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Research paper

Zombie Ants VR: Using Trial-and-error Gameplay Mechanics to Intuitively Teach Players About Natural Selection

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ABSTRACT

Understanding the process of evolution is important for making informed decisions about the use of antibiotics and vaccinations to combat pathogens. Unfortunately, discussing the intersection of evolution and infectious diseases can be difficult due to preexisting religious views and/or political beliefs. We sought to explore whether gamification techniques like trial-and-error gameplay could overcome this problem by teaching the process of evolution without explicitly defining the theory. To do so, we created the freely available virtual reality game *Zombie Ants VR: Definitive Edition*, where players take on the role of the zombie fungus *Ophiocordyceps* with the goal of infecting and behaviorally manipulating ant hosts. The player's in-game decisions determined whether they succeeded and reproduced or if they died and needed to try again as a new fungal spore. By emphasizing that each new attempt took place with a new individual, we aimed to intuitively teach how natural selection acts at the population level and dispel common evolutionary misconceptions. To test if the gameplay mechanics would have this effect, we performed a small-sample exploratory study in which we compared participant responses on pre- and post-game questionnaires. Our results demonstrated that playing *Zombie Ants VR: Definitive Edition* increased players' understanding of evolution, independent of preexisting beliefs.

Keywords: evolution, infectious disease, gamification, virtual reality, serious games

Teaching evolution remains challenging due to its conceived incompatibility with students' religious and/or political beliefs (Barnes & Brownell, 2016), particularly at institutions with religious affiliations (Tolman et al., 2021). This issue is further reflected in the public sphere of countries like the United States of America where over one third of the population rejects evolutionary principles (Miller et al., 2022). Moreover, online platforms and algorithms increase science illiteracy by preferentially pushing controversial misinformation — which often generates higher rates of clicks, comments, and views (Park et al., 2023). While the severity of this problem can differ between countries (Miller et al., 2006), it remains a waxing global issue in part due to the resurgence of science skepticism (Rutjens & van der Lee, 2020) emboldened by nationalism and other anti-intellectual movements (e.g., Neo-Calvinism in the Netherlands (Flipse, 2012)). The COVID-19 pandemic, for example, was highly politicized and particularly fraught with misinformation that has since made earnest discussions about infectious disease more difficult (Baxter-King et al., 2022; Hornik et al., 2021). This is occurring at a time when

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global warming is contributing to the evolution of thermotolerant human pathogens (de Oliveira & Tegally, 2023) and multi-drug-resistant organisms are becoming increasingly problematic (Miller & Arias, 2024).

Many educators have been pushing back against misinformation about evolutionary principles to increase the theory's acceptance. However, mere acceptance does not necessarily translate to a clear understanding of evolutionary processes, nor the ability to properly apply these principles to major life choices. Even in academic circles, educated individuals often misunderstand evolution as a process that affects individuals; a misinterpretation that is more in line with Lamarckian views (Beckerson, 2024). This misattribution of selective pressures as the driving force behind change in an individual is just one of many fallacies that makes teaching evolution a persistent challenge in biology education (Smith, 2010; Sickel & Friedrich, 2013; Gregory, 2009). Both the rejection of and ignorance towards evolutionary science can have major societal impacts when it comes to public health choices, including vaccination status and its contribution to herd immunity (Fine et al., 2011).

The time-sensitive nature of such global issues can lead to a sense of urgency and move educators to push too aggressively against those with non-conforming views. This approach has repeatedly been shown to elicit psychological reactance in those who feel their freedom of choice is being threatened, resulting in a "boomerang" or "backfire" effect where people become even more entrenched in their beliefs (Courtright, 2013; Douglas et al., 2024; Jonason & Dane, 2014; Lewandowsky et al., 2012). Therefore, science communicators may be going about things the wrong way when trying to win an uphill battle against personal anecdotes and misinformation that fuels conspiracy theories and science denial by chastising ignorance and droning on about the scientific facts. In the end, whether one acknowledges evolution as the driving force behind the emergence of new pandemics is less important — with regards to the societal impact of their decision-making — than a foundational level of understanding of the process. Instead, teaching about the underlying mechanisms of evolution — i.e., how selective pressures drive small, stepwise changes to the genomes of bacteria, fungi, and viruses that result in new host ranges and various forms of resistance — might provide a more effective strategy.

Discussing evolutionary principles in the context of emotion-laden human diseases can trigger predisposed opinions and contribute to the further alienation of people opposed to this information. For this reason, using examples of infection processes from other natural systems may help tap into an individual's curiosity instead, reducing this risk. We therefore asked whether it would be possible to teach about the process of evolution in the context of other infectious diseases — primarily zombie fungi — without using trigger words that can elicit strong emotional responses that effectively halt the learning process (Malyuga & Rimmer, 2021; Capraro & Vanzo, 2019; Brady et al., 2017). To answer this question, we used a gamification technology approach which recent research has shown is suitable for facilitating engaging learning activities that help improve understanding of abstract scientific concepts (Kalogiannakis et al., 2021). Game mechanisms in particular can positively affect motivation and cognitive development, ultimately improving scientific thinking and learning (Zainuddin et al., 2020). However, such an approach requires adapting the game mechanisms to the specific needs of individual learners in order to result in more effective science learning throughout (Zourmpakis et al., 2024). Moreover, the gameplay should be designed such that it fits the educational content well (Monterrat et al., 2017; Zourmpakis et al., 2023). As such, we reasoned that games using failure as an opportunity to elaborate on player choices and improve their gameplay could be particularly well suited for teaching evolution by means of natural selection. This dynamic is based on conceptual change, also known as "productive failure," in psychology (Loibl & Leuders, 2019). Error-full learning, followed by corrective feedback, has been associated with greater learning outcomes than traditional error-avoidant instruction — particularly when individuals have a strong confidence in the errors they are making (Metcalfe, 2017). With this in mind, we set out to develop an activity that could teach the process of evolution in the context of a natural infection while maintaining the fun and engaging elements of trial-and-error gameplay.

In our gameplay design, we emphasized the need to move beyond a traditional lecture-style conversation in favor of an active learning exercise that incorporates higher-order thinking (Adams, 2015). Towards this end, we leaned on our scientific work and expertise across the fields of microbiology and neuroparasitology to create a game about zombie ants. Reminiscent of some zombies depicted in movies, TV series, and video games, zombie ants are living hosts infected by the fungal parasite *Ophiocordyceps* which changes ant behavior in ways that benefit the parasite's ability to spread to new hosts. *Ophiocordyceps* accomplishes this feat by first causing infected ants to abandon their social roles in the nest to avoid defense behaviors of nestmates that might destroy the fungus (Beckerson et al., 2025; Trinh et al., 2021). Next, it causes them to climb nearby vegetation to position the host at an elevated vantage point that promotes both the growth of a fungal reproductive structure (i.e., its fruiting body) and the effective spread of infectious spores (Will et al., 2023). This is where the fungus ultimately causes the ant to bite down irreversibly onto plant material to prevent the host from falling after death — a behavior known as "the death grip" (Hughes et al., 2011). By causing the host to climb to a higher location and attach itself there, the fungus is better able to use the wind to spread its next generation of infectious spores to new hosts. This is a common transmission strategy found amongst many behavior-manipulating parasites called

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"summit disease" (de Bekker et al., 2021). Ultimately, these infection-related host behaviors are the result of biomolecules encoded in the fungal parasites' genomes; a phenomenon known as an "extended phenotype" (Dawkins, 1982). These extended phenotypes have evolved over millions of years of reciprocal selection through a process called coevolution. As such, zombie ants and other behavior-manipulating parasites make for charismatic examples to teach about natural selection, symbioses, and disease transmission.

In addition to their suitability for teaching important biological concepts, zombie ants are an increasingly well-known pop science topic, thanks in large part to media like the HBO series *The Last of Us* (Mazin & Druckmann, 2023) based on a video game series of the same name (Naughty Dog, 2013-2025). As stated by its creative leads, this series is famously based on zombie ants and has been discussed in many science communication outlets including *The Biology Behind The Last of Us* with WIRED (Web Link 1); *The Fungus Among Us* with The Colin McEnroe Show (Web Link 2); and *True Facts: Fungi That Control The Insects They Eat* with Ze Frank (Web Link 3). The topic's popularity has benefited greatly from the morbid curiosity that "real-life-zombies" instill in the public eye. This makes the topic of zombie ants an incredibly useful tool for getting a foot-in-the-door to discuss biology with the general public. Furthermore, focusing educational outcomes pertaining to natural selection and disease transmission on ants instead of on humans can assist in mitigating triggering stimuli or social cues that may invoke a defensive response through dissociation of the individual from the subject matter.

To gamify the topic of evolution as it applies to the context of zombie-making fungal parasites, we used the trial-and-error format of memory games; however, we implemented one important change relating to the identity of the player. Instead of allowing the player's character to retry failed activities, they are instead required to start the game over as a new character after each failed attempt. While this does not change the game's overall functionality, this deliberate requirement aims to impress upon the player the importance of population-level dynamics involved in natural selection. Applied to the topic of zombie-making fungi, each new attempt must thus be performed using a new spore and involves the infection of a new host. We hypothesized that structuring the game in this way would teach players about the process of evolution by natural selection without explicitly explaining the theory.

As a medium for our game, we chose virtual reality (VR) technology to allow the player to view the world from the perspective of a zombie ant. VR provides an unparalleled sense of immersive presence and a strong association with virtual objects that promotes learning (Lin et al. 2024; Liu et al., 2023; Merchant et al., 2014). It also allows players to experience an environment on limitless scales — like visualizing the entire universe (e.g., Galactic Center VR; Russell, 2020), or the human body at the microscopic level (e.g., BloodBlast VR; Kalinka, 2020). Furthermore, using an immersive virtual environment assisted in our goal of dissociating the player from their personal perspectives to facilitate a more open mindset for the educational experience.

By designing the game from the perspective of a fungal spore and infected ant, we were also able to include additional information that teaches the player about fungal infections and the social structures of ants as secondary learning objectives. In addition to their educational value, these elements help to instill a sense of fascination with the biological sciences in young players. Ultimately, this *Zombie Ants VR* project was brought to life through an interdisciplinary effort. It involved collaboration between researchers who study the zombie ant phenomenon in detail, game developers across all career stages, and educators in biology, game design, and interactive media, all of whom are listed in the acknowledgment section for their important contributions. Upon its completion, we tested whether the zombie ant example — along with the trial-and-error gameplay mechanics and an immersive VR atmosphere — could improve understanding of evolutionary principles at its intersection with infectious diseases.

METHODS

Incorporation of educational components

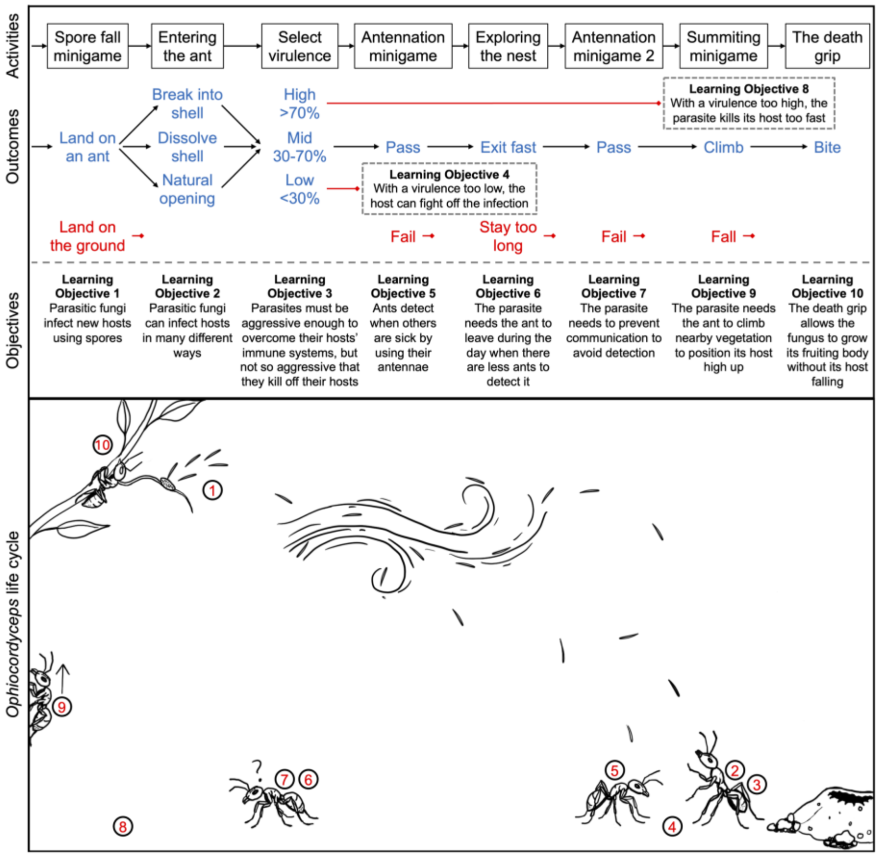
We designed the *Zombie Ants VR* game with children and young adults in mind (ages 12 to 25), reflecting the population most familiar with VR technology and in keeping with the age limitations suggested by Meta Quest headsets (Meta Platforms, Inc.). Because parasites — including *Ophiocordyceps* and other disease-causing agents — operate at a much smaller scale than is experienced by human beings, VR was immediately attractive as a medium for this project. Using VR, we aimed to enrich learning by creating an immersive environment that transports the player into the tiny world of parasites with a perspective that is entirely new to them. We hypothesized that this element of escapism would also help remove players from preexisting beliefs that could hinder learning about evolution (Petersen et al., 2022). Being as small as a fungal spore, and later the size of an ant, players can explore and interact with a wilderness of small plants, animals, and fungal organisms — as if a blade of grass were the size of a tree. Similar approaches have been used by other games with great success since the origin of three-dimensional visuals (e.g., A Bugs Life by Traveller's Tales, 1998; Pikmin by Nintendo, 2001; and Grounded by Obsidian Entertainment, 2020).

While the immersive capabilities of VR tools have been demonstrated to improve learning when applied in various educational settings (Lin et al. 2024; Liu et al., 2023; Merchant et al., 2014), a recent systemic review has also shown that creators often focus too heavily on the application of VR itself and not enough on the underlying educational theory, resulting in poor learning outcomes (Radianti et al., 2020). We sought to avoid this common mistake by prioritizing gameplay mechanics directly associated with our evolution learning objectives. By letting players make their own choices in the game — most of which result in failure — we mirror the essence of natural selection and create a myriad of productive failure opportunities (Loibl & Leuders, 2019; Metcalfe, 2017). Allowing the players to make mistakes and incorporate adjustments through repetition induces positive reinforcement through a feeling of fulfilment from accomplishing something challenging. This leads to longer-lasting impact on memory — a strategy that is commonly used for memory-based studying (Karpicke & Blunt, 2011).

We also emphasized secondary learning goals relating to disease transmission, ant biology, and the life cycle of *Ophiocordyceps* fungi using a narrative-driven, choose-your-own-adventure format with several branching paths and multiple endings (see **Figure 1**). In total, there are ten possible secondary learning objectives, nine of which are accessed through incorrect choices made during the adventure (see **Figure 1**). While it is unlikely that every player will access all ten endings on a single playthrough, this design provides a more targeted instruction in areas where misconceptions exist. In essence, if the player intuitively makes the correct choice, they will not access the learning objective for the corresponding incorrect choice. The game thus functions in a formative assessment manner comparable to test corrections in an academic setting.

Figure 1

Storyboard for Zombie Ants VR: Definitive edition



Note: The top panel depicts the underlying storyboard divided into three categories: the choices and minigames presented to the players throughout the game, top row, the possible outcomes for each activity, middle row, and the learning objectives for each event outcome, bottom row. Learning objectives 3 and 8 are shown to the right of their corresponding incorrect choices. The bottom panel depicts the life cycle of ant-infecting Ophiocordyceps fungi, with numbers associated with each learning outcome in the game.

Originally, we included additional information — primarily information pertaining to the life cycle of ants — as in-game pop-up text boxes near points of interest for players to read at their leisure. However, alpha testing of the game showed that many participants, particularly adolescents, skipped these text boxes as they appeared on screen so they could immediately continue exploring the virtual world. Therefore, to help facilitate these learning objectives whilst maintaining the immersive feel of the game, we collaborated with acting students to record in-game voice narrations. These voiceovers were split into two characters: a naturalist who took on the role of the narrator and a fungal "hive mind" who took on the role of the player's parasite mentor. By using two separate

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voices, we were also able to further categorize the in-game information into fungus-related and ant-related information (see **Supplementary Materials 1**). Other in-game text that pertained to gameplay elements (e.g., movement controls and mini-game instructions) were not narrated.

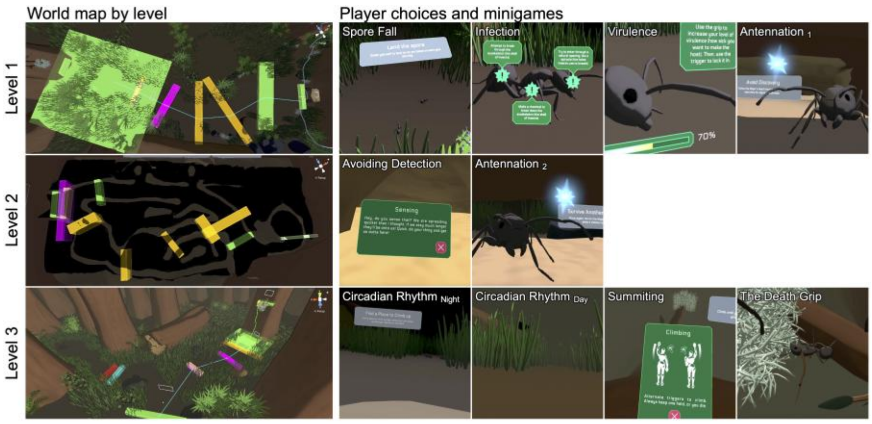
Game development

The creation of this game presented an opportunity for mutual learning and career development of students at all stages of the project. The prototype for the game was created as part of an undergraduate Game Design course focusing on VR. Students were first given a survey of published games and a set of tutorials on using Unity to produce VR applications. Then, they formed groups to "pitch" sponsors for the opportunity to work on their projects, which ensured that student participation in the game's construction was interest driven. Those who elected to work on the prototype of *Zombie Ants VR* developed a proposal in response to the research team's Request for Proposals document (RFP) and used it as a guide throughout development. This RFP included the following objectives: 1) educate the players about behavior manipulation of ants via fungal infection, 2) allow players to participate in these processes by simulating an immersive experience, and 3) showcase the latest scientific research and our current understanding of zombie ants. It was also made clear that players should be tasked with making a series of decisions based on their scientific understanding of the disease dynamics and be given formative feedback during the experience. The concept of merging these choices with the structure of a walking simulator was ultimately suggested to reinforce the narrative of the player enacting the role of the fungus and its infected host. Students then worked as a team and met regularly with the sponsor, implemented the basic scene structure, and created some of the VR interaction mechanics. The final course version of the game included a combination of custom gameplay logic, student-created models and animation, and narrator dialogue that was reviewed by the sponsor.

After completion of the course, bachelor's students in digital media and game design as well as a recent master's graduate in game and interactive media design were hired to build upon the prototype to create an alpha model for gameplay testing. This testing would inform future work on the definitive (beta) version of the game. They were tasked with further developing and improving the game's graphics and overall gameplay dynamics. This was largely done using the cross-platform game engine Unity (Unity Technologies) in combination with UtilitySO for scripting objects. This tool provided unity events with easy access methods from other key game scripts, simplifying them to fit into Unity events and allowing for event triggers to be used. These event triggers were placed throughout the game to prompt text boxes, voice acting lines, and minigames (see **Figure 2**). The selectable choices and minigame dynamics were designed with action-based outcomes that are tied to each of the ten secondary learning objectives.

Figure 2

Virtual environment.



Note: Zombie Ants VR: Definitive Edition can be divided into three levels corresponding with their respective loading zones. The left-most panel in each row depicts the map of the virtual environment for each level. The panels to the right show screenshots of each in-game event. The top row shows level 1, in which the players learn about how fungal parasites infect new hosts. The middle row shows level 2, in which players explore the ant nest and learn about how ants communicate, detect infections, and organize their colonies. The bottom row shows level 3, which can be accessed in either day mode or night mode depending on choices made in level 2. Here, players learn why Ophiocordyceps parasites manipulate daily rhythms in their hosts and that they induce summitting and death grip behaviors in manipulated ants to improve the spread of new spores. At the end of level 3, players are congratulated for completing one successful life cycle, at which point the whole game starts again.

Game modes

We created three different game modes for *Zombie Ants VR: Definitive Edition* to facilitate its use in different educational environments. In the primary "Survival" mode, the game plays as originally intended. This mode most resembles natural selection, requiring all players to start over from the very beginning as a new spore after each mistake. Through this mechanic, the game reinforces learning through active recall in the same manner as other common metacognition learning tools and retrieval-based active learning strategies (e.g., flash cards, spaced repetition, or dual coding) that are associated with greater learning outcomes (Karpicke & Blunt, 2011).

While Survival mode is hypothesized to result in the greatest degree of learning, public engagement events often require a more fast-paced experience with a higher degree of turnover for participants. For this reason, we also created the "Exhibit" mode, which reduces the overall gameplay time by allowing players to continue from spots at which they fail. Importantly, this mode still maintains elements of the Survival mode that are vital for teaching about evolution — primarily the use of restart and continue buttons that instead say "Spawn New Spore". Since the players can correct their mistakes in this mode, it was imperative that we make it clear that any repeated attempt is performed with a new spore that has made it back to this stage of the game. Like in Survival mode, this should reinforce an understanding that natural selection acts at the level of populations. Failure to make this clear may have otherwise misconstrued learning outcomes towards a more individualistic, Lamarckian view of evolution.

Exhibit mode reduces the overall gameplay time to around 10-15 min depending on the number of failed attempts and the degree of active exploration performed by the player. This flexibility preserves the investigative options that fosters curiosity in an immersive virtual environment. However, unpredictable length in gameplay can introduce challenges when trying to implement the game in a classroom environment with more strict time constraints for instruction. To address this concern, we created a third "Educational" mode that has a more linearized progression design — sometimes referred to as "railroading" in the gaming community. To achieve this, we made two further changes to the Exhibit mode: 1) we removed the player's movement capabilities and replaced them with a teleportation system, and 2) we changed the continue mechanic to respawn "new spores" on the other side of failed choices or minigames as if they had succeeded. Nevertheless, players are still confronted with the death screen and its associated learning materials upon failure. Moreover, while the Education mode does not allow the player to move their character, they are still able to look around at each teleportation junction. This helps retain some of the immersive gameplay experience. Together, these changes make gameplay duration much more predictable, allowing the game to be used alongside a projector and a volunteer to accompany lectures or other types of timed presentations about the zombie ant life cycle. Furthermore, our preliminary testing suggested that this game mode is also more amenable for children under the age of 12 for whom the minigames were often a bit too difficult to complete.

Accessibility

VR provides new opportunities for visual learners and those with physical disabilities (Chițu et al., 2023) which help to bridge inclusivity gaps in education. However, the use of VR hardware also comes with potential risks for some users. These risks include musculoskeletal issues such as neck, shoulder, or back strain from the weight of the headset, eye or vision strain, fatigue, or dryness resulting from vergence-accommodation conflict, and potential motion sickness from a disconnect between visual and vestibular system inputs (Saredakis et al., 2020). Users can also experience neurological or cognitive issues including "VR hangover" (Porter III & Robb, 2022), cognitive overload, and risk of seizure. Fortunately, many of these risks can be mitigated with proper supervised use of the hardware and through the incorporation of in-game accessibility features.

Towards this end, we assured our game did not to include any flashing lights that could induce epileptic seizures (Hermes et al., 2017). We also included a motion sickness option in which all smooth video transitions are replaced with a blinking effect. This blinking effect darkens the screen during non-player-directed movements and returns only after movement to the next instance. This dramatically improved the game's playability for individuals with more severe forms of motion sickness.

In addition to health and safety concerns, we also used colorblind-friendly color palettes, incorporated stationary game controls for those with physical disabilities, and provide in-game text box popups for those with auditory impairments. The game also has two language options, English and Dutch, and includes a coding framework to facilitate easy addition of other languages. To make the game accessible to participants of all education levels and ages, the text and voice acting lines for both English and Dutch were written at the standardized language level B2 according to the Common European Framework of Reference for Languages (CEFR) and verified with the Dutch CEFR text analysis tool (Velleman & van der Geest, 2014). Language level B2 is characterized by short sentences and commonly used words, representing an upper intermediate proficiency at which individuals can interact fluently. Exceptions to this rule were made when scientific terms were needed as part of the learning objectives.

Questionnaires to test educational outcomes

To test whether playing *Zombie Ants VR: Definitive Edition* could increase understanding of disease evolution, we compared pre-game and post-game questionnaire responses for each participant. We designed these questionnaires with careful consideration to avoid common pitfalls outlined by Kishore et al. (2021). This included techniques to mitigate testing biases that commonly lead to unreliable survey results. Questionnaires

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were also written in B2-level language based on the same CEFR standards used for in-game text and audio lines. The questionnaires consisted of four-answer multiple-choice questions and five-point Likert scale responses. To deliver these questionnaires to study participants, we used the software Qualtrics (Silver Lake and CPP Investments). Responses were anonymized using randomized three-letter codes that were entered at the top of each questionnaire. The order of all other questions was randomized in each new iteration to prevent test-taking effects (Stefkovics & Kmetty, 2022; Tourangeau et al., 2000). We also randomized the arrangement of answers for each multiple-choice question except those which asked about age range and education level. Instead, the answers to these questions were arranged in a logical, incremental order from lowest to highest age/degree of experience (see **Supplementary Materials 2** and **Supplementary Materials 3**). Furthermore, we limited the number of questions on each questionnaire to avoid testing fatigue associated with rapid-guessing behavior and a decrease in satisfaction (Lindner et al. 2019).

A single multiple-choice question on both questionnaires completed by participants was related to their understanding of evolution. These two correlated questions were designed to specifically test the player's pre-existing understanding of evolution and measure if their understanding improved after playing the game. Participants were provided with four possible answers to this question; a single correct answer reflecting the proper Darwinian definition of evolution and three common misconceptions. The three incorrect answers included one which was designed to reflect an individual's acceptance of evolutionary theory but an incorrect understanding of its mechanism. This response presented a Lamarckian view of evolution, suggesting that natural selection acts at the level of individuals. The remaining two incorrect answers reflect common philosophical responses from creationist and essentialist viewpoints — mainly that things are either "created" the way that they are or simply "have always been" the way that they are. By presenting two possible scientific responses — one for a Darwinian (D) view and one for a Lamarkian (L) view — and two non-scientific responses — one for creationism (C) and one for essentialism (E) — we were able to distinguish between mere acceptance of scientific principles and a true understanding of evolutionary principles. By comparing the ratio of DL responses to CE responses, we gauged the general level of scientific acceptance in our test population, while further comparison between the ratio of D responses to LCE responses illuminated the level of scientific literacy. This approach thus goes one step beyond typical science literacy studies which often rely merely on the acceptance of evolutionary theory as a metric for science literacy.

To further eliminate testing biases related to recall (i.e., familiarity with the questions), we reworded the evolution question on the post-game questionnaire. While the pre-game questionnaire asked, "*Which of the following best describes how bacteria, fungi, and viruses change to infect new hosts?*" the post-game version asked, "*How does Ophiocordyceps infect new ants over time?*" By shifting the focus of the question from all pathogens to just *Ophiocordyceps* pathogens, we aimed to prevent participants from simply answering the post-game question with the same answer used in the pre-game question based on memory. This strategy was maintained across all possible answers to survey questions (see **Table 1**).

Table 1

Questionnaire response options for "How do bacteria, fungi and viruses change to infect new hosts?" (pre-game) and "How does Ophiocordyceps infect new ants over time?" (post-game).

	Pre-game Answers	Post-game Answers
Darwinian	They change randomly with only the strongest infecting new hosts.	Each spore tries to infect new hosts, but only the successful ones survive
Lamarckian	They learn how to better infect new hosts through experience.	Each spore learns how to better infect new hosts over time
Creationist	They don't change; they are designed to infect new hosts.	Spores are designed to be able to infect new hosts
Essentialist	They don't change, the hosts become easier to infect.	The ants become easier to infect over time.

In addition to the question about evolution, we also included another science-based question in each questionnaire that asked the participant about their understanding of disease transmission. However, it is important to note that *Zombie Ants VR: Definitive Edition* does not provide a trial-and-error mechanism for reinforcing any learning outcome related to this topic, as all three actions in the corresponding in-game activity (Learning Objective 2) are viewed as potentially correct and result in success (see **Figure 1**). As such, we expected the answers on the post-game questionnaire for the question on disease transmission to closely match either the players' pre-game answers or their selected choice in-game. This set of questions therefore acts as a negative control for the formatting of our questionnaires.

The remaining questions on the pre-game questionnaire asked participants about their age, experience with video games, education level, and their appreciation for biological topics (i.e., nature). The remaining questions on the post-game questionnaire asked participants about the difficulty and perceived quality of the game, as well as their overall experience while playing the game. These answers were used to screen for any other sort of variables that may be correlated with learning outcomes. All questions and possible answers for the pre-game and post-game questionnaires can be found in the **Supplementary Materials 2** and **Supplementary Materials 3** documents, respectively.

Exhibition and data acquisition for *Zombie Ants VR: Definitive Edition*

Zombie Ants VR: Definitive Edition was debuted as a temporary exhibit at the University Museum Utrecht (UMU) in the Netherlands. The exhibit took place over four separate weekends with a showcase from 10:00 – 16:00 every Saturday and Sunday. Museum attendees could view an informational poster about zombie insects written for a young audience (de Bekker et al., 2023), observe real-life samples of zombie ants under a stereomicroscope, and play the *Zombie Ants VR: Definitive Edition* game. To ensure data protection for all players, the game was run directly from a local laptop using a hardline to our Meta Quest 3 VR headset (Reality Labs).

Individuals of ages 12 and older who were interested in playing the game were offered the opportunity to participate in the study. Before enrolment, each participant was given a copy of the consent form to read (see **Supplementary Materials 4**). Subsequently, a member of the research team who previously completed IRB training through the Collaborative Institutional Training Initiative (CITI) discussed all contents of the form with the participant to ensure that they understood the goals of the study, potential risks involved, as well as their right to opt out of the study at any point. This included information on age restrictions, health and safety risks of VR hardware, vague research goals, the participation process, data collection, privacy and data protection rights, ethics review board approval, and frequently asked questions. Contact information for the project leader and ethics review committee were also included. Notably, the goal of the study was worded such that participants understood the basic reason for conducting it — to test the games ability to teach biology — without informing them about the evolutionary component of the learning objectives. As such, participants who wished to contribute to the study were only told that the goal of the study was to test the educational merit of the game. This was an essential aspect of the research design to avoid triggering pre-conceived notions or beliefs about evolution during or prior to gameplay and completion of questionaries.

Following this process, each participant was asked for a final verbal confirmation that they understood the risks and were willing to participate before being enrolled in the study. If the answer was "yes," the participant was given a randomized three-letter identifier to use on the questionnaires in lieu of any personal identifiers and asked to sign the consent form. A copy of the consent form labeled with their unique three-letter identifier was also provided to the participant in case they decided later — but prior to publication of this work — that they wished to withdraw their data from the study.

All participating individuals with minority status according to Dutch law — excluding any exceptions that allow for adult status before the age of 18 — required additional consent from a legal guardian to participate. Hereto, research staff verbally explained the information on the consent form to both the legal guardian and the minor. During this process, the research staff asked for verbal confirmation that the minor understood each of the points as they were discussed. Furthermore, minors were specifically asked if they had ever experienced a seizure or motion sickness before. They were also assured that they could stop playing the game at any point for any reason and were told that they should immediately alert the research staff if at any point during the game they started to feel nauseous or have a headache. Once the research staff had finished explaining the consent form, one final verbal confirmation about willingness to participate was required from both the minor and their legal guardian, after which the legal guardian was asked to sign the consent form on behalf of the minor.

We would also like to note that the original version of the consent form included a typo incorrectly stating that "Children between 12 and 16 years old will require the following consent to participate," when, in fact, any participant under the age of 18 required parental consent. This typo has since been corrected in the **Supplementary Materials 4** included in this publication to avoid confusion and was mentioned to all participants during the verbal explanation of the consent form. No participants under the age 18 were allowed to participate in this study without their legal guardian's consent.

Participation involved answering the pre-game questionnaire, playing the game, and then answering the post-game questionnaire. Questionnaires were provided on an iPad through links to Qualtrics surveys available in both English and Dutch. In total, the exhibit received 421 attendees and approximately 200 total players. However, due to the young family target audience of the museum, many of these players were slightly too young to participate in our study. For those who were old enough to participate, a majority agreed to join the study, resulting in a total of 30 participants. Of these 30 participants, only one requested withdrawal of their data from the study. From the remaining 29 participants, one individual did not answer the question about evolution, and another did not answer the control question about disease transmission on the post-game questionnaire (see **Supplementary Materials 5**). As such, our efforts resulted in a small sample size study of 28 data points for which direct correlations can be drawn between participants' pre-game knowledge and post-game learning outcomes (see **Supplementary Materials 5**).

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During the event, the gameplay of each player was displayed from the headset to a large TV screen positioned behind them, allowing other museum attendees to watch their progress. This gameplay was also recorded using an HDMI AVerMedia USB Live Gamer Portable 2 Plus AVT-C878 Plus DV478 capture card (AVerMedia) and saved under file names using the same three-letter identifier code as their questionnaires. Because the use of the TV screen in our museum setup could have affected participant's prior knowledge about the game before playing, we were careful not to include participants in the study who had already watched other people play the game — which further contributed to the lower testing population compared to the total event attendees.

Data analysis

Gameplay footage of participants was scored manually using time stamps that started as soon as the player exited the instruction panel and ended when the screen faded to black for the game completion prompt. The number of mistakes made throughout the game and subsequent number of times the player spawned new spores was counted using each instance that a failure screen appeared. This information together with the biographical information, perceived entertainment values, and the difficulty level of the game was analyzed alongside the directionality of responses for the question about evolution. With this approach, we aimed to determine if the game significantly improved understanding of evolution and whether these other variables contributed to its success.

All statistical analyses were performed using R and R-studio Version 2023.06.0+421 (2023.06.0+421). To test if there was a significant increase in the number of correct answers about evolution provided on post-game compared to pre-game questionnaires, we used the McNemar's statistical test designed for paired binary outcomes where the correct answer was assigned the numerical value "1" and all other wrong answers were assigned the numerical value "0". This was followed by a Fisher's exact test. To test if length of gameplay was correlated with learning outcomes, we used a logistic regression for data involving continuous predictor, time, and binary outcomes (i.e., correct or incorrect answers on the post-game questionnaire). To ask whether an individual's duration of gameplay affected learning outcomes, we used a Wilcoxon rank-sum test. Finally, a paired odds ratio comparison was used to determine the degree of improvement or decline of learning outcomes, and Spearman's rank correlations were used to screen for other effects between learning outcomes and information about the player. The code used to perform these tests was written with assistance from artificial intelligence (AI) and is provided in **Supplementary Materials 6**. This was the only use of AI in the project. Furthermore, AI was not used in the writing of this manuscript in accordance with the ethical guidelines of the European Journal of STEM Education.

Consent to participate declaration

All participants provided informed consent to participate in this study prior to data collection. They were informed of the study's purpose, procedures, and their right to withdraw at any time during or after the study. All adult participants who agreed with the terms were asked to sign a consent form (see **Supplementary Materials 4**). Participants under the age of 18 required a signature from their legal guardians, as well as a verbal statement of understanding regarding the experimental procedures and a verbal agreement to participate. After signing, each participant was provided a physical copy of the consent form in addition to information regarding project members and oversight personnel with contact information should they have further questions or wish to withdraw from the study later. The consent form (see **Supplementary Materials 4**) detailed the purpose of the survey, use of data, data handling procedures, potential risks, and provides contact information should the participant wish to withdraw their data. To minimize pressure to participate, all interested parties were given the option to play the game whether they chose to participate in the study or not. Direct identifiers (e.g., names, email) were not collected. Instead, each participant was assigned a random three-letter identifier to anonymously link their gameplay footage to their questionnaire responses. Furthermore, survey questions were designed to avoid unnecessary collection of sensitive data. The only sensitive data collected included the participants' age and level of education.

Data handling and privacy

Despite not collecting any personal identifier information, we treated all data as if it were sensitive data throughout the study. Gameplay data was recorded on the same gaming laptop used to run the game with robust software protections including disk encryption. This allowed our gameplay footage acquisition to be completely offline and to protect against unauthorized access and cyber threats. All survey information was temporarily stored in the secure, access-controlled Qualtrics online database through an Utrecht University access point until it could be downloaded on the same laptop used to record the gameplay footage. Data transfer in this manner occurred no later than 24 hours post collection, after which the data on Qualtrics was promptly deleted. Access to this data for statistical analysis was restricted to three authorized team members and only accessible using a single universal login on the same laptop. No participant information was transferred via cloud or email software.

Furthermore, physical copies of the consent forms collected from the exhibit — which connected participant signatures to their three-letter codes should the request their information be removed from the study — were securely stored in a locked filing cabinet. Forms were kept up to the submission of this manuscript. Following submission of this manuscript for review, these documents were destroyed to protect participant identities. To further ensure participant anonymity, all three-letter identifiers used during the data collection and analysis phase of this research project have been replaced with randomized, sequential participant numbers in the data made available as **Supplementary Materials 5** for transparent data reporting.

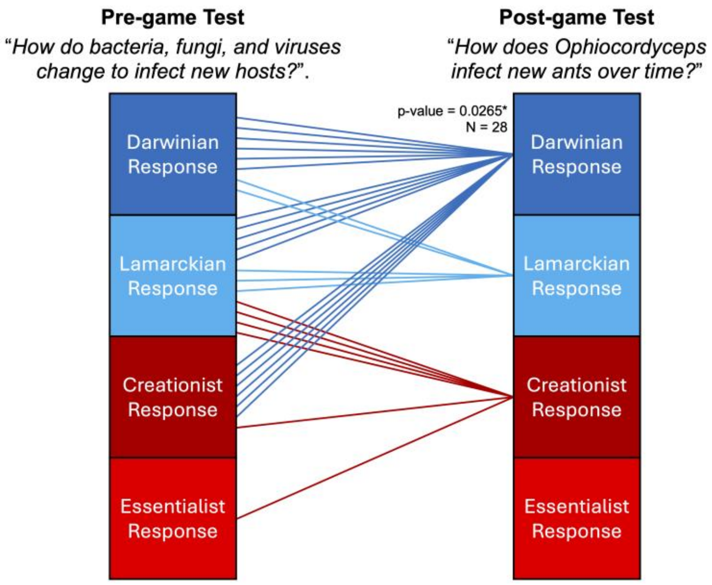
RESULTS

Does playing *Zombie Ants VR: Definitive Edition* improve evolution literacy?

The number of correct answers on the pre-game test was eight (28.6%) which significantly improved to 17 on the post-game test (60.7%, McNemar's p-value of 0.0265*; see **Figure 3**). A paired odds ratio test showed that this result was correlated with participants going from an incorrect response to a correct one after playing the game, which occurred 5.5 times more often than the inverse effect (5% confidence interval between 1.219 and 24.814). We further compared these results to our negative control test questions about disease transmission, which did not show any significant increase in correct responses (McNemar's test p-value of 0.7237 NS).

Figure 3

Learning outcomes for Zombie Ants VR: Definitive edition



Note: Results showed that out of 28 responses, only eight individuals answered with the correct Darwinian response on the pre-game questionnaire; however, after playing Zombie Ants VR: Definitive Edition, the number of correct responses improved to 17 (McNemar's p-value of 0.0265). While two participants who originally selected the correct response answered incorrectly on the post-game questionnaire, a Paired Odds Ratio tests showed that overall participants were 5.5 time more likely to improve in their understanding of evolution after playing the game (5% confidence interval between 1.219 and 24.814).*

Are preexisting views correlated with learning outcomes?

To test if a participant's preexisting understanding or acceptance of evolution was predictive of the choice they made after playing the game, we used a Chi-square test of independence (**Supplementary Materials 6**). Because some of the groups contained fewer than five participants, we used the Fisher's Exact Test variant. We were particularly interested to know if a player's preexisting non-scientific views were correlated with a corresponding non-scientific answer after playing the game. This was shown not to be the case with the Fisher's Exact Test for Count Data determining a lack of significant correlation between pre- and post-game answer types (p = 0.1212). Of the 28 participants who answered the evolutionary question on both questionnaires, 20 individuals provided a science-based response (71.4%) while seven participants gave creationist responses (25%), and one answered with an essentialist response (3.6%). Of those providing a scientific response, only eight (38.1%) gave the correct Darwinian response while the other 13 (61.9%) chose the Lamarckian response reflecting a misunderstanding of evolutionary principles. This suggests that nearly two thirds of our study participants who accept evolution misunderstand the process. After playing the game, 22 of the answers on the post-game questionnaire reflected scientific responses, suggesting only a marginal improvement in the overall number of scientific answers (71.4% to 78.6%). However, as was noted in the previous test, the number of correct Darwinian responses significantly increased. Six of these correct responses came from the seven

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participants who had previously selected creationist responses on the pre-game questionnaire, indicating that the game might be able to successfully teach evolutionary principles to those with creationist views.

Does age or prior experience with video games affect learning outcomes?

The group with the highest amount of video game experience in our study — with an average score of 3.6 out of 5.0 on a Likert scale — was 12 to 15-year-olds. This was much higher than other groups which all scored between 1.0 and 2.0. Despite this advantage, we saw an increase in the number of correct responses after playing the game in every age bracket, regardless of video game experience — with the exception of 22 to 30-year-olds for whom the number of correct answers remained the same (see **Table 2**).

Table 2

The relationship between learning outcomes and the age or average gaming experience of participants.

Age	Number of participants	Average gaming experience	Correct answers Pre-game	Correct answers post-game
12 – 15	8	3.6	1	4*
16 – 18	1	1.0	0	1*
19 – 21	2	1.0	0	1*
22 – 30	7	2.0	5	5
31 – 40	5	1.6	1	3*
> 40	6	1.5	1	3*

** Increase in overall number of correct answers*

Does level of education affect learning outcomes?

In our data, recent university graduates were the group with the highest ratio of initial correct answers. However, a person's level of education did not appear to significantly affect learning outcomes (see **Table 3**). Scores were improved across all groups, except for four-year university graduates and those who had obtained doctoral degrees for whom the number remained the same (see **Table 3**).

Table 3

The relationship between learning outcomes and prior education of participants.

Education	Number of participants	Correct answers Pre-game	Correct answers post-game
Elementary School	2	0	1*
Middle School	4	1	2*
University Preparatory Education	5	1	3*
2 Years University	1	0	1*
4 Years University	6	2	2
Master's Degree	7	1	5*
Doctoral Degree	4	3	3

** Increase in overall number of correct answers*

Does appreciation for nature affect learning outcomes?

Our collected data also suggest that there might be a positive correlation between a participant's interest in nature and their correct response on the post-game questionnaire. Individuals who indicated to have no appreciation for nature (answering "1" or "2" on a five-point Likert scale) did not appear to improve in their understanding of evolution after playing the game (see **Table 4**). Individuals with neutral responses (answering "3" on a five-point Likert scale) saw an increase in correct responses from 33% to 66%, while individuals who indicated that they appreciate nature (answering "4" or "5" on a five-point Likert scale) saw an increase in correct responses from 28.6% to 61.9%. However, our sample size was too small to demonstrate a significant effect (Spearman's rank correlation, $p = 0.6853$, $\varrho = 0.0786$).

Table 4

The relationship between learning outcomes and the participants' level of appreciation for nature.

Appreciation for Nature	Number of participants	Correct answers Pre-game	Correct answers post-game
1	1	0	0
2	1	0	0
3	6	2	4*
4	8	2	6*
5	13	4	7*

** Increase in overall number of correct answers*

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Does entertainment value affect learning outcomes?

Overall, participants stated that they enjoyed playing the game with an average score of 3.62 out of 5.00 on a five-point Likert scale, reflecting a slightly positive view. While the one participant that provided a neutral answer (answering "3" on a five-point Likert scale) did not improve their understanding of evolution, all other groups showed an increase in number of correct answers on the post-game questionnaire (see **Table 5**). This included an increase in correct answers from 30% to 65% among participants who viewed the game as enjoyable (answering "4" or "5" on a five-point Likert scale) and an increase from 25% to 50% for participants who viewed the game as unenjoyable (answering "1" or "2" on a five-point Likert scale).

Table 5

The relationship between learning outcomes and level of enjoyment experienced by participants during the game.

Enjoyed the game	Number of participants	Correct answers Pre-game	Correct answers post-game
1	3	1	2*
2	5	1	2*
3	1	0	0
4	11	3	8*
5	9	3	5*

** Increase in overall number of correct answers*

Does performance affect learning outcomes?

Analysis of the gameplay footage showed that the average completion time of the game was 00:12:58 (hours: minutes: seconds). To test if gameplay length could be correlated with learning outcomes, we used a logistic regression and Wilcoxon rank-sum test. In both cases, we found that length of gameplay was not a significant indicator of learning in our small sample size study (Logistic regression p-value of 0.331 and a Wilcoxon rank-sum p-value of 0.3938). While we hypothesized that a longer gameplay experience would result in greater odds of positive outcomes, we found that the average amount of time played by individuals who answered incorrectly on the post-game questionnaire was actually longer than those who chose the correct response by nearly two minutes (111.5 s; see **Supplementary Materials 5**). This finding was consistent when only including individuals who fully completed the game as well (Logistic regression p-value of 0.597 and Wilcoxon rank-sum p-value of 0.7544). Our small dataset also did not show a possible association between the number of mistakes made and an individual's learning outcome (4.59 on average with a median of 4 and a mode of 3; Logistic regression p-value of 0.600 and Wilcoxon rank-sum p-value of 0.3831 for full dataset, 0.964 and 0.7202 for data limited to complete runs).

DISCUSSION

By using trial-and-error gameplay mechanics — as opposed to traditional informational prompts — to teach players about the process of evolution, *Zombie Ants VR: Definitive Edition* significantly improved evolution literacy in our small sample size study, regardless of players' age, education level, (previous) gaming experience, and appreciation for nature. We found this result to be true for both participants who answered with a scientific but incorrect answer on the pre-game questionnaire as well as for those who initially provided non-scientific answers. In total, six out of the seven participants who answered with a creationist response on the pre-game questionaries changed their response to the correct Darwinian view after playing the game. At the same time, five out of the 11 participants who answered with a Lamarckian view on their pre-game questionnaires changed their answer to the correct Darwinian answer response after playing the game. These results suggest that *Zombie Ants VR: Definitive Edition* has been successful in its goal of addressing misconceptions about the process of evolution in the context of infectious disease without explicitly explaining the theory in our small study group.

While none of the participants who answered with a Darwinian response in the pre-game questionnaire changed their answer to a non-scientific choice, two did change their answers to the Lamarckian response. This could be indicative of a counterproductive outcome from playing the game. Though, this small number could also be explained by guesswork, a common characteristic of survey data (Ward & Meade, 2023). While, ideally, we do not want anyone to change their answer from a correct understanding of evolution to an incorrect one, the much higher degree of improvement compared to regression suggests that playing the game had an overall positive educational impact (Botes, 2022; Islam et al., 2026).

In addition to validating the educational potential of gamification techniques and VR technology, our study also helps illuminate other issues pertaining to the state of evolution literacy in our community. While the Netherlands has comparatively higher rates of scientific literacy and acceptance of evolutionary principles than other countries like the United States of America (Miller et al., 2006), our study shows that only about a third of

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participants correctly understood these evolutionary principles (Muciaccia & Macchia, 2025). When combined with the non-scientific responses, only about a quarter of participants properly understood evolution to a degree required for educated decision making with regards to public health. This provides further evidence that a mere acceptance of evolution is not necessarily correlated with an understanding of evolution (Winning, 2018) and highlights a greater need for additional public outreach efforts, even in countries where science is more generally accepted (Yurtseven & Altun, 2015).

Our study also suggests that gamification and VR can be used for inclusive biology education when the gameplay is designed to match a deliberate teaching goal (Webb, 2026; Garbe et al., 2020). Our target audience was originally children and young adults ages 12 to 22 to spark fascination for the natural world and science during their formative teenage years when these interests tend to wane (Bonnette, 2019; Potvin & Hasni, 2014). However, we found that the game had a positive educational impact on nearly all participants, regardless of age or experience with video games. While we noticed that older players typically needed more time to get used to the controls for the game, many participants who kept with it and completed large portions of the game appeared to have benefited from the desired learning outcomes. As such, our preliminary findings provide additional support for the use of gamification techniques to educate a diverse audience outside of traditional academic settings.

Furthermore, while our study did not provide any metrics for the comradery or group learning offered by displaying participants' gameplay on the screen during the exhibit, the collaborative learning that appeared to occur between families and friend groups who played the game together was noteworthy. Parents who were watching their children playing *Zombie Ants VR*: *Definitive Edition* would frequently ask the researchers conducting the experiment about the biology portrayed in the game. Quite often, just instilling inherent curiosity to the level of genuine inquiry and establishing a personal level of communication is the biggest barrier facing science outreach. Creating a tool that is entertaining enough to permeate that barrier is, in itself, a valuable resource for science communication.

LIMITATIONS

Despite our efforts to showcase *Zombie Ants VR: Definitive Edition* to a large audience of museum attendees across multiple successive weekends, we were only able to collect and analyze data from 28 participants for this study. This was due in part to the fact that most kids who attended the museum with their families were too young to participate. These kids were excited to try out the game nonetheless, which we encouraged. As such, the statistical power of the study is limited, and its significant findings should not be casually generalized to a broader population. However, this study does present a promising positive correlation between our educational VR approach and improved evolution literacy. This suggests that further exploration of the educational value of the game, particularly with additional demographics, would be worthwhile.

This small sample size study was conducted in the Netherlands with museum attendees at the UMU. Because UMU largely caters to young families as their target audience, our data set has a bimodal distribution of participants skewing towards children (ages 12 to 15) and older adults (30+). It is also important to note that we intentionally did not collect data on sex, nationality, or residence status of study participants to provide a greater feeling of inclusion and safety for study participants. We therefore cannot draw any conclusions about demographics variables beyond age. We can however make inferences about the nationality of participants based on their voluntary selection of Dutch as the primary language for gameplay. From this information, we infer that most participants in this study were Dutch. Our results thus largely reflect the current state of scientific literacy in the Netherlands. Other studies seeking to draw upon and repeat our work should consider the socio-political situation in other nations as an attenuating factor.

Furthermore, because we conducted our study with a limited number of museum attendees, it is possible that our data skews more towards scientifically inclined portions of the general population. This may have impacted the relative ratio of DL answers to CE answers on our pre-gameplay questionnaire and may not be an accurate representation of the general views of people from the Netherlands. The gallery style limitations of the museum environment where attendees do not spend much time at each exhibit also limited the learning objectives that we could test. For this reason, our questionnaires were designed to be intentionally short and focused on testing one learning objective — the process of evolution. This study therefore does not include any test data for the secondary learning objectives of the game pertaining to the pathogenic life cycle of behavior-manipulating fungi and the social structure of ants.

Finally, the survey data collected in this study was analyzed under the assumption that participants fully understood the meaning of each possible response to the evolution questions. Without controls for ensuring participants' understanding of the intended meaning for each question, it is possible that some answers were given with a different interpretation of the text. We did not incorporate such controls because discussing, for example, any information that may stem from a participant's religious or political background could have elicited the very defensive responses that we sought to circumvent. Furthermore, the fast-paced museum format of the study also limited our ability to have participants explain their answers in a longer written response format. We therefore cannot be certain that participant responses accurately reflect conceptual knowledge or if they are skewed by one's ability to express that knowledge correctly or discern written descriptions within the parameters of this study.

Due to these limiting factors, we encourage readers to view our findings as a positive trend for improved understanding of evolutionary principles — particularly for younger and older audiences. More work with a larger and more diverse samples size is needed to confirm these effects are not due to local confounding variables. Furthermore, because different countries and different cultures have different baseline understandings of evolutionary concepts, future studies examining the effectiveness of *Zombie Ants VR: Definitive Edition* — or other forms of outreach activities that seek to provide a safe space for connecting with the community about charged topics using a fictional platform — are necessary to understand the full effects that such an approach may have on learning. With *Zombie Ants VR: Definitive Edition* freely available for use (Web Links 4 and 5), we encourage other educators to use the game and continue testing the effectiveness of the game both in and out of the classroom.

CONCLUSIONS

The results from our project suggest that gamification, particularly the use of trial-and-error mechanics, can be used to teach the process of evolution within the context of infectious disease in a way that does not conflict with people's preexisting political or religious views. This makes gamification a powerful tool capable of improving science literacy, both in the classroom and in the greater community. By understanding how evolution contributes to disease transmission dynamics and the emergence of new thermotolerant and antimicrobial-resistant pathogens, we hope that educated individuals will be able to make better public health decisions in the future.

Acknowledgement

We would like to thank the Utrecht University Science-Geosciences Ethics Review Board for their careful consideration of our project during the approval process, the Utrecht University Studio 041 for use of their recording equipment, and the University Museum Utrecht for hosting our exhibit to test *Zombie Ants VR: Definitive Edition*. We would also like to thank the Orlando Science Center for inviting us to test the alpha version of the game at their annual Otronicon event. Additionally, we would like to thank the many individuals who have contributed to the creation of the game along the way, in no particular order: Programmers: Sebastian Saavedra, Brian Flores, and Noah Jervey; Art & Animation: Mykolas Metelionis, Alana Brunson, Roman Starner, Audrey Luce, Jaeline Sanchez, Alexander Grant, Colby Breitenbach, Clarisse Cockrill, and Meaghan Archer; Audio & Music: Be Boyd, Kimber King, Drew Stark, Ezra Koppenjan, Bregje de Berg, Thomas Harrison, and Nikhil Desai.

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Ethical statement

Gameplay testing of the pilot version (alpha testing) of *Zombie Ants VR* received internal review board approval from the University of Central Florida. Testing the educational merit of the definitive edition (beta testing) received approval from the Utrecht University's internal Science-Geosciences Ethics Review Board to be conducted at the UMU. Both oversight bodies adhere to international standards for testing educational intervention with human subjects and ensured our project methodology was aligned with international ethics standards for research involving children. Specifically, the Science-Geosciences Ethics Review Board provides professional and independent reviews of research proposals involving human subjects and advises on ethical and privacy issues. They primarily review studies that do not fall under the scope of the Dutch Medical Research involving Human Subjects Act (Wet medisch wetenschappelijk onderzoek met mensen). The committee had no

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objections to the research activities as described in our proposal titled *Zombie Ants VR: Using virtual reality to engage the public and improve science literacy*, which was approved on April 18th, 2025. The resulting research project was then carried out in the month of June 2025. By securing ethics approval for both stages of the game's development, we met the due diligence and required standards for participant safety, data handling, and scientific integrity.

Competing interests

The authors of this manuscript were directly involved in the creation of *Zombie Ants VR: Definitive Edition*. However, the game has been made freely accessible as an education tool and does not provide any financial benefit to any of the authors. The promotion of the game in this paper is thus free from any financial conflict of interest.

Author contributions

Conceptualization: WCB, JM, CdB; Methodology: WCB, MG, CdB; Software: BJM, NSC; Validation: WCB, MG, CdB; Formal Analysis: WCB; Investigation: WCB, MG, BJM, CdB; Resources: WCB, CdB; Data Curation: WCB; Writing – Original Draft: WCB; Writing – Review & Editing: WCB, MG, BFM, NSC, JM, CdB; Visualization: WCB, BJM, NSC; Supervision: WCB, NSC, JM, CdB; Project Administration: WCB, NSC, JM, CdB; Funding Acquisition: WCB, CdB

Data availability

The data acquired and used for statistical analyses in this study is provided as **Supplementary Materials 5**. The educational VR game that we developed and tested as part of this study is freely available and can be downloaded from Steam (Web Link 4) or the Meta Quest Store (Web Link 5).

AI disclosure

The only use of AI in this project was to assist in the creation of R-code used for statistical analysis of the data, provided as **Supplementary Materials 6**. Furthermore, AI was not used in the writing of this manuscript in accordance with the ethical guidelines of the European Journal of STEM Education.

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SUPPLEMENTARY MATERIALS 1. VOICE ACTING LINES

Fungal parasite internal monolog lines:

###Player begins spore freefall### Line EP1
Hey it's me, your fungal hive mind. Try not to get us killed straight away, ok? Should be easy enough in our current protective spore form, but we'll need to land on a host if we want to gain some mobility. Aim for one of those ants down there!

###Player fails spore freefall### Line EP2
I'm impressed, not gunna lie. It takes a lot of skill to die in the first 60 seconds of the simulation…

####Player enters the ant### Line EP3
Well I'll be. You actually did it. Gotta say, I had my doubts, but the challenges have just begun. Let's try out our new legs, shall we?

###Player finishes tutorial on how to move the ant### Line EP4
Took you long enough, I nearly jumped to another host out of shear boredom. Anyway, now that we have firm control over our host, let's try to find the nest!

Line EP5
Obviously, how do you think we are controlling this ant right now.

###Player approaches nest entrance### Line EP6
Uh oh, majors. If they smell our presence we're done fore. Play it cool while they check out our host with their antenna.

###Player fails mirroring game### Line EP7
well, that was… disappointing. You'd think after millions of years of evolution our species would have produced a spore capable of fooling a single major. Better luck with the next spore I guess.

###Player completes mirroring game### Line EP8
Shew that was close. What is this, your first time in an ant!? I've seen bread molds do a better job than that!

###Player finds nursing chamber#### Line EP9
We must be getting close to the queen. Just look at all these juicy larvae just waiting to be infected! Tasty!

Line EP10
Hey, do you sense that? We are spreading quicker than I thought. If we stay much longer they'll be onto us! Quick, do your thing and get us outta here!

###Player stays in the nest and is detected### Line EP11
I told yah they were onto us. As we spread through our host, the ant's scent changes, making us more likely to be detected. I hope the next spore actually LISTENS to my advice...

OUTCOME BASED:
###Virulence selected too low### Line EP12
Can you feel it? The host… its… fighting back… we cant… hold…on…

###Virulence selected just right### Line EP13
Can you feel it? The final stages have begun. That tree looks like as good a place as any to complete the cycle. Quick you fool, use the rest of the host's energy to climb!

###Virulence selected too high### Line EP14
Oh no, I fear we've been burning the candle at both ends. We've siphoned too much energy from our host and she's outta gas… what a disappointing end.

###Player moves to branch### EP15
This is it! Directing all energy towards the growth of our fruiting body!

Narrator lines:

###Player selects begin### Line EN1
The life cycle of Ophiocordyceps fungi is unusual but quite fascinating. The choices you make during this simulation will determine if you are able to survive and reproduce. Make the wrong choice or fail to execute and you'll have to start all over as a new spore… But complete the life cycle and you'll learn what it takes to be a 'Zombie Fungus'!

###Player lands on ant### EN2
As the Zombie fungus finds its new host, it must emerge from its spore coat and enter the exoskeleton of the ant

###Player moves toward the nest### EN3
Fungal pathogens like Ophiocordyceps are known for secreting many chemicals during infection, some of which can manipulate the host's behavior!

###Player continues towards the nest### Line EN4
Carpenter ants are social insects, working together in colonies and performing different roles.

###Player starts mirroring game### Line EN5
Ants communicate with one another through sense of smell, among other things. Using pheromones, they can tell one another where to find food, notify others of impending danger, and even smell if an ant is sick. To prevent the spread of any diseases to the rest of the nest, sick ants are promptly…. Terminated…

Line EN6
There are four types of carpenter ants, also known as castes.

Line EN7
These are the drones, the only males in the nest, which are the smallest ants and have tiny wings.

Line EN8
And here are the workers, who collect resources and tend to the larvae of the nest.

Line EN9
Those are the majors, I believe you've met a few of these large guardians already.

###Player finds the queen### EN10a-b
And alas! there is the queen, in all her royal glory! Contrary to popular belief, this massive ant is not responsible for ruling the nest, but rather focuses on the important task of laying all the eggs. Eggs become larvae, larvae become pupae, and pupae undergo metamorphosis to become a brand-new ant for the colony!

###Player stays in the nest and finds refuse pile### Line EN11
Ants are quite civilized creatures. They store their trash, along with the husks of dead ants in a location called a "refuse pile". You can think of it as a sort of landfill-graveyard combo!

###Player leaves the nest### Line EN12

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One of the most common behavioral manipulations is climbing. By enticing the ant to a higher location, the fungus can spread its spores much further on the wind. Scientists call this 'Summit Disease'.

###Player heads towards tree### Line EN13
Even though these carpenter ants are nocturnal, infected ants are often found during the day! A likely result of compounds secreted by the fungal parasite to keep their hosts awake!

###Player reaches the top of the tree### Line EN14
Alas, the fungus directs its host to the very tip of the branch to complete its life cycle with one final manipulation… THE DEATH GRIP

###Player bites onto branch### EN15a-d
"Congratulations! You have successfully completed one life cycle as the Zombie Fungus, Ophiocordyceps! Just like in the game, sometimes these fungi are unsuccessful in real-life. It is only the few spores that do everything just right that form the next generation. Over time, the Ophiocordyceps species as a whole has learned how to best infect its ant hosts through this process of trial and error, life and death. "

SUPPLEMENTARY MATERIALS 2. PRE-GAME QUESTIONNAIRE

Pre-game questionnaire

What is your 3-letter code?

< Open response question>

To which age group do you belong?

- 12-15
- 16-18
- 19-21
- 22-30
- 31-40
- 41-50

Which of the following best describes how bacteria, fungi, and viruses change to infect new hosts?

- They learn how to better infect new hosts through experience.
- They change randomly with only the strongest infecting new hosts.
- They don't change, the hosts become easier to infect.
- They don't change; they are designed to infect new hosts.

How do most bacteria, fungi, and viruses infect human hosts?

- Most get in through our skin and into the bloodstream.
- Most enter through our eyes, nose, or mouth.
- Most are already in our bodies but change to make us sick.
- Most randomly appear in our bodies.

How much do you enjoy nature?

- Not at all
- Not very much
- An average amount
- More than average
- A lot

How often do you play video games?

- Not very often
- 1-3 days per week
- 4-6 days per week
- Almost every day

What is your current level of education?

- Middle school
- Preparatory vocational secondary education (VMBO)
- Senior general secondary education (HAVO)
- University preparatory education (VWO)
- 2 years university
- 4 years university
- Master's degree
- Doctoral degree
- Elementary School

SUPPLEMENTARY MATERIALS 3. POST-GAME QUESTIONNAIRE

Post-game questionnaire

What is your 3-letter code?

< Open response question>

How well was the game made?

- It is very bad
- It is not very good
- It is average
- It is pretty good
- It is very good

How difficult was the game for you?

- Very hard
- Somewhat hard
- Average
- Somewhat easy
- Very easy

How does Ophiocordyceps infect new ants over time?

- Each spore learns how to better infect new hosts over time
- Each spore tries to infect new hosts, but only the successful ones survive
- The ants become easier to infect over time
- Spores are designed to be able to infect new hosts

How does Ophiocordyceps infect ants?

- The spores enter through the shell of the ant
- The spores enter through weak spots in the ant
- The spores appear inside the ants at random
- The spores already exist in the ants and change to infect them

How did you enjoy the game?

- It was very fun
- It was pretty fun
- It was ok
- It was kind of boring
- It was very boring

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SUPPLEMENTARY MATERIALS 4. CONSENT FORM

Consent form (English)

Participation of minors:

Children between 12 and 18 years old will require the following consent to participate:

- Their parent/legal guardian consents to their participation in the study.
- The child provides a verbal yes confirming their interest in playing the VR game.
- The parent/legal guardian has confirmed that their child does not have a history of epilepsy or uses a pacemaker.

Health and safety information:

Ensure you are able to safely use the product
You should not participate in this study if you have any serious health conditions that affect your ability to safely perform physical activities (such as a heart ailment), if you have any psychiatric conditions (such as anxiety disorders or post-traumatic stress disorder), or if you are pregnant. Virtual Reality products can also emit radio waves that can interfere with the operation of nearby electronic devices. Therefore, if you have a cardiac pacemaker or other implanted medical device, please do not participate.

Photosensitive seizures
Virtual Reality simulations can trigger epileptic seizures, seizures, fainting, or severe dizziness even in people who have no history of these conditions. Participants should not have a previous history of epilepsy or seizures, loss of awareness, or other symptoms linked to an epileptic condition.

Repetitive stress injuries
When playing the game, make sure that you are sitting in a comfortable position. Do not grip the product too tightly, press the buttons lightly, and if you have tingling, numbness, stiffness, throbbing, or other discomfort, immediately stop playing the game.

Physical and psychological effects
Content viewed using the product can be intense, immersive, and appear very life-like and may cause your brain and body to react accordingly. If they have a history of negative physical or psychological reactions to certain real-life circumstances, particularly pertaining to insects, you should not participate.

Explanation of research project:

Title of Project: Zombie Ants VR: Teaching the public about disease through gamification of microbiology concepts

Principal Investigators: William C. Beckerson and Charissa de Bekker

Research Goals: The purpose of this research project is to learn if the game Zombie Ants VR (Virtual Reality) is effective in teaching participants about topics in biology. The information learned through playing the game is based on a real natural phenomenon and our own biological research.

Participation: You will be asked to play the Virtual Reality game Zombie Ants VR using the VR headset and setup that we provide. Before and after playing the game, you will also be asked to answer a 5-10 minute questionnaire about your experience.

Data: In addition to the data from your survey answers, we will also record your gameplay footage. Your participation in this study is voluntary and you are free to withdraw your consent and discontinue participation in this study at any time. No identifiable private information will be collected as part of this study.

Study contacts for questions about the study or to report a problem: If you have questions, concerns, or complaints, please contact Dr. William C. Beckerson, MSCA Postdoctoral Research Fellow, Department of Biology, Utrecht University w.c.beckerson@uu.nl

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Ethics Review Board contact about your rights in this study or to report a complaint: If you have questions about your rights as a research participant, or have concerns about the conduct of this study, please contact The Ethics Review Board of Utrecht University at etc-beta-geo@uu.nl

Frequently asked questions:

Will being in this study help me in any way?

There are no benefits to you from your taking part in this research other than that you hopefully enjoy playing the game and learning about zombie ants. We cannot promise any benefits to others from your taking part in this research. However, possible benefits to others include the further development and free availability of an educational game that teaches students about biology.

What happens if I do not want to be in this research?

Participation in research is completely voluntary. You can decide to participate or not to participate.

What happens if I say yes, but I change my mind later?

You can leave the research at any time. If you decide to withdraw from the research, the data collected to the point of withdrawal will be removed from our data analyses.

What happens to the information collected during this research?

Data collected will be limited for use by professionals trained for review such information. Because no identifying information will be collected, your data will be assigned a numerical value in case you wish to withdraw from the study. Organizations that may inspect the information we collect for educational purposes. Data will be retained on an encrypted hard drive for a minimum of 5 years after the study.

Can I be removed from the research without my consent?

Although unlikely, the person in charge of the research can remove you from the research study without your approval. Possible reasons for removal include errors with the data collection or incomplete data.

What else do I need to know?

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Signature Block for Capable Adult

Your signature documents your permission to take part in this research.	
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Printed name of subject or legal guardian	
Signature of person obtaining consent	Date
Printed name of person obtaining consent	

SUPPLEMENTARY MATERIALS 5. DATA

Player	Age	Evo-lution Pre	Evo-lution PreType	Trans-mission Pre	Nature	Gaming	Education	Diffi-culty	Evo-lution Post	Evo-lution Post Type	Trans-mission Post	Enjoy	Game play Length	Mis-takes	Finish

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Participant 1	22 - 30	1	D	1	3	1	Doctoral degree	3	1	D	0	4	329	2	0
Participant 2	16 - 18	0	L	1	4	1	Middle school	4	1	D	1	4	805	6	1
Participant 3	19 - 21	0	C	1	5	1	University preparatory education (VWO)	4	1	D	1	4	262	1	0
Participant 4	> 40	0	C	1	5	1	2 years university	3	1	D	0	4	319	2	0
Participant 5	31 - 40	0	C	1	3	2	Master's degree	4	1	D	1	5	835	9	1
Participant 6	31 - 40	1	D	1	3	1	Doctoral degree	4	1	D	0	5	378	8	1
Participant 7	> 40	1	D	1	5	1	Doctoral degree	3	1	D	1	5	987	3	1
Participant 8	> 40	0	L	1	5	1	Master's degree	5	0	L	1	4	271	3	0
Participant 9	> 40	0	L	0	4	4	Master's degree	4	1	D	1	4	202	2	0
Participant 10	> 40	0	L	0	3	1	Master's degree	4	0	C	0	5	1086	8	1
Participant 11	31 - 40	0	L	1	4	1	Master's degree	3	1	D	1	5	769	5	1
Participant 12	22 - 30	1	D	0	5	2	Master's degree	2	1	D	0	4	198	1	0
Participant 13	22 - 30	0	L	1	5	3	4 years university	3	0		0	4	903	9	1
Participant 14	12 - 15	0	C	1	4	2	Middle school	3	1	D	1	4	719	3	1
Participant 15	22 - 30	1	D	0	5	2	Middle school	3	0	L	0	5	711	7	1
Participant 16	31 - 40	0	C	1	5	3	4 years university	3	0	C	1	5	794	4	1
Participant 17	22 - 30	0	L	0	5	3	Master's degree	3	1	D	0	5	628	6	1
Participant 18	22 - 30	1	D	1	5	2	4 years university	2	1	D	1	4	622	4	1
Participant 19	19 - 21	0	L	0	1	1	4 years university	4	0	L	1	5	363	3	0
Participant 20	> 40	0	L	1	2	1	Doctoral degree	1	0	C		3	664	3	0
Participant 21	12 - 15	0	C	0	5	4	University preparatory education (VWO)	1	1	D	1	1	1109	12	1
Participant 22	12 - 15	0	E	0	3	4	Elementary School	2	0	C	0	2	776	8	1
Participant 23	12 - 15	0	C	1	4	4	Elementary School	3	1	D	1	1	616	3	1
Participant 24	22 - 30	1	D	1	4	1	4 years university	4	1	D	1	2	518	2	1
Participant 25	31 - 40	0	L	1	5	1	4 years university	2	0	C	1	4	555	3	1
Participant 26	12 - 15	0	L	1	5	4	Middle school	3	0	L	1	2	756	0	1
Participant 27	12 - 15	0	L	1	4	3	University preparatory education (VWO)	3	0	C	1	2	792	6	1
Participant 28	12 - 15	0	L	1	3	4	University preparatory education (VWO)	2	1	D	0	2	907	5	1
Participant 29	12 - 15	1	D	1	4	4	University preparatory education (VWO)	2	0	L	1	1	668	5	1

SUPPLEMENTARY MATERIALS 6. R-CODE

```
### Test for improved scores on evolution answers ###
# 1) Make sure the two columns are numeric 0/1 and drop NAs
df <- within(LearningZAVR, {
  EvolutionPre  <- as.numeric(as.character(EvolutionPre))
```

```
  EvolutionPost <- as.numeric(as.character(EvolutionPost))
})
df <- subset(df, !is.na(EvolutionPre) & !is.na(EvolutionPost))

# 2) 2x2 contingency table
tab <- table(
  factor(df$EvolutionPre,  levels = c(0,1), labels = c("Pre0","Pre1")),
  factor(df$EvolutionPost, levels = c(0,1), labels = c("Post0","Post1"))
)
cat("\nContingency table (Pre x Post):\n"); print(tab)

# Extract cell counts
a <- tab["Pre0","Post0"]; b <- tab["Pre0","Post1"]
c_ <- tab["Pre1","Post0"]; d <- tab["Pre1","Post1"]

# 3) Descriptive counts
n <- sum(tab)
improved  <- b
worsened  <- c_
same      <- a + d
pre_correct  <- sum(df$EvolutionPre == 1)
post_correct <- sum(df$EvolutionPost == 1)

cat(sprintf("\nN = %d\n", n))
cat(sprintf("Improved (0→1): %d (%.1f%%)\n", improved, 100*improved/n))
cat(sprintf("Worsened (1→0): %d (%.1f%%)\n", worsened, 100*worsened/n))
cat(sprintf("Unchanged:       %d (%.1f%%)\n", same,     100*same/n))
cat(sprintf("Pre correct:  %d (%.1f%%)\n", pre_correct,  100*pre_correct/n))
cat(sprintf("Post correct: %d (%.1f%%)\n", post_correct, 100*post_correct/n))
cat(sprintf("Change in %% correct: %.1f%%\n",
            100*(post_correct - pre_correct)/n))

# 4) McNemar's test
mc <- mcnemar.test(tab)
cat("\nMcNemar's test:\n")
print(mc)

# 5) Manual odds ratio and CI (Woolf method)
or <- b / c_
se_log_or <- sqrt(1/b + 1/c_)
ci_low <- exp(log(or) - 1.96 * se_log_or)
ci_high <- exp(log(or) + 1.96 * se_log_or)

cat(sprintf("\nPaired Odds Ratio (improve vs worsen): %.3f\n", or))
cat(sprintf("95%% CI: [%.3f, %.3f]\n", ci_low, ci_high))

### Association between pre- and post-game answers ###
# 1) Drop rows where either Pre or Post is missing
df <- subset(LearningZAVR, !is.na(EvolutionPreType) & !is.na(EvolutionPostType))

# 2) Simple counts for Pre and Post separately
pre_counts  <- table(na.omit(LearningZAVR$EvolutionPreType))
post_counts <- table(na.omit(LearningZAVR$EvolutionPostType))

cat("\nCounts of answers on Pre test:\n")
print(pre_counts)

cat("\nCounts of answers on Post test:\n")
```

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```
print(post_counts)

# 3) Full contingency table (Pre x Post)
tab <- table(df$EvolutionPreType, df$EvolutionPostType)
cat("\nContingency table (PreType x PostType):\n")
print(tab)

# 4) Fisher's Exact Test
fisher_result <- fisher.test(tab)
cat("\nFisher's Exact Test:\n")
print(fisher_result)

# 5) Cramér's V
if (!requireNamespace("lsr", quietly = TRUE)) install.packages("lsr")
library(lsr)

cv <- cramersV(tab)
cat(sprintf("\nCramér's V: %.3f (0 = no association, 1 = perfect association)\n", cv))

### Answers by age and experience with gaming ###
# Drop rows with missing values
df <- subset(LearningZAVR, !is.na(Age) & !is.na(Gaming) &
             !is.na(EvolutionPre) & !is.na(EvolutionPost))

# Summarise sums of EvolutionPre and EvolutionPost
agg_table <- aggregate(
  cbind(EvolutionPre, EvolutionPost) ~ Age,
  data = df,
  FUN = sum
)

# Calculate average Gaming per Age
avg_gaming <- aggregate(Gaming ~ Age, data = df, FUN = mean)

# Calculate participant count per Age
count_participants <- aggregate(Gaming ~ Age, data = df, FUN = length)
colnames(count_participants)[2] <- "Participants"

# Merge all summaries
result <- merge(merge(agg_table, avg_gaming, by = "Age"), count_participants, by = "Age")

# Round average gaming
result$Gaming <- round(result$Gaming, 2)

# Reorder columns: Age, Participants, Gaming, EvolutionPre, EvolutionPost
result <- result[, c("Age", "Participants", "Gaming", "EvolutionPre", "EvolutionPost")]

cat("\nSum of EvolutionPre and EvolutionPost by Age + Average Gaming + Participants:\n")
print(result)

### Answers by appreciation for nature ###
# Drop rows with missing values for Nature
df_nature <- subset(LearningZAVR, !is.na(Nature) & !is.na(Gaming) &
                    !is.na(EvolutionPre) & !is.na(EvolutionPost))

# Sum of EvolutionPre & EvolutionPost by Nature
nature_sums <- aggregate(
  cbind(EvolutionPre, EvolutionPost) ~ Nature,
```

```
  data = df_nature,
  FUN = sum
)

# Average Gaming per Nature
nature_gaming <- aggregate(Gaming ~ Nature, data = df_nature, FUN = mean)

# Count of participants per Nature
nature_count <- aggregate(Gaming ~ Nature, data = df_nature, FUN = length)
colnames(nature_count)[2] <- "Participants"

# Merge all
nature_result <- merge(merge(nature_sums, nature_gaming, by = "Nature"), nature_count, by = "Nature")

# Round Gaming
nature_result$Gaming <- round(nature_result$Gaming, 2)

# Reorder columns: Nature, Participants, Gaming, EvolutionPre, EvolutionPost
nature_result <- nature_result[, c("Nature", "Participants", "Gaming", "EvolutionPre", "EvolutionPost")]

cat("\n=== Table: By Nature ===\n")
print(nature_result)

### Spearman correlation: Nature vs Pre-game answers ###

# Drop missing values
df <- subset(LearningZAVR, !is.na(Nature) & !is.na(EvolutionPre))

# Convert Nature to numeric if it isn't already
df$Nature <- as.numeric(as.character(df$Nature))

# Spearman's rank correlation
cor_result <- cor.test(df$Nature, df$EvolutionPre, method = "spearman")

cat("Spearman's rank correlation between Nature and EvolutionPre:\n")
print(cor_result)

### Answers by how much they enjoyed the game ###
# Drop rows with missing values for Enjoy
df_enjoy <- subset(LearningZAVR, !is.na(Enjoy) & !is.na(Gaming) &
                    !is.na(EvolutionPre) & !is.na(EvolutionPost))

# Sum of EvolutionPre & EvolutionPost by Enjoy category
enjoy_sums <- aggregate(
  cbind(EvolutionPre, EvolutionPost) ~ Enjoy,
  data = df_enjoy,
  FUN = sum
)

# Average Gaming per Enjoy category
enjoy_gaming <- aggregate(Gaming ~ Enjoy, data = df_enjoy, FUN = mean)

# Count of participants per Enjoy category
enjoy_count <- aggregate(Gaming ~ Enjoy, data = df_enjoy, FUN = length)
colnames(enjoy_count)[2] <- "Participants"

# Merge all
enjoy_result <- merge(merge(enjoy_sums, enjoy_gaming, by = "Enjoy"), enjoy_count, by = "Enjoy")
```


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```
# Round Gaming
enjoy_result$Gaming <- round(enjoy_result$Gaming, 2)

# Reorder columns: Enjoy, Participants, Gaming, EvolutionPre, EvolutionPost
enjoy_result <- enjoy_result[, c("Enjoy", "Participants", "Gaming", "EvolutionPre", "EvolutionPost")]

cat("\n=== Table: By Enjoy category ===\n")
print(enjoy_result)

### Answers by prior education ###
# Drop rows with missing values for Education
df_edu <- subset(LearningZAVR, !is.na(Education) &
                 !is.na(EvolutionPre) & !is.na(EvolutionPost))

# Sum of EvolutionPre & EvolutionPost by Education
edu_sums <- aggregate(
  cbind(EvolutionPre, EvolutionPost) ~ Education,
  data = df_edu,
  FUN = sum
)

# Count of participants per Education
edu_count <- aggregate(EvolutionPre ~ Education, data = df_edu, FUN = length)
colnames(edu_count)[2] <- "Participants"

# Merge sums with counts
edu_result <- merge(edu_sums, edu_count, by = "Education")

# Reorder columns: Education, Participants, EvolutionPre, EvolutionPost
edu_result <- edu_result[, c("Education", "Participants", "EvolutionPre", "EvolutionPost")]

cat("\n=== Table: By Education ===\n")
print(edu_result)

### Correct post-game answer by gameplay length ###
#Logistic regression#

# Toggle: set to TRUE to only include data from completed runs, FALSE to use all data
use_finish_filter <- FALSE

# Filter dataset based on toggle
if (use_finish_filter) {
  df <- subset(LearningZAVR, Finish == 1 & !is.na(GameplayLength) & !is.na(EvolutionPost))
} else {
  df <- subset(LearningZAVR, !is.na(GameplayLength) & !is.na(EvolutionPost))
}

# Ensure correct data types
df$GameplayLength <- as.numeric(df$GameplayLength)
df$EvolutionPost <- as.numeric(as.character(df$EvolutionPost))

# Logistic regression
model <- glm(EvolutionPost ~ GameplayLength, data = df, family = binomial)

cat("Logistic regression result:\n")
summary(model)
```

```
#Wilcoxon rank-sum test#

# Toggle: set to TRUE to only include data from completed runs, FALSE to use all data
use_finish_filter <- FALSE

# Filter dataset based on toggle
if (use_finish_filter) {
  df <- subset(LearningZAVR, Finish == 1 & !is.na(GameplayLength) & !is.na(EvolutionPost))
} else {
  df <- subset(LearningZAVR, !is.na(GameplayLength) & !is.na(EvolutionPost))
}

# Ensure correct data types
df$GameplayLength <- as.numeric(df$GameplayLength)
df$EvolutionPost <- as.numeric(as.character(df$EvolutionPost))

# Wilcoxon rank-sum test
wilcox_result <- wilcox.test(GameplayLength ~ EvolutionPost, data = df)

cat("Wilcoxon rank-sum test result:\n")
print(wilcox_result)

# Also show medians for each group
medians <- tapply(df$GameplayLength, df$EvolutionPost, median)
cat("\nMedian GameplayLength by EvolutionPost:\n")
print(medians)

### Correct post-game answer by number of mistakes made during gameplay ###
#Logistic regression#

# Toggle: set to TRUE to only include data from completed runs, FALSE to use all data
use_finish_filter <- TRUE  # toggle for Finish filter

if (use_finish_filter) {
  df <- subset(LearningZAVR, Finish == 1 & !is.na(Mistakes) & !is.na(EvolutionPost))
} else {
  df <- subset(LearningZAVR, !is.na(Mistakes) & !is.na(EvolutionPost))
}

df$Mistakes <- as.numeric(df$Mistakes)
df$EvolutionPost <- as.numeric(as.character(df$EvolutionPost))

model <- glm(EvolutionPost ~ Mistakes, data = df, family = binomial)

summary(model)

#Wilcoxon rank-sum test#

wilcox_result <- wilcox.test(Mistakes ~ EvolutionPost, data = df)
print(wilcox_result)

medians <- tapply(df$Mistakes, df$EvolutionPost, median)
cat("\nMedian Mistakes by EvolutionPost:\n")
print(medians)

### Test for improved scores on disease transmission answers ####
# Drop rows with missing data
df <- subset(LearningZAVR, !is.na(TransmissionPre) & !is.na(TransmissionPost))
```


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```
# Create 2x2 table
tab <- table(df$TransmissionPre, df$TransmissionPost)

# Run McNemar's test and print p-value only
p_val <- mcnemar.test(tab)$p.value
cat(sprintf("McNemar's test p-value: %.4f\n", p_val))
```