to prompt students to challenge unsupported information [7]. Our study seeks to verify if the game truly engages students' personal epistemology through their in-game interactions and responses.

Geome combines role-playing games (with students as nature experts), puzzles (presenting as riddles) and simulation (using the systemic map to represent the ecosystem complexity). Reviewing GBL and critical thinking literature in the context of Geome suggests that its gameplay resonates with problem-based learning and social-conflict theories [10,11]. Game features like the tree of life, evolving narrative and feedback mechanisms, can prompt players to critically assess information potentially enhancing their critical thinking [11,12]

In Geome, the complexity of problems and incomplete puzzles can spark players' epistemic curiosity [23,24]. Encountering fake news or controversies pushes them to seek new information and confront uncertainty [24,30]. Interactions with diverse characters in the narrative challenge players' perspectives, promoting critical thinking skills. Broadly, the game cultivates open-mindedness toward varying opinions. Specifically, it deepens understanding of human-nature interrelations.

Our study examines the game experience by considering both the game artifact and the situation experienced by the player [31,32]. Play, in this context, is an epistemic experience based on the exploration of the museum exhibition and the use of creative thinking to solve problems. Such games merge tangible and digital elements to foster learning through investigation and discussion. As players engage, knowledge becomes an active performance, blending thought and action [32,33]. Geome offers a hands-on learning experience that can apply to real-world situations, aligning with personal epistemology framework [3,4,5].

Players' responses to the game's ill-structured problems depend on their critical thinking skills, personal epistemology, epistemic curiosity, and the museum subject (natural sciences). The following section delves into game experience subjectivity, unique player behavior, and the link between knowledge relation and critical thinking.

3. Player Experience and Personal Epistemology

3.1 Play, a Subjective Experience

Games, unlike other media like books or movies, have unpredictable outcomes based on player choices [34,35]. While gamified systems, like playful museum visits, aim to engage users for specific outcomes they may not always succeed. If players feel forced into a behavior or limited in their choices, it can undermine their intrinsic motivation, impacting both the gaming and learning experience [36-38].

Game design frameworks often emphasize pedagogical goals, but solely focusing on design can miss events during gameplay since players might deviate from the intended path [36, 39]. Thus, understanding "player experience" which emphasizes the player's role and interaction with the game, is vital and is typically studied during and post-gameplay [40].

Player experience transcends just playability[1] and game usability[2], including cognitive, perceptual, and emotional experiences such as immersion, flow, challenge, curiosity, tension, affects, and other psychological responses. Playing behavior encompasses all possible game-related behaviors and interactions [40]. This experience is multifaceted, and while it's subjective, players' behaviors can be analyzed. We'll examine this experience in light of critical thinking and attitudes towards knowledge, hypothesizing that personal interpretations can impact learning if they diverge

[1] "A game has good playability when the user interface is intuitive and the gaming platform is unobtrusive, so that the player can concentrate on playing the game" [41]

[2] "Game usability is the extent to which a game allows the users to complete their tasks intuitively and with minimal frustration, the user interface not coming between the player and the fun" [42]

significantly from the game's intent. Our focus is on how players critically engage with the game's knowledge narrative.

3.2 Student's Personal Epistemology and Critical Thinking

Critical thinking involves logical evaluation to make informed decisions when faced with conflicting claims. It assesses evidence strength and reasons within context [43,44]. This skill varies among students [45] and encompasses identifying reasoned case elements, evaluating assumptions, interpreting ideas, judging claim credibility, and producing arguments [43,46]. Critical thinking has two dimensions: affective dispositions or open-mindedness towards varying perspectives and cognitive skills like interpretation, analysis or evaluation. The affective dimension refers to a critical thinking disposition, which requires less domain-specific knowledge or criteria than critical thinking skills [9]. A critical thinking disposition is more transferable and generalizable across domains as it requires few domain-specific knowledge.

Reasoning and critical skills are essential skills, especially for teenagers facing daily misinformation on platforms like social media [49]. A Twitter study showed that false news is more frequently shared than true news [50], and platforms like TikTok often promote disinformation [52]. It's vital to provide youth with tools to discern and counteract hoaxes [53]. Therefore, integrating courses on assessing fake news into educational curricula is crucial [5].

Critical thinking, a core educational goal, relies on utilizing a broad use of different types of knowledge [53,54] and involves a complex and reciprocal relationship between critical thinking, knowledge and knowing. The concepts of knowledge and knowing are therefore substantial aspects of conceptualizing critical thinking [43,46]. We see museum and in-game information as the premise of the ability to process, link and connect information related to student's personal epistemology, allowing them to develop procedural knowledge [46]. Research indicates that critical thinking corresponds with epistemological beliefs [55,56]. Students with poor critical thinking skills have an absolute view of knowledge. When students move on to the most developed epistemological level, their critical thinking tends to improve as well [14,56]. Therefore, students' personal epistemology plays an important role in their capacity to judge information credibility [56].

Student's epistemological beliefs, also known as personal epistemology, shape their critical thinking. It's essential for discerning the reliability of knowledge, making their epistemological beliefs central to their critical thinking ability [46]. Personal epistemology refers to an individual view of the nature of knowledge and knowing, which includes their own beliefs as knower [5,27,57]. Organized as a system of beliefs, called dimensions [3], personal epistemology is organized in four dimensions classified in two axes: the nature of knowledge and the act of knowing. The first axis pertains to an individual's beliefs about what knowledge is while the second relates to how the individual acquires knowledge [3]. The first dimension, certainty, refers to the degree to one's perception of knowledge as either fixed or fluid. Simplicity, the second dimension, describes how knowledge is viewed on a continuum ranging from an accumulation of facts to highly interrelated concepts. The third dimension, source, delineates the origin of knowledge, ranging from an external authority to one's capacity to create meaning. The fourth dimension, justification, concerns how individuals evaluate evidence, authority, and expertise. These dimensions span a continuum, extending from less sophisticated (naive) to more sophisticated ways of knowing. Personal epistemology tends to develop over time towards more relativistic and sophisticated beliefs [3,4] and critical thinking and epistemological beliefs are embodied in social practices [7,56]. Consequently students are expected to assess the reliability and relevance of evidence, to identify arguments, to analyze information and to address opposing viewpoints based on their personal epistemology. It is worth noting that students' personal epistemology, beliefs and critical thinking may differ within the same field of study [46]. Generally, students with advanced epistemological beliefs exhibit better critical thinking than those with simpler beliefs [5,46].

3.3 Research Questions

We hypothesize that players develop their own subjective interpretation of gameplay, which may deviate from the intended learning experience. While this subjective appropriation is inevitable, it may pose a risk if players stray too far from the designed game scenario [36-39]. Although the player experience is subjective, their behaviors and attitudes can be observed. We believe that personal epistemology is one of the factors that can cause students to deviate from the intended playful learning experience. As a result, our study aims to examine the player experience, with a specific emphasis on their critical reflections on the knowledge and information incorporated into the game [7,56,57]. In order to characterize the personal epistemology induced by the playful experience in the museum, we address the following issue: How do students' personal epistemology dimensions manifest themselves through their reasoning and critical thinking during the game? In particular we want to know:

(1) Based on the four dimensions of the Hofer & Pintrich model (Certainty, Simplicity, Source, Justification) we want to know what dimensions of epistemology can be inferred from their responses?

(2) Based on the same model, we want to know where do students fall on a continuum from naive to sophisticated in terms of personal epistemology dimensions?

(3) Considering that play is a subjective experience, we ask how critical thinking influences and shapes this player experience?

4. Research Method

This section details our method for tracking player experience, the collected data, and indicators for gauging personal epistemology. We employed a design-based-research approach to iteratively develop and analyze Geome [58].

4.1 Design-Based Research in a Museum Context

Based on a Design-Based Research methodology [59,60] our approach fosters collaboration among researchers, teachers, and museum staff to co-design and co-evaluate the game. They work together in designing, testing, and interpreting data, with an iterative process that involves several cycles. The prototype and theoretical models are modified for each iteration. The game prototype is tested in a naturalistic setting with students aged 12 to 15 years old. Figure 3 shows the intertwined co-design and co-evaluation processes [61].

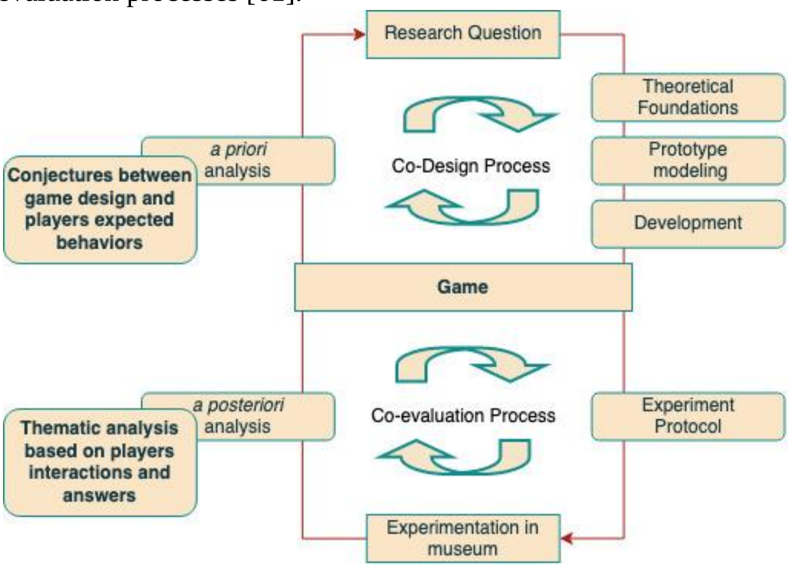

Figure 3. Research method: an articulation of co-design and co-evaluation [61]

Recent years have seen growing interest in studying player experiences qualitatively. While the importance of interaction between players and game is acknowledged, most research tends to focus on the game's structure (such as game theory or game studies) or the player separately from the game (e.g socio-psychology studies). This has resulted in a dearth of empirical research examining players' experiences and the limited understanding of methods that can be employed [35]. To truly understand player experiences beyond mere action counts, we advocate for frameworks from play design [62], didactic engineering [63] personal epistemology and critical thinking [46].

Previous studies often used quantitative tests or qualitative interviews to explore critical thinking and personal epistemology. However, the reliability and adequacy of such methods has been questioned [5]. As a result, there is a need for research that directly assesses student performance [5,46,64]. However, a single assessment might not capture intricate cognitive processes like reasoning. To address this challenge, we combined an *a priori* analysis, observations conducted with on-board cameras and thematic analysis of interactions between players and the game (a *posteriori* analysis). Another approach is self-report interviews. We have not retained this one at this stage of the research project, nevertheless we believe that this approach could be valuable to collect additional data in the future.

Our study explores qualitative methods to understand the relationships between players, their knowledge, and a museum game. This research aims to offer a more nuanced approach to studying player experiences than traditional methods.

4.2 A priori Analysis

An a *priori* analysis evaluates if a game design will likely produce the desired players' behavior and interpretation. This involves examining the design hypotheses by explicitly defining the player actions at specific points in the game and predicting their expected effects. In a research context, the *a priori* analysis enables designers and researchers to develop a shared vision of the design choices and formulate hypotheses about the game's effects. Presented as a report, the a *priori* analysis describes and justifies the design choices based on the educational objectives and enables evaluation through inspection [65]. We used *a priori* analysis [7] to identify game moments engaging students' personal epistemology and incorporated an audio recording feature for these instances.

The *a priori* analysis that the game will trigger specific dimensions of students' personal epistemology. For instance, players might question information reliability, activating the certainty dimension. Recognizing connections between museum elements and ecosystemic maps could tap into the simplicity dimension. When players see themselves as meaning-makers amid authoritative sources like media and museum data, the source dimension may arise. The justification dimension might come into play when information lacks strong arguments [7]. This study aims to analyze in-game student reactions to see if these dimensions are activated. This study will enhance understanding of designing educational games that foster students' critical thinking skills and epistemological growth.

4.3 Collected data

This study took place in a nature museum with 3 classes of students 12-15 years old. Accompanied by their teachers, they engaged in game-based museum school visits. The teachers participated in designing the game, puzzles, and debriefing [66]. There were 9 teams of 2 to 3 students each. The students had a similar cultural background with 2 classes being French speaking and one bilingual (French-German). During each experiment, some students wore a shoulder-mounted camera.

Figure 4. Players wearing on-board camera

The data collected includes audio from the digital tablet. Initially, players responded to: Can you trust the media's published information? After gathering sufficient data and scanning all enigma-related elements (2 clues and 7 elements scattered throughout) they answered 2 additional questions: Do they believe the article accusing the Great Capricorn beetle was credible, and who might be responsible for the oak holes/marks?

We collected 87 audio files, but some were incomplete due to the student reaction or communication struggles. 66% (N=58) of the recordings were usable and transcribed. On-board cameras on 9 students yielded 405 minutes of video (averaging 45 minutes per group). This video access mitigated server issues and provided a closer look at student responses. Notably, for camera-equipped groups, we could review discussions before the audio recording, helping determine if answers were group consensus or led by a team leader.

4.4 Thematic Analysis

Observations let us study the interactions between the player and the game [35]. We also consider the interactions with the environment including museography, other players, and adults attending present (teachers or cultural mediators). This is deemed an *a posteriori* analysis done via thematic analysis.

Prior research on critical thinking and personal epistemology often used quantitative surveys, or qualitative interviews [67]. However, the validity of self-report questionnaires has been questioned [5] leading to calls for direct assessment of students' performance [5,64]. Our methods evaluate how players interact and deal with ill-structured problems potentially engaging their critical thinking and personal epistemology. We employed a qualitative approach, particularly thematic analysis centered on indicators of personal epistemology. Thematic analysis identifies and interprets patterns in data through a systematic process [68, 69].

We chose thematic analysis to pinpoint students' personal epistemology using indicators to determine if their remarks pertains to knowledge's nature or to the act of knowing. Personal epistemology is context-specific revealing a momentary epistemological expression. We examine this expression within a group context, capturing individual epistemologies often resulting from group consensus. In thematic analysis, indicators serve as key elements that help researchers in identifying and comprehending the themes or subjects discussed in a data corpus. Indicators, like repeated words, phrases, or concepts, highlight themes in the data [68]. They guide researchers in forming thematic categories, linking categories, and interpreting findings. Indicators streamline data analysis by highlighting relevant extracts and filtering out unrelated information [70]. Essentially, they're crucial in understanding themes in data, enriching future research.

Indicators span from naive (na) to sophisticated (so), with an intermediate (in) midpoint [3]. Adapted from prior research and main dimension definitions [27], these indicators aided post-game debriefing and were trialed with students in focus groups. We analyzed students' interactions and responses to complex game problems, transcribing and coding their statements based on the indicators detailed in table 2.

Table 2. Indicators of personal epistemology

Dimensions	***Indicators***	**Levels**
Certainty In what way does a player consider knowledge, either as rigid and unalterable or as dynamic and flexible	He/she expresses an absolute truth that cannot be questioned. Finite knowledge exists.	Naive
	He/she expresses possibilities of alternative truths, there is not only one truth, but several degrees of truth.	Intermediate
	He/she expresses that knowledge in a field is not finite, nor fixed, that it is bound to evolve, to be modified.	Sophisticated
Simplicity Player tends to perceive knowledge as composed of distinct and concrete facts that can be easily understood. At upper levels they view knowledge as being more subjective, dependent on specific circumstances, and open to interpretation.	He/she indicates a specific knowledge without linking or relating it to other knowledge.	Naive
	The information obtained is discussed, put in relation with each other in the light of context.	Intermediate
	The information is linked, considered, and organized in a matrix, in an interrelated network.	Sophisticated
Source Knowledge is acquired by the player from external sources such as authoritative figures. However, as he develops his own critical thinking, he moves from spectator to active constructor of meaning and knowledge.	He/she ensures that the knowledge is transmitted by an external authority.	Naive
	He/she does not see himself/herself as a potential producer of knowledge, does not feel legitimate.	Naive
	The student indicates that he/she wants / has to verify the information by himself/herself.	Intermediate
	The information transmitted by someone is evaluated by the player (e.g. age, diploma, belonging to an institution, experience,...)	Intermediate
	He/she indicates the source of the information he/she obtains and the characteristics of this source of information.	Intermediate
	He/she expresses a personal opinion to justify the choice of an external authority. His or her personal opinion supports the argument.	Intermediate
	He/she indicates being able to produce knowledge in interaction with his/her environment.	Sophisticated
Justification Process by which teenagers assess and appraise claims of knowledge, encompassing their consideration of evidence, reliance on authority and expertise, as well as their critical evaluation of experts.	He/she is not able to justify his/her choice / decision.	Naive
	He/she justifies himself/herself based on personal opinions that are not well argued.	Naive
	He/she arbitrarily selects specific information to support his/her reasoning.	Intermediate
	He/she expresses a personal opinion to justify the choice of an external authority. His/her personal opinion supports his/her argument.	Intermediate
	He/she has several points of view, but the reasoning to construct his/her own justification is an arbitrary choice.	Intermediate

	He/she expresses the ability/willingness to verify for him/herself in the field whether the information is useful, relevant or correct.	Sophisticated
	He/she uses rules of research, a process for evaluating expertise and justifies his/her reasoning with evidence.	Sophisticated

Using indicators of personal epistemology, we evaluated students' in-game responses, including enigmas containing potential fake news (audio) and collaborative moments between players (video). This helped us discern gameplay patterns and the influence of critical thinking on students' knowledge approach, emphasizing the subjectivity of players' experiences. Though there was no double coding, the 3 article authors co-created the epistemological indicators. They were discussed with museum members and teachers. One individual performed the coding, with input from the other two authors. Data interpretations were collaboratively examined in seminars with museum members, the design team, teachers and researchers.

5. Results

5.1 Students' Personal Epistemology

The thematic analysis of the audio records (verbatims) allows us to: (1) Classify students by their personal epistemology when faced with potential fake news; (2) Detect growth in their personal epistemology when they devise a solution to the enigma; (3) Track the evolution of players' throughout game. The results are outlined below. Upon encountering the enigma (table 1), players discussed media reliability. This conversation helped us categorize the 19 players teams (N=19) into 4 groups. Those labeled POV (point of view) had onboard cameras. Other groups had audio recordings from tablets, with players recording start, end, and answer validation. All responses have been translated to english.

(a) Players who doubt media information, often based on personal opinions, express a desire to validate this information firsthand. They see themselves as potential knowledge producers (*source* intermediate, *justification* naive to intermediate). They argue for evidence-based information related to the enigma content (*simplicity* intermediate). These students consider an alternate to what the media present, indicating an intermediate stance on the *certainty* dimension. We label these groups "*Verifiers*" (N=2).

Table 3. Excerpts of answers from Verifiers when they read the enigma

Verbatim (audio responses provided by players)	**Dimensions and levels na: naive in: intermediate so: sophisticated**
POV_3P1: Because actually on the internet, things are not necessarily true, and, anyway, we haven't fully explored nature, so we can't know if the trees are dying or not. *POV_3P2: We can say anything on the internet without it being true or false, that's it.*	Simplicity in Certainty in Source in Justification na
POV_9P1: Because we haven't seen the evidence ourselves.	Source in Justification in

(b) Players expressing skepticism towards media information view it as external authority (*source* - intermediate). Their reasoning leans on personal belief with limited arguments or selective information use categorized as naive. While they highlight the importance of evidence, they don't specify its source, not viewing themselves as valid knowledge producers (*source* naive). They hint at alternative truths to media (*certainty* - intermediate). These groups often see information as binary, true or false, suggesting facts are straightforward and don't need to be interconnected with other knowledge (*simplicity* - naive). One group G5 (table 3.) emphasizes the need for expertise, discounting media credibility. We label these groups "*Doubters"* (N=11).

Table 4. Excerpts of answers from Doubters when they read the enigma

Verbatim (audio responses provided by players)	Dimensions and levels
G0_10.02: Actually, because we don't have our sources... well, in fact, to have concrete information, you need to have several sources. *G0_10.02: 'Arguments.' Yeah, arguments. So, that's it.*	Source in Certainty in Justification na
G1_10.02: We cannot know since we have no evidence, that's it.	Source na Certainty in
POV_2: Firstly, they did not receive the correct information, and we do not know if the media is still reliable	Source in Justification na Certainty in Simplicity na
POV_4: simply because the media is not always very reliable, and does not always have the true information, and collects the true information that they summarize.	Source in Justification na Certainty in Simplicity na
G3_18.02: The media says stuff to make people feel better, but they can totally twist the truth	Certainty in Source in Justification na
G5_18.02: Since they're not experts, they can't really prove if it's right or not, and anyways it's always like, way exaggerated	Source in Justification na
POV_8: Often the info is whack 'cause it keeps spreading by word of mouth. They just wanna be in the headlines, even if it's not true. They'd rather be popular than tell people the truth.	Certainty in Source in Justification na
G2_22.02: The media isn't always a reliable source, you can't verify everything they say	Source in Justification na
G3_22.02: Because we're not sure about what social media is saying.	Source in Justification na
POV_7: Well...uh, the media isn't always reliable because anyone can post on it	Source in Justification na
POV_5: Basically for me and xxx, the media tells a little bit of truth, but most of the time it's lies, because... it's to attract people's interest, and as soon as they see an article they directly go see what it is. That's basically what the media are.	Simplicity na Certainty in Source in Justification na

(c) The "*Believers"* (N=3) are players who also view the media as reliable information sources, even in contexts where they should be wary of potential fake news. Their trust in the media is rooted in personal beliefs, marking it as naive justification. They perceive media as an authoritative entity delivering trustworthy, scientifically-backed information. Yet, the POV_6 admits that their views might evolve as they explore the museum, indicating openness to alternate perspectives and hinting at an intermediate certainty in their beliefs.

Table 5. Excerpts of answers from Believers when reading the enigma

Verbatim (audio responses provided by the players)	Dimensions and levels
POV_1: Because I trust the media.	Justification na
G0_18.02: Because this is a situation that can be real	Justification na Simplicity na
POV_6: Well, I think it's true because if it was on the news, then it could potentially be true. So with xxx, we stick to the idea that... I think it's true, but we'll see later.	Justification na Certainty in

(d) The group labeled as "*Undecided*" (N=3) is characterized by players who can't articulate their choices, typically offering "I/we don't know" or being sidetracked by inaudible laughter. Their recordings are largely unusable due to their naive justification.

The four identified groups generally display weak reasoning, rooted in naive justification. This early-game behavior is understandable since players haven't yet accessed enigma-related museum information. While they're expected to develop their arguments as they progress and gather information, most, except the *Verifiers*, don't see themselves as knowledge producers, even though they're cast in the role of nature expert. The dimensions most frequently referenced are source and justification, with few allusions to certainty and simplicity. Typically, during audio recording, one player takes charge, and it's rare for team members to answer without prior group consultation. After gathering sufficient clues and completing an ecosystem map, players were questioned about the media's reliability and potential solutions to the enigma. Their recorded answers, analyzed using our personal epistemology indicators, were categorized. They addressed whether the press article that accused the Great Capricorn Beetle was credible and hypothesized the origins of the marks/holes on the trees.

A synthesis of their responses revealed four main perceptions regarding the enigma's complexity and the proposed solutions. Given the complexity of the problem, multiple considerations and answers are expected. Initially, the information was misleading since the Great Capricorns do not target young oaks but rather old dying trees. Players who meticulously reviewed the beetle's technical sheet in the museum would discover this. Possible explanations for the marks on the younger trees could be human activity or deer rubbing their antlers. Additionally, the media's phrasing, alternating between "marks" and "holes," could confuse readers. While marks might be attributed to deer or humans, holes could be the work of woodpeckers, later used by creatures like martens or Leisler's bats. Therefore, there is no single solution, but various potential explanations. The Great Capricorn Beetle as incorrectly implicated by the media for targeting young oaks. The piece article was incomplete and misleading, having skewed the information. This setup challenges the players to utilize their critical thinking, resulting in four distinct response categories from the students.

(a') The enigma has *multiple solutions* and players recognize the Anthropocene complexity by suggesting open ended solutions (N=9). While the media singled out the insect for the oak's demise, players viewed it as part of the ecosystem, not the sole culprit (see table 5). Drawing on museum insights, players formed interpretations. Although some might have misconceptions, they challenged the media, giving nuanced responses rooted in the museum's displayed ecosystem, showcasing a sophisticated understanding of simplicity.

Throughout the game, these players shifted from seeing information as absolute truths (simplicity na) or partially doubts (simplicity in) to recognizing knowledge's fluidity. Such growth is significant for students at this age, as they begin to see knowledge not as black-and-white but as evolving. For those behind the game, this outcome was the anticipated conclusion.

Table 5. Excerpts of answers from players who suggest that the enigma has multiple solutions

Verbatim (audio responses provided by the players)	**Dimensions and level**
G0_10.02: It's not the great capricorn, because it has no interest in breaking trees, and other animals eat trees, not like the great capricorn, which does not eat them.	Certainty in Simplicity so Justification in
G0_18.02: Well, it's not just the great capricorn beetle, it's the other animals that live in the forest that make these marks and holes	Certainty in Simplicity so Justification in
POV_4: Uh, the holes are dug by animals to make their burrows, the marks could simply be from animals hitting things, or it could be humans causing deforestation and damaging nature.	Certainty in Simplicity so Justification in

POV_6: Well, I think it's the natural species that are in the forest that are doing it because there are several species, there's the deer, there's the marten, there are other species.	Certainty in Simplicity so Justification in
G5_18.02: It is the woodpecker that made holes, which allowed other species to live inside the trees. Because perhaps the great capricorn beetle feeds on the sap of trees. But there are other species that eat the great capricorn beetle, which creates a life cycle, and therefore prevents there from being too many great capricorn beetles.	Certainty in Simplicity so Justification in
G6_18.02: Um, nearly all the animals of the forest, and the insects.	Certainty in Simplicity so Justification na
G2_22.02: From certain animals or mushrooms. There are plenty of other possibilities.	Certainty in Simplicity so Justification in

(b') The second category players offer *a unique solution* to the enigma, differing from the media's assertion (N=4). Their answers suggest a belief in absolute truth, aligning with the naive dimension of *certainty*. Their new conclusion arises from connecting museum information and considering context (intermediate *simplicity*). While game designers and researchers find this conclusion acceptable because players challenged the media's authoritative narrative and dismissed the Great Capricorn beetle as the culprit, there's a lingering issue. These players perceive answers as singular, limiting their openness to multi-faceted situations. As students delve into topics like ecology, food production, and sustainability, they'll often face multifaceted challenges. Though not incorrect in their conclusions, they missed the nuance, not recognizing the enigma's open-ended nature.

Table 7. Excerpts of answers from players who suggest that the enigma has a unique solutions unlike the one presented in the media

Verbatim (audio responses provided by the players)	**Dimensions and levels**
POV_1: What do you call the bird that makes holes? The woodpecker.	Simplicity in Justification na
POV_3: According to us, the one who made the holes is none other than the great spotted woodpecker.	Simplicity in Justification na
POV_8: No, because we saw that it's the great spotted woodpecker.	Simplicity in Justification na
POV_7: It's the great spotted woodpecker who made the holes.	Simplicity in Justification na

(c') Players propose a *unique solution*, identical to the one initially proposed by the media (N=1). They believe that valid information comes from an external authority (naive source) and that an absolute truth is possible (naive *certainty*).

Table 8. Excerpts of answers from players who suggest that the enigma has a unique solutions similar the one presented in the media

Verbatim (audio responses provided by the players)	**Dimensions and levels**
POV_9: Because all the evidence were consistent	Source na Certainty na

Given the researchers and game designers' expectations, the current solution for Geome falls short. Indeed, Students should scrutinize media information and delve into various investigative elements of the enigma.

(d') Players who did not manage to complete the game and for which data are missing (N=6 due to software issues or because of lack of time to complete the game.

However, the thematic analysis is not flawless. Teams like POV_3 might suggest diverse solutions for the enigma but then pinpoint a single cause, such as the great spotted woodpecker. This can result in an open ending where the group suggests various possibilities such as: "*I think they come from all elements, animals, nature, elements, wind, drought and all that...*" but when asked who made the marks/holes, they propose a single answer: *the great spotted woodpecker*. Despite these overlaps, we have categorized such teams under "Multiple solution".

5.2 Evolution of Player's Personal Epistemology

As predicted by the a priori analysis [7] players presented solutions to the enigma. Regardless of the solution's accuracy, they recognize themselves as meaning makers (*source* intermediate). Therefore, most players identify the complex relationships in the information provided by the museum exhibition (*simplicity*). Their beliefs shifted based on the nature of their proposed solution, underscoring the idea that knowledge adapts in light of new evidence (*certainty*) [3,64]. As for justification, players had to rationalize their decisions grounded in their knowledge comprehension and information gathered. Initially, their justification was rather simplistic upon encountering the enigma. But, as the game unfolded, their responses became more structured and deliberated, grounded in a selective choice of solution and a scrutiny of accessible information (intermediate justification). Figure 5 illustrates the evolution of students' personal epistemology from the game's onset to its conclusion and the enigma's resolution. All "*Believers*", who initially perceived the information as credible (which was in fact a fake news) proposed alternative solutions, distancing themselves from this perceived authority. Those "*Doubters*" who completed the game converge towards the idea that media information is inaccurate.

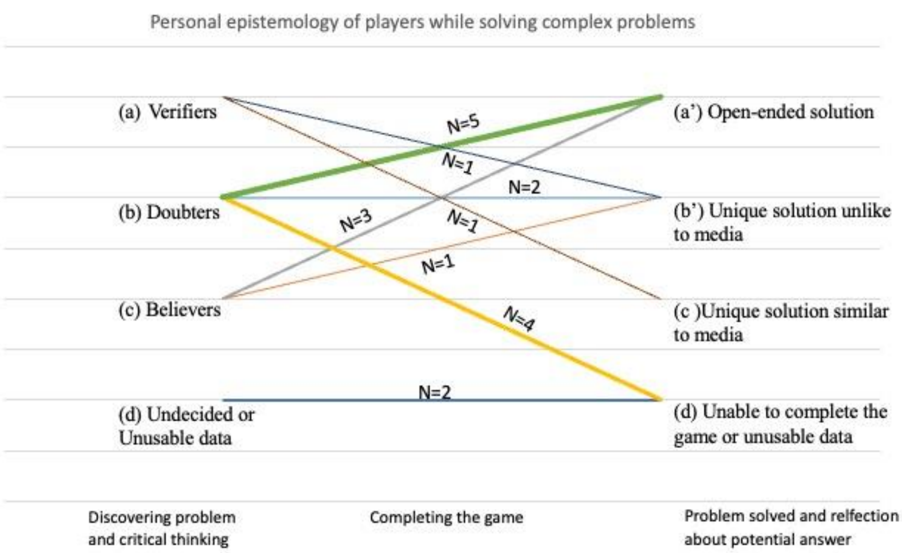

Figure 5. Categorization of the player's according to their ability to process information and solve a complex problem

"Doubters" who completed the game were inclined to believe that the media information was unreliable. From the 9 teams we monitored using onboard cameras, gleaned insights about personal epistemology and gameplay. Teams typically discussed and reached a consensus before recording, especially at the game's start when they evaluated media information. During the game, some teams exhibited disagreements, prompting them to revisit the enigma or negotiate to find common ground. This mutual understanding illustrated their shared personal epistemology. In one notable instance (Pov_4), a player made a unilateral decision without seeking team input. While this team completed the game, they omitted their final recording to prioritize the ecosystemic map. This choice, combined with their comprehensive discussion about inter-animal relationships in the museum, categorized them under (a’). To address such oversights in future sessions, game-masters should emphasize the importance of completing the end questionnaire.

Figure 5 shows that despite their sophisticated epistemology, a team of *Verifiers* concluded that the media was accurate. Camera data revealed only one out of three players was genuinely engaged. While they collected all clues, they failed to harness them effectively. Instead of critically evaluating conflicting details, they approached it as a simple clue-collection quest. This finding aligns with previous research on the subjectivity of game experiences, where the game as intended by the game designer may be interpreted by players [31].

Of the 9 groups that arrived 6 were from the same class. This class displayed a notable team spirit, especially after a setback in the game's first half. In the museum puzzle-solving segment, these students were particularly collaborative, sharing clues and discussing findings. They also consulted the museum curator and their teacher frequently. These interactions likely enhanced their grasp of the game's intricacies. Unique to this class, they consistently worked on the systemic map during the game, whereas others typically did so after concluding their investigations.

Recently, while some players seemed reluctant to record audio notes, their recordings were more detailed than earlier written responses. Using on-board cameras to track student interactions during their visit proved unobtrusive and effective.

5.3 Players Behavior and Critical Thinking

By observing players' behaviors, we found that understanding their experience requires considering multiple factors. This includes not only game interactions but also interpersonal dynamics, attitudes, and displayed emotions. Such multifaceted insights help elucidate GBL within a museum setting. The following table, informed by studies on critical thinking and personal epistemology [46], summarizes factors influencing a player's journey towards an open-ended understanding of complexity. It also highlights potential obstacles or processes that might result in students only engaging superficially with knowledge, often hovering between naive and intermediate levels based on our indicators.

Table 9. Synthesis of our results illustrating the relationship between epistemology and critical thinking for a game-based museum visit

<table>
<tr><td rowspan="4">Epistemic flexibility
↕</td><td>Reaching an open-ended solution</td><td>Attitudes toward Novelty</td></tr>
<tr><td>+ Defining the problem at hand
+ Skills in problem-solving including analysis, interpretation, evaluating various options before making an informed decision.
+ Linking information (simplicity).
+ The capacity to respect expert opinions while also critically (source and justification).
+ Prior knowledge or interest in the topic.</td><td>+ Epistemic curiosity and a drive to fill a knowledge gap.
+ Seeing oneself as being able to build knowledge (source).
+ A genuine interest in exploring the subject.
+ Believing that one's knowledge can evolve (certainty).
- Roaming the museum without focusing on game-relevant elements.
- Limited engagement in reading, and exploring new information.</td></tr>
<tr><td>Reaching a limited solution</td><td>Attitudes between Players</td></tr>
<tr><td>- Expecting a problem to have a clear correct answer (certainty).
- Placing minimal emphasis and attention on game information
- Challenge in linking related information (systemic thinking - simplicity).
- Limited skepticism towards statements from external authorities (source).</td><td>+ Empathy, active listening, and appreciating teammates input.
+ Verbally sharing information with the group when only one player has the tablet.
+ Being proactive in seeking information from available individuals when faced with challenges (teacher, game-master).</td></tr>
</table>

Epistemic rigidity	- Underestimating the value of the systemic map.	+ Rotating the tablet among team members and/or assigning roles. - Individualized decision-making and distancing oneself from the group. - Getting sidetracked, joking around, or attempting to cheat.

6. Discussion and Conclusion

The current work states that games that immerse students in ill-structured problems can foster active information processing and critical thinking. However, their ability to process information is influenced by their personal epistemology. Some players express their willingness to verify media information themselves, while others are doubtful and express personal opinions without presenting arguments. Throughout the game, these players encounter evidence that may challenge their trust in certain information sources, leading to shifts in their epistemological beliefs about certainty. We posit that the game offers a platform for honing scientific reasoning during a museum visit. It integrates the eight key epistemic activities applicable across scientific disciplines: problem identification, questioning, hypothesis formation, artifact construction and redesign, evidence collection, evidence assessment, conclusion drawing, and communication and critique [71]. However, for some students, the game doesn't alter their reliance on external authorities as sole knowledge sources, depriving them of recognizing their potential to derive knowledge independently. This unyielding trust in external authority mirrors a naive perception of knowledge sources [3,64], posing a significant challenge for educators.

The game presents students with a realistic, intricate scenario that challenges their personal epistemology through ill-structured and non-deterministic problems. However, for some, a naive understanding can hinder their ability to navigate the game effectively. Although the game does not shift the personal epistemology of certain players, we believe the gameplay remains valuable. Indeed, missteps made during the game can be examined in a subsequent debriefing. This allows for discussions on information evaluation, anchored in a direct experience that resonates with the players.

Our findings suggest we should temper expectations. Cultivating students' personal epistemology in a game setting can be tough, as the playful nature might cause them to treat information lightly. Nonetheless, we consider this critical attention to information is crucial for learning. It seems that the playful attitude might prompt students to accept the risk of failure and not apply their critical thinking skills, as they might, in a more formal learning situation.

To delve deeper into the subjective nature of the player experience, our analysis of the video data revealed many phenomena that were not anticipated during the game design phases, specifically concerning player attitudes. These are tied to the concept of playful attitude [72] anchored in several factors: the players' own persona, their beliefs, their interest in the game's theme, and their personal values. Additional factors to consider include the context. Since the game is set in a museum, a hub for the dissemination of knowledge, players expect to obtain credible information. Group dynamics among players can shape the nature of their interactions, the level of interest in the given task, and the quality of their exchanges. The proficiency with which a game master introduces and orchestrates gameplay is paramount. Finally, the game itself presents affordances that can motivate students to engage in problem-solving drawing up their personal epistemology.

7. Limits and perspectives

Several limitations have emerged in our study. First, given that personal epistemology is contextual and stems from negotiations among teammates, "group epistemology" might be a more fitting term. Relying solely on verbatim analysis may not fully capture personal epistemology; post-game interviews could offer deeper insights [64]. Drawing from the varied epistemic activities tied to scientific reasoning, we could structure the game's phases more meticulously, pinpointing activities that pose challenges for students [70]. Future endeavors might harness the game's emotional aspects to craft immersing situations that challenge student's personal epistemology, building on existing epistemic emotions research [38]. Although primarily analyzed on-board camera data tied to audio recordings, this data has potential for a more comprehensive examination of players' personal epistemology. Lastly, we acknowledge that debriefing can shape personal epistemology, and reflecting on both playful and epistemic experience could further evolve one's epistemological stance.

From a game-design perspective, we recommend designing games that feature ill-structured and non-deterministic problems without a unique solution, often categorized as open-ended games. For this, the problems to be solved must be interdisciplinary, not frequently encountered or emphasized in educational contexts. Collaborative gameplay should be prioritized, as it fosters epistemic interactions and harnesses students' critical thinking

From a methodological perspective, comprehensively assessing student cognitive skills and dispositions is intricate and demanding. External measures of critical thinking, intelligence, prior knowledge were not assessed but might moderate the identified effects. However, in such a realistic setting in the field it is hardly feasible and should be investigated, for instance with mixed methods approaches, in greater detail. A holistic approach to the situation is essential, utilizing mixed methods for evaluation using post-game questionnaires, focus groups, or interviews. This approach underscores the growing importance of mixed methods.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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