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Teaching genetics and evolution with cross-scale concepts: An interactive board game for secondary school students

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Abstract
An educational board game, *THE LIFE*, was designed with the aim of enhancing students' understanding of genetics and evolution. The game integrates key scientific concepts–including gene combinations, mutations, and natural selection–as game mechanics. The board game represents evolutionary processes on both the macro and micro scale to help students engage with these abstract concepts, improving their cognitive structures and affecting their perspectives on biological topics. The game was evaluated in junior high school students in Taiwan by comparing pre- and post-test results to measure learning outcomes. The students' understanding of genetics and evolution was found to be significantly improved, as was their perspective regarding biological socio-scientific issues. The results indicate that board games such as *THE LIFE* can be effective tools in science education by providing an engaging and structured approach to learning cross-scale topics.

Keywords: board game environment, cross-scales concepts, cognitive structure, biological issues

INTRODUCTION

Biotechnology has profound impacts on human society (Fatima et al., 2024; Gupta et al., 2016). Genetics and evolution are key concepts in not only healthcare and agriculture but also in nonbiological fields, such as economics and computer science (Futuyma & Meagher, 2001; Harms & Reiss, 2019). Education regarding genetics and evolution is essential but often challenging for learners because of the abstract nature of many necessary concepts, such as randomness and temporal and spatial variation. A coherent cognitive structure that connects key biological concepts enhances students' abilities to recall and apply biological knowledge when learning abstract scientific concepts (Tsai & Huang, 2001, 2002). Students' cognitive structure can be strengthened using metaphorical thinking exercises (e.g., exercises in which analogies are used to represent genetic functions or mutation). These exercises can also reinforce students' conceptual understandings of genes and evolution. Board games, through their contextual scenarios and game mechanics, can serve as tools for analogising genetic and evolutionary processes (Miralles et al., 2013). They also enhance learning engagement and support the development of cognitive structures for scientific concepts (Cheng et al., 2019). Building on these benefits, this study developed a board game titled *THE LIFE* as an educational tool aligned with Taiwan's junior high school curriculum. The game aims to enhance students' cognitive structures in genetics and evolution and broaden their perspectives on biological issues. The questionnaires will be used to assess junior high school students' performance before and after playing the game.

THEORETICAL BACKGROUND

Evolution and Genetics

The concepts of genetics and evolution are central to modern biology (Bishop & Anderson, 1990). For example, genetics is applied in areas such as crop

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Contribution to the literature

- This study integrated macroscopic and microscopic scientific systems into a single game.
- The developed game allows students to develop a cross-scale perspective for understanding the interactions between genetics and systems in biology.
- The developed game enhances students' knowledge structures related to genetics and genes while improving their critical thinking regarding biological issues.

improvement and drug development. Traits shaped by natural evolution have also inspired advances in materials science, leading to the creation and enhancement of new materials (Gupta et al., 2016; Sager, 2001). Regarding evolutionary theory, the modern neo-Darwinian theory is a synthesis of Darwin's theory of natural selection with Mendelian inheritance (Huxley, 1942). The theory is applicable to various biological levels from cells to organisms and populations and explains evolutionary mechanisms at both the micro and macro scales (Geraedts & Boersma, 2006).

In the context of genetics, mutations at the cellular level affect genes and protein functions that affect an organism's fitness (Soskine & Tawfik, 2010). Genetic variation arising from mutations and recombination leads to differences in survival and reproduction among the individuals in a population. Beneficial differences are retained through natural selection, driving evolutionary change(Soares et al., 2021). Understanding the roles of mutations, recombination, and selection is essential for learning evolutionary biology and practical applications of evolutionary principles.

Learning About Evolution and Genetics in Secondary School

Evolution and genetics have long been recognised as fundamental elements of science education globally (Bishop & Anderson, 1990; Harms & Reiss, 2019). For example, The US Next Generation Science Standards (2013) includes key life science topics, such as inheritance, evolution, and biodiversity. Similarly, the Taiwanese Ministry of Education (2018) published the 12-year basic education curriculum, in which "evolution and continuity" is a core theme in secondary school. Many countries in Europe, Africa, and the Middle East include these topics in their curricula, further demonstrating the topics' significance in science education (Carvalho & Clément, 2007; GOV.UK, 2015). In Taiwan, the secondary school curriculum on evolution and genetics includes topics such as the levels of ecological organisation (e.g., individuals, populations, and communities), variations in genetic material (e.g., changes in traits and inheritance through germ cells), biotechnology, characteristics of biological morphologies and structures, and sexual reproduction (Ministry of Education, 2018). This study is consistent with the Taiwan curriculum guidelines of 12-year basic education, which specify the content requirements for teaching evolution and genetics in secondary school biology.

However, students often struggle to learn genetics and evolutionary concepts. Personal experiences and religious views can influence their understanding of evolution (Downie & Barron, 2000), and the randomness of genetic processes, such as mutations, and complexity of these processes at various biological scales are difficult to understand, leading to frequent misconceptions (Karagoz & Cakir, 2011). Regarding evolution, students often adopt a Lamarckian or teleological view and focus on individuals instead of populations (Kalinowski et al., 2010); thus, they find it difficult to grasp the mechanisms of adaptation and species development (Yates & Marek, 2015), and misconceptions hinder their understanding of evolutionary principles (Gregory, 2009; Harms & Reiss, 2019). Additionally, genetics involves abstract concepts, and evolution involves diverse mechanisms and influencing factors (Hogan & Fisherkeller, 1996). Thus, students often find it challenging.

Cognitive Structure in Learning

A cognitive structure is a mental framework of the interconnections between concepts within a learner's long-term memory (Shavelson, 1974). The students' cognitive structure represents their learning state, and the ability to recall information depends on the completeness of a student's cognitive structure (Anderson & Demetrius, 1993; Tsai & Huang, 2002). Understanding evolution and genetics requires abstract thinking to connect ideas across vast spatial and temporal scales (Banet & Ayuso, 2000). Students must comprehend how genetic variation originates within the genome; how such variation influences the traits expressed by individual organisms; and how these differences, when subjected to environmental pressures, can lead to changes at the population level (Dauer & Long, 2015). Grasping the progression from molecular mechanisms to observable evolutionary outcomes requires students to reason across different biological scales, with this process involving the connection of microlevel genetic processes with macrolevel patterns, such as natural selection and population adaptation. Developing this cross-scale reasoning ability is essential for acquiring a comprehensive understanding of genetics and evolution (Ministry of Education, 2018).

Encouraging metaphorical thinking, such as by using visual representations for abstract ideas, can strengthen cognitive structures and improve knowledge retention (Navaneedhan & Kamalanabhan, 2017). Cognitive structure has two primary components: the set of concepts and the connections between them (West et al., 1985). Tsai and Huang (2002) identified five methods for assessing students' cognitive structures in science: free word association, controlled word association, tree construction, concept mapping, and flow mapping. Concept maps and flow maps offer the deepest insights into cognitive structures. This study uses concept mapping because it clearly shows students' ideas and how those ideas are connected, giving a more detailed view of their cognitive structures. This makes it especially useful for examining how they integrate their understanding of genetics and evolution. Concept maps represent meaningful connections between concepts as propositions (Novak et al., 1983) and can be assessed through various criteria, such as the numbers of valid propositions, cross-links, hierarchical levels, and examples (Ruiz-Primo & Shavelson, 1996).

Board Games and Learning

A board game is a type of play in which players engage with physical components to create an interactive game experience (Hinebaugh, 2009). Board games are inexpensive, easy to use, and versatile as learning tools. They help students break through communication and cognitive barriers, boost motivation and engagement, and foster learning and skill development (Teixeira et al., 2024). Moreover, board games include physical components that help concretise abstract concepts, allowing players to manipulate and assemble elements that represent key ideas in the subject matter. Thus, board games provide students with opportunities to engage with abstract concepts (Eterovic & Santos, 2013; Muell et al., 2020). Game-based learning has been shown to enhance student motivation and interest (Hogle, 1996) and is an effective tool for improving concept comprehension and learning outcomes. This study presents a board game that can support students in learning concepts in evolution and genetics. The game created in this study has the key characteristics of board games. The game is interactive; players must actively engage with the game and other players (Cheng et al., 2019).

1. **Role-play simulations:** In a game, players can take on roles and attempt to solve problems or achieve goals (Dewey, 2005). In the game developed in this study, dice and cards are used to simulate the randomness of inheritance, a board represented the environment, and game pieces were organisms. This hands-on simulation allows students to explore the connections between genetics and evolution through active learning.
2. **Game-win goal:** The goal of winning motivates players to apply their knowledge and skills in alignment with educational goals (Prensky, 2003; Tang et al., 2009). In the developed board game, the goal of species survival teaches players about natural selection, gene–trait relationships, and how traits influence survival and reproduction.
3. **Procedural rules:** In each round, the players are presented with tasks and scenarios that require them to apply knowledge and adjust their thinking (Garris et al., 2002). The rules guide the players to observe the effects of genetic variation in reproduction on interactions between organisms and their environment. This structured process enables the players to grasp the principles of heredity and evolution through the rules and gameplay.
4. **Feedback mechanisms:** Feedback encourages reflection and strategic adjustment. It helps in deepening an understanding of complex concepts and the connections between actions and outcomes (Huang & Yeh, 2016; Kiili, 2005). In board games, feedback mechanisms are conveyed through game mechanics. Game mechanics refer to the rules that govern how players behave, interact with game elements, and receive feedback (Hinebaugh, 2009). In the proposed game, random genetic phenomena influence trait expression, and feedback is obtained by observing the effects of these traits on population survival.
5. **Player interaction:** Competition provides students with a dynamic learning experience (Coil et al., 2017; Teixeira et al., 2024). Interactions involving collaboration or competition foster students' learning engagement and facilitate their understanding of scientific concepts (Cheng et al., 2020). In the present study, intense competition was used to help students grasp evolutionary concepts from a population-level perspective.
6. **Repeated rounds:** Through repeated rounds, the players can refine their understanding and skills and continually reconstruct their cognitive frameworks (Eterovic & Santos, 2013; Yeh et al., 2016). Each round involves the simulation of an evolutionary process within the game, guiding students to explore evolutionary and genetic concepts across different temporal and spatial scales.

Board Games for Learning Biology

Certain features of board games, such as game goals, game mechanics, and playing pieces or tokens, can be used to illustrate scientific concepts (Tsai et al., 2020). Multiple board games have been developed for learning biological concepts such as genetics and evolution. "DNA Re-EvolutioN", a board game developed by

Miralles et al. (2013), presents key concepts such as gene expression, mutation, and natural selection. The game uses tangible components to represent DNA, mRNA, and proteins and incorporates random card draws to simulate mutation events. This design effectively helps students understand gene function and evolutionary mechanisms. "ACAGATATA", a board game created by Eterovic and Santos (2013), simulates mutation and molecular evolution, emphasising how random mutations affect genotypic and phenotypic variations. The game features a tree diagram that represents generational evolution and includes mutation events. By tracking genetic changes and differences across generations, students gain insights into genetic encoding and decoding and the effects of random variations on phenotypes.

The aforementioned two games use concrete visual representations to support the learning of microlevel biological concepts. Nevertheless, the games incorporate only two or three core features of educational board games. After reviewing several biology-themed games, Teixeira et al. (2024) suggested that effective educational games should incorporate elements such as role-playing, competitive or cooperative mechanisms, physical components (e.g., cards and boards), and strong player interaction. They believed that highly interactive games have strong potential as teaching tools for enhancing learning outcomes in biology education. Building on these findings, the present study developed an interactive board game that integrates six key features: role-play simulations, a winning objective, rules of the game, a feedback mechanism, player interaction, and a round-based format. In addition, Dauer and Long (2015) suggested that when students are learning cross-scale concepts related to evolution and genetics, their cognitive frameworks can be activated by providing them embedded models, scenarios related to their prior knowledge, or tasks that involve model construction. Accordingly, the game designed in this study presents familiar animal traits such as speed, diet, and body size. It also incorporates elements that represent observable genotypes of these traits, along with tasks and mechanisms related to genetics and evolution.

Research Objective

This study focused on developing a biology board game, assessing its impact on student learning, and identifying the key features of the game that drive educational outcomes. The study was guided by the following research objectives:

1. To examine how playing the biology board game *THE LIFE* influences students' cognitive structures related to evolution and genetics.
2. To understand changes in students' perspectives on topics in evolution and genetics by comparing their views before and after learning through the board game.
3. To identify the game features that support students' learning of evolution and genetics.

MATERIALS

The board game, *THE LIFE*, was developed to improve the teaching of evolution and genetics. The game's scenario and mechanics were designed with consideration of students' cognitive abilities, ensuring its suitability as an educational tool. This study was guided by the input-process-outcome model of game-based learning in its design of the game (Garris et al., 2002). In this model, *input* refers to the content that students are to learn and the characteristics of the game, *process* describes the players' behaviour and system feedback during gameplay, and *outcome* represents the how well the students have mastered the material after the game. The input factors of this study were knowledge on genetics and evolution and the six features of educational board games. The game process focuses on the generational survival of organisms, and the outcomes were students' understanding of cross-scale concepts and their perspectives on issues related to genetics and evolution.

Input Component of *THE LIFE*

Junior high school students in Taiwan were selected as the research subject. The developed game integrates concepts from several levels, ranging from the cellular level to the population level, and aligns with guidelines of the Taiwanese science education curriculum for secondary schools (Ministry of Education, 2018) and the cross-scale conceptual framework proposed by Dauer and Long (2015). A concept map of evolution and genetics was created as the foundation for the game's mechanics (**Figure 1**). Concepts related to genetics are presented in red and blue zones, and green and purple zones display concepts relating to population genetics and evolution. In the concept map, basic genetic concepts are shown in the orange section, blue indicates genetic variation, green covers population genetics, and purple focuses on evolution. The text along each line describes the relationships between the connected concepts. Red lines highlight cross-scale links between genetics and evolution, and brown lines show cross-concept connections related to genetic variation. The red lines illustrate how cross-concept connections affect populations, population genetics, and evolutionary processes.

In red and blue zones, genes are the basic units of heredity; they determine an organism's traits and are passed down through reproduction (Carlson, 1991; Germain & Jurca-Simina, 2018). The genetics concepts in the orange sections of the concept map include genetic material (genes), trait expression, and inheritance. The

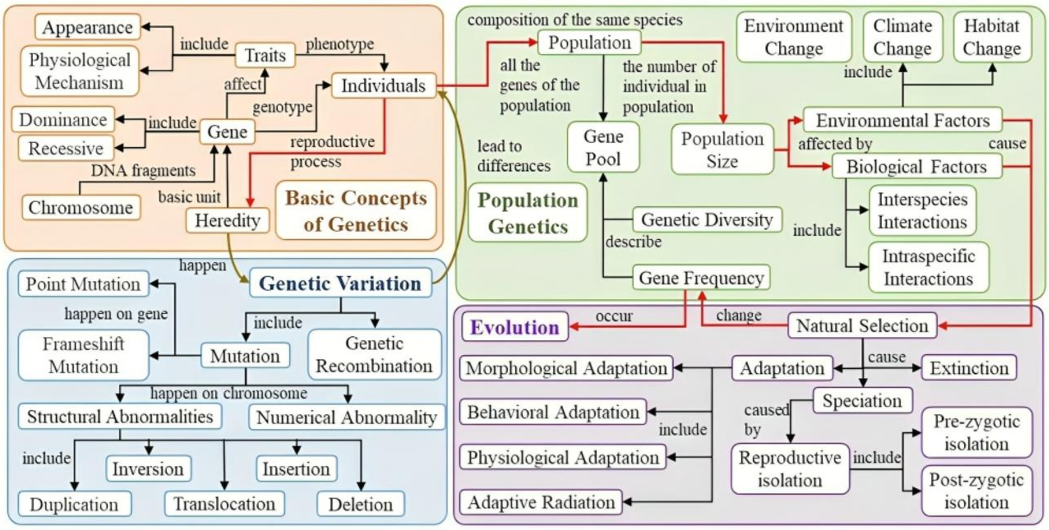


Figure 1. Evolution and genetics concept map (Source: Authors' own elaboration)

brown lines connect these to genetic variation, indicating both the creation of variation and types of mutations. Red lines indicate that genetic variation within populations results in individual differences, revealing connections between genetics and population concepts.

In green and purple zones, population genetics plays a key role in modern evolutionary theory (Pigliucci, 2008). The green sections of the concept map contain the concepts of populations and population genetics and act as a bridge between micro and macro levels. These concepts include the definition of a population, the gene pool, and factors influencing population size. These are connected to natural selection, illustrating the occurrence and effects of natural selection and how these changes lead to shifts in gene frequencies. This represents the process of evolution in modern theory (Cook et al., 1976). The six features of board games and their integration into the game will be described in the next subsection.

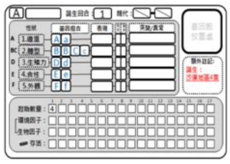
Process Component of *THE LIFE*

The board game *THE LIFE* was developed that has a design integrating key concepts of evolution and genetics. Various features commonly found in board games are included in the design. **Table 1** outlines how each evolutionary and genetic concept is conveyed through the game mechanics and structure. The game is set in a mysterious environment. Each player represents a population of diploid organisms and aims for their population to survive, reproduce, and expand in

Table 1. Elements representing evolution and genetics in the board game

Knowledge concept	Board game design	Game component
Genetics 1. Nature of genetic material 2. Expression of genes and traits 3. Reproductive process and trait inheritance	Process rules and feedback mechanism: During the "(1) reproduction phase," the players roll the **gene dice**. The random results of these rolls dictate the genetic makeup of offspring. The **gene dice** represent the possible genetic combinations of a species. Each side indicates a chromosome carrying unique genes (assembled from gene components). The **gene–trait chart** determines which traits players' species will express in accordance with these genes. Each player's **gene–trait chart** is different, ensuring that every participant has a distinct genetic profile and unique trait expressions.	 Gene dice  Gene-trait chart
Genetic variation 1. Generation of genetic variations 2. Types of mutations	Process rules and feedback mechanism: During the "(1) reproductive phase," a dice roll determines whether a mutation occurs. If a mutation is triggered, a **mutation card** is drawn. The mutations include loss of chromosome function, translocation, inversion, and other functions. The card's instructions guide the player on how to adjust the **gene dice** or document the mutation status on the **species sheet** accordingly.	 Mutation card

Table 1 (Continued). Elements representing evolution and genetics in the board game

Knowledge concept	Board game design	Game component
Population inheritance 1. Composition of the population 2. Gene pool 3. Factors affecting population size	Process rules and player interaction: During the "(2) event phase," a player draws an environment card that alters the environmental factors of the region, such as its temperature. These changes affect whether a population can survive in that particular environment. The regional board represents the habitat that the organisms live in. It has environmental characteristics, such as temperature and plant availability. Each region has a limited capacity for inhabitants and populations. Player interaction: In the "(3) interaction phase," players engage in the following interactions: Migration: Organisms relocate to other regions in accordance with their traits. Herbivory: Herbivores consume plants available in the region. Predation: Carnivores prey directly on other organisms; the success rate is determined by specific traits. Role-play simulations: Each player plays as a species in the game. The genetic combination of an organism is represented by **wooden discs** of various colours, which are placed on a **regional board** for interactions. The **species sheet** records the genetic combination of each group and the traits that they express. It also records the group's evolutionary history, including birth and death cycles, the numbers of births and deaths, and causes of death. Goal: The player with the highest score (best species survival) is the winner.	 Wooden discs  Species sheet  Regional board  Environment card
Evolution 1. Occurrence and effect of natural selection 2. Mechanism of evolution	Process rules and feedback mechanism: In the "(4) natural selection phase," organisms that were unsuccessful in foraging or were unable to adapt to the environment die. The unviable organisms' **wooden discs** are then removed from the **regional board**. In the "(5) outcome phase," the number of organisms is recorded on each **species sheet** and compared with the initial population to determine the outcome of evolution.	

influence. At the beginning of the game, each player starts with an organism with a unique gene combination and set of traits. The central playing area is created by arranging regional boards to form the initial environment.

The goal of the game is to achieve the highest score. Players score points in accordance with their number of surviving organisms at the end of the game. Additional points are awarded for acquiring new species tiles (gene combinations), and points are subtracted for gene combinations that go extinct. This structure aims to highlight the critical role of genetic diversity and the survival of organisms in the process of evolution. Each game round (**Figure 2**) guides students from a microlevel perspective of genetic variation to an understanding of its macroscale outcomes. Each round begins with the reproduction phase and concludes with the outcome phase; the red arrows indicate the order of events in the round.

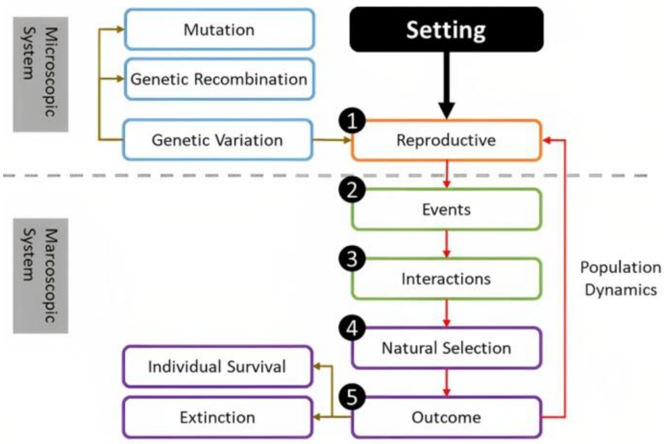


Figure 2. Flowchart of a game round in *THE LIFE* (Source: Authors' own elaboration)

Outcome Component of *THE LIFE*

In Taiwan, seventh-grade students study genetics and evolution in separate courses. The course on genetics focuses on sexual reproduction and mutation, whereas that on evolution focuses on natural selection and evolutionary processes. The developed board game integrates the content of both courses, and teachers and students can play this game during either course while simultaneously engaging with cross-scale concepts. Through repeated gameplay cycles, students are encouraged to link molecular mechanisms, such as mutation, to organism-level traits and population-level changes, which fosters in them a multilevel understanding of evolutionary processes. In addition, event cards and natural selection tasks promote reflection on issues related to genes and evolution. The game accommodates 2-4 players and requires approximately 2 hours to complete. The developed game served as the primary instructional intervention in this study, and its effects on students' learning outcomes and perspectives on scientific topics were assessed using pre-tests, post-tests, and questionnaires related to specific game features that support learning.

METHODS

Instruments

Three instruments were used to collect data in this study: a cognitive structures test, designed to assess students' understanding of genetics and evolution; an evolution and genetics issues questionnaire, used to examine students' perspectives on related scientific topics; and a game-based learning questionnaire, which asked students to identify the features of the game that supported their learning.

Cognitive structures test

To assess the effect of the game on learning outcomes, a cognitive structure test was developed on the basis of the grade 7 biology curriculum outlined in Taiwanese textbooks published by the National Academy for Educational Research and the corresponding learning indicators specified in the national curriculum guidelines (Ministry of Education, 2018). This test consisted of open-ended questions and concept map drawings. The questions were drafted in accordance with key concepts in genetics and evolution. An initial pool of open-ended questions and concept map tasks was reviewed by one biology education expert and one secondary school teacher to ensure that their content aligned with the learning objectives. These questions and tasks were then revised on the basis of the feedback of these individuals.

The open-ended questions on the test were designed to evaluate students' understanding of the relationships between genetics and evolution concepts and their ability to explain the corresponding phenomena. The questions are "What do you think the possible reasons regarding the differences between many individuals?" and "Please explain the possible reasons that ladybugs on a certain island had similar characteristics to a certain group of ladybugs in the interior." The responses were analysed quantitatively on the basis of established criteria, including the number of concepts, the connections between concepts, and the completeness of the content. If a student's explanation aligned with the concepts of genetics and evolution and met the scoring criteria, they were assigned 1 point. The total number of correct responses and the total score for each student were then calculated.

To evaluate whether students' cognitive structures for evolution and genetics were improved after they had used the board game, the test also involved concept map drawing (Novak et al., 1983). Students were asked to draw concept maps of genetics and evolution, and the scoring method was used for quantitative scoring of their maps. The scoring of the concept maps was based on the principles of cross-scale reasoning proposed by Dauer and Long (2015), which include reasoning at a single scale or cross-scale. Each student's concept map was analysed and categorized as either single-scale or cross-scale, with one count assigned per student per category. For those identified as cross-scale, further classification was conducted to determine whether the conceptual linkage progressed from the microscopic to the macroscopic level or from the macroscopic to the microscopic level. Subsequently, the total number of students demonstrating single-scale or cross-scale reasoning was calculated. Concept maps containing fundamental misconceptions were assigned a score of zero and excluded from further categorization. The cognitive structures test was administered as both a pre- and a post-test to evaluate changes in students' cognitive structures.

Evolution and genetics issues questionnaire

A questionnaire was used to examine changes in students' perspectives on evolutionary and genetic concepts after they had engaged in game-based learning. According to Kuhn (2005), the three elements of scientific argumentation in teacher–student dialogues are one's own perspective, the opposing perspective, and supporting evidence or theory. The questionnaire focused on social scientific issues, such as genetic technology and the management of patients with genetic diseases. It evaluated students' ability to analyse and craft a response on the basis of their stance, scientific reasoning, and viewpoints. The students' responses were analysed to categorise their perspectives, and the number and percentage of students with accurate statements were recorded. Pre- and post-test results were then compared.

Game-based learning questionnaire

To identify the aspects of *THE LIFE* that assist students with their learning, a questionnaire targeting six key concepts related to genetics, evolution, and their cross-scale links was developed. Students were asked to identify the features of the game that aided their learning and to describe this learning briefly or in detail. The questionnaire was administered after the gameplay.

Sample

Purposive sampling was used to recruit seventh-grade students in Taiwan as the research participants. A total of 69 students (39 boys and 30 girls) participated in the study. Their average age was approximately 13 years. In compliance with institutional review board regulations, the researchers provided a thorough explanation of the study's purpose and procedures before initiating the research. The activities and surveys were designed to gather data for research purposes and to refine the game prior to its wider use. Participation was voluntary, and all students discussed the study with their parents before providing verbal consent. They signed an attendance sheet, then participated in the game, and completed the questionnaire.

Procedural and Statistical Analysis

Initially, the cognitive structures test and evolution and genetics issues questionnaire were given as a pre-test to assess the students' prior knowledge. Following the board game intervention, the same questionnaires were administered as a post-test to determine whether the students had developed a deeper understanding of genetics and evolution concepts and whether this had led to significant improvements in their learning outcomes. Additionally, the game-based learning questionnaire was used to explore students' perceptions of how the game's features supported their learning.

Data from the cognitive structures test and the evolution and genetics issues questionnaire were analysed using paired-sample t-tests to compare pre- and post-test scores. The paired-sample t-test is suitable for within-subject comparisons in which the same participants are measured at two different time points (Field, 2024). Also, effect sizes (Cohen's [1962] d) were calculated to indicate the magnitude of the differences, with values of 0.2, 0.5, and 0.8 conventionally interpreted as small, medium, and large, respectively.

The responses provided by the students for the game-based learning questionnaire were examined through thematic analysis with a descriptive approach (Braun & Clarke, 2006, 2013). To identify how the game supported learning, the students' descriptive responses regarding the specific features that helped them understand key concepts were considered as themes in the analysis. Some examples of these features include the survival goals of populations, mechanisms of genetic combination and mutation, processes linking environmental changes to species survival, and biological interactions among players.

Table 2. Pre- and post-test open-ended question scores on evolution and genetics (N = 69)

Knowledge content	Pre-test M (SD)	Post-test M (SD)	t (pre-post)	Effect size (Cohen's d)
Genetics	3.28 (2.77)	4.49 (2.81)	-4.11**	0.43
Evolution	2.59 (2.04)	3.96 (2.48)	-5.25**	0.60

Note. **p < .01; M: Mean; & SD: Standard deviation

RESULTS

Results of the Cognitive Structures Test

Open-ended questions

Table 2 presents the quantitative results for the students' responses to the open-ended questions on the cognitive structures test. The average post-test score was higher than the average pre-test score ($t[69] = -4.11$, $p < .01$; $t[69] = -5.25$, $p < .01$), with medium (0.43) and large (0.60) effect sizes discovered for genetics and evolution, respectively. **Table 3** presents example student responses. For the question on 'individual genetic processes', student A's pre-test answer was fragmented and did not describe the relationship between genes and traits. Similarly, student B's pre-test answer to the question on 'evolutionary processes and population genetics' lacked conceptual coherence and was incomplete. This student initially viewed biological adaptation as a purposive process, suggesting that they misunderstood the role of mutation in evolution. After playing the board game, the students were able to explain the relevant concepts by effectively describing causal relationships in alignment with the game's logical progression. Student A referred to genotype combinations in the post-test and included scientific terms such as 'genes' and 'chromosomes'. Their responses exhibited improved conceptual connections and a more coherent logical structure. Student B, who initially considered biological adaptation a purposive process, maintained this perspective in the post-test but provided a more logically consistent explanation.

Table 3. Students' responses to open-ended questions on evolution and genetics

Question	Test	Students' responses
Question 1 about individual genetic processes) (student A)	Pre	*Our genes come from our parents, and our traits will be similar to our parents'.*
	Post	*The offspring produced by combining parents' genes do not necessarily have the same gene combination as their parents. For example, if the father is Aa and the mother is Aa, the offspring may be Aa or aa.*
Question 2 about evolutionary process and population inheritance (student B)	Pre	*They may have been originally the same species, but the ladybugs mutated to adapt to environment.*
	Post	*To survive and adapt to the environment, the organism mutates or changes, changing its original traits. In reproduction, the gene combination of the offspring could be different from the parents'.*

Table 4. Results for student concept maps of evolution and genetics (N = 69)

	Pre-test	Pro-test	t	Effect size
	M (SD)	M (SD)	(pre-post)	(Cohen's d)
TS	16.94 (12.03)	22.84 (15.27)	-5.81**	0.43

Note. **p < .01; TS: Total score; M: Mean; & SD: Standard deviation

Table 5. Categorization of students' post-test concept maps by cross-scale understanding (N = 69)

Category	Type of relationship	Frequency	Percentage
Cross-scale	Separate but connected	7	10.1%
	Microscopic →macroscopic	18	26.1%
	Macroscopic →microscopic	9	13%
Single-scale	Separate with no connection	14	20.3%

Analysis of concept maps related to evolution and genetics

Table 4 reveals that the knowledge structure in the concept maps was significantly more complete after the game-based learning (t[69] = -5.81, p < .01); the effect size was medium at 0.43. To assess whether the students could link the concepts of evolution and genetics (cross-scale linking), a simple classification comparison was made on the basis of the students' performance on the post-test concept maps.

Table 5 presents the students' post-test performance in drawing concept maps related to evolution and genetics. A total of 10.1% of the students represented the microscopic and macroscopic scales separately while attempting to illustrate the relationship between them. By contrast, 39.1% of the students showed cross-scale conceptual understanding in their concept maps, with 26.1% and 13% describing the relationship between the two scales from the microscopic level to the macroscopic level and from the macroscopic level to the microscopic level, respectively. Finally, 20.3% of the students separated the two scales but did not establish a connection between them.

In the pre-test, the students tended to have a fragmented understanding of the concepts. However, in the post-test, they were able to integrate concepts more effectively, with some students successfully developing cross-scale links between the themes of evolution and genetics. **Figure 3** displays one student's responses in the pre- and post-test, illustrating the changes in their

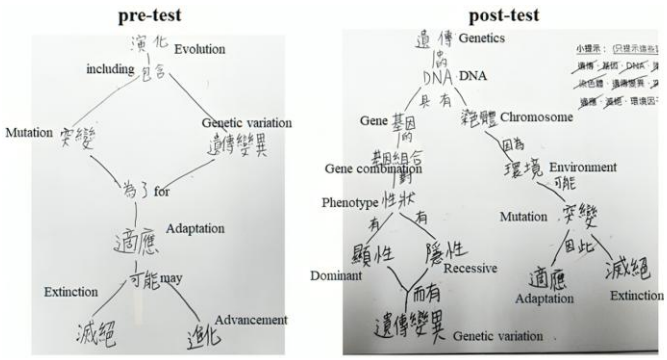


Figure 3. Example pre- and post-test evolution and genetics concept maps (Source: Field study)

conceptual understanding. The student's pre-test concept map was brief and contained few terms. The description of mutation and genetic variation as purposeful mechanisms for adaptation represented a conceptual misunderstanding and was therefore assigned a score of 0. By contrast, the post-test concept map contained more vocabulary and had a clearer hierarchical structure, with linking words being applied more logically. Although the student's concept map did not reach the level of an expert, it showed marked improvement in the post-test. The student incorporated terms such as genes, genetic variation, and adaptation and established some connections among them. However, the map did not depict interactions between the two scales and was therefore classified as 'separate but connected' in the cross-scale category.

Changes in Students' Views on Issues Related to Evolution and Genetics

The questionnaire results (**Table 6**) indicated that the students' thinking skills regarding socio-scientific issues were improved after they had played the game. In response to the first question about genetic technology breakthroughs, the post-test results revealed that the students' support for genetic technology had increased. More of the students could analyse the issue from a scientific perspective, and they had a greater capacity to consider multiple viewpoints. Similarly, for the second question concerning the treatment of patients with genetic diseases, the students had increased personal approval in the post-test with improved scientific analysis skills and better analysis from various perspectives.

Table 6. Statistical results regarding student views on issues related to evolution and genetics

Elements of personal views	Genetic technology		Genetic disease	
	Pre-test	Pro-test	Pre-test	Pro-test
Personal approval for biological issues	23.2%	29.0%	21.7%	26.1%
Analysing biological events with a scientific perspective	14.5%	27.5%	13.0%	39.1%
Analysing biological events from multiple viewpoints	33.3%	42.0%	24.6%	40.6%

Table 7. Genetics-related concepts and game mechanisms that assist learning

	Genes control traits	Effects of mutations
Game mechanics	1. Dice rolling about gene combination and reproductive process 2. Mutation cards about occurrence of mutations 3. Environmental change stage by environment cards drawing	1. Occurrence of mutations 2. Gene combination & reproductive stage 3. Group death and survival records

Table 8. Evolution-related concepts and game mechanics that assist learning

	Effect of evolution on organism changes	Randomness of evolution
Game mechanics	1. Dice rolling about gene combination and reproductive process 2. Environmental change stage by environment cards drawing 3. Mutation cards about occurrence of mutations	1. Occurrence of mutations 2. Gene combination & reproductive stage 3. Group death and survival records

Game Features Affecting Learning of Evolution and Genetics

This section examines which elements of the game contributed to the students' learning of genetics and evolution. The students identified multiple game mechanisms that they had found beneficial and provided qualitative explanations for their selections. We summarise these reports sorted by quantity.

Learning for genetics-related concepts

Table 7 lists the genetics-related concepts and lists the three game mechanisms that the students selected as most helpful for understanding these concepts. The students' responses on the factors that assisted in their learning of the concept of gene-controlled traits mainly highlighted the processes of rolling the gene dice and of combining offspring genes.

> Student D: When filling out the offspring card, I needed to roll the dice, which showed me that traits are controlled by multiple genes.

> Student E: When playing this game, I had to combine offspring genes. I learned that traits are controlled by multiple pairs of genes.

The game mechanics illustrate how changes in an organism's traits influence its survival and interactions with the environment. Regarding mutation and its effects, the students noted that mutations were not necessarily harmful. Mutations alter biological traits and can aid survival; the game helped the students understand that mutations may produce genetic structures suitable for environmental adaptation.

> Student B: In the game, mutations are not always negative. By recording the survival or death of a population, I learned that some mutations are beneficial for survival whereas others are not.

> Student D: My organism was originally herbivorous, but after drawing a mutation card, it became carnivorous. The mutation phase showed me how mutations can cause changes and are one of the driving forces of evolution.

Although student D described a herbivore that immediately became a carnivore after a single mutation–an outcome that does not align with natural biological processes–this response reflected an emerging understanding that mutations can lead to considerable changes in an organism's traits. Student D's answer also provides valuable insight for improving the game design. The current version of the developed game may oversimplify biological complexity. Therefore, attempts can be made to refine mutation outcomes and scenarios in future iterations of the game to better reflect realistic evolutionary transitions or incorporate additional teacher guidance to support accurate scientific understanding.

Learning for evolution-related concepts

Table 8 lists the game mechanics that helped the students understand that evolution reflects how organisms change over time. The students with a limited understanding of genetics tended to view evolution as involving purely physical changes. However, their responses after the game demonstrated that they recognised that evolutionary changes extend beyond physical appearance and also include alterations of genetic combinations and behavioural traits.

> Student D: Even though my friend's organism went extinct three times without mutations, evolution was occurring in this process.

> Student E: In the game, different genotypes can exhibit the same phenotype, such as AA and Aa both resulting in expression of the dominant trait.

Regarding the randomness of changes in evolution, the students noted that evolutionary changes are not controlled or initiated by the organism but are influenced by "reproductive processes" and "mutation cards" that introduce genetic variations. Through the game, they experienced the randomness of evolution.

> Student A: I can't change my organism's traits on my own. Changes only occur through mutations or reproduction; I cannot directly alter inherent traits.

Table 9. Cross-scale concepts of evolution and genetics and game mechanisms to assist learning

	Effect of genetic diversity on population	The relationship between evolution and genetic
Game mechanics	1. Dice rolling about gene combination and reproductive process 2. Mutation cards about occurrence of mutations 3. Biology components and relationships from board game items	1. Gene combination and reproductive process 2. Occurrence of mutations 3. Environmental change stage

> Student F: In the game, organisms cannot change their traits on their own but rely on mutations or genetics.

Learning for cross-scale concepts

Table 9 lists the game mechanics that helped the students understand the concept of genetic diversity and its effect on populations. The students noted that, in the game, "genetic variation is introduced through gene recombination or mutations." This suggests that the game setting caused them to think about these concepts.

> Student D: In the game, genetic variation arises because of gene recombination or mutations that make offspring different from their parents.

> Student E: There is a chance of mutations occurring during the reproductive stage.

Regarding the relationship between biological evolution and genetic variation, the students explained that producing offspring with "different gene combinations" results in variation within the population. Genetic diversity helps prevent extinction when an organism's environment changes. The students indicated that the game elements contributed to their understanding of cross-scale concepts. This result underscores the effectiveness of the game's structure in promoting the students' thinking regarding the relationships between genetic variations, environmental conditions, and survival outcomes.

> Student C: Different genes create different organisms, and large variation in the evolutionary process can lead to the formation of new species.

> Student H: Different gene combinations are suited to different environments, and genetic diversity helps species survive.

> Student I: Genes recombine during reproduction, causing differences in traits, which contribute to the evolutionary process.

DISCUSSION

Enhancements in Cognitive Structures Related to Evolution and Genetics

The students' provided much better answers at the post-test than the pre-test. The post-test answers were more logical and better structured, with the students using scientific terms and concepts more correctly in coherent explanations. Linking game content with real-life situations has been shown to enhance students' learning outcomes (Kiili et al., 2012). In addition, playing in a game scenario has been demonstrated to make abstract concepts more concrete, enabling students to better understand the relationships between these concepts (Lham & Sriwattanarothai, 2018). *THE LIFE* generated scenarios involving the survival of biological populations, allowing the students to experience and understand the factors that influence survival. Moreover, interactions within the game enhanced the students' understanding of causal relationships in scientific phenomena, thereby fostering their scientific reasoning ability (Arboleya-García & Miralles, 2022). As students' reasoning abilities, such as their induction and deduction skills, improve, they can better understand how various concepts are related to each other as a cohesive whole. After playing the developed game, the participants could better explain evolutionary and genetic mechanisms and present clearer causal explanations and more coherent narratives.

The game cycle is a key element of a board game, and designers must understand it if they wish to influence students' learning behaviours. In *THE LIFE*, the students observed the consequences of their actions across multiple rounds, with interactions and feedback playing a key role in improving their learning performance (Cheng et al., 2020). This board game led the students from microscopic genetic processes to macroevolution through a situated activity, and its structured game cycle required the students to integrate information and make inferences. Thus, the board game experience effectively enhanced the students' understanding and construction of concepts in genetics and evolution, thereby supporting the development of more organised and interconnected cognitive structures.

Changes in Students' Views on Evolution and Genetics Issues

More students could analyse events from a scientific perspective in the post-test than in the pre-test. This improvement was attributable to the developed board game, whose gameplay reflected structured knowledge and helped the students become familiar with problem contexts and apply logical reasoning to solve problems (Chen et al., 2021; Kiili, 2007). The game met educational targets while providing a positive experience and favourable outcomes for the students, indicating that growth and discovery occurred when the participants played the board game.

In the pre-test, the pre-test students held neutral views on issues involving disadvantaged groups and issues that did not directly affect them. However, after playing *THE LIFE*, the students showed greater empathy towards others' perspectives. These findings suggest that board game activities can improve students' interpersonal interactions and empathy. A key design element of *THE LIFE* is to have students directly role-play as organisms, enabling them to acquire a first-hand experience of the impact of genetics on living beings. Similar conclusions have been drawn in previous studies on board games with biological themes (Tsai et al., 2019). The aforementioned findings suggest that the developed game not only enhanced conceptual understanding but also facilitated attitudinal shifts, reinforcing its broader educational value.

Game Features Affecting the Learning of Evolution and Genetics

Most evolution-themed board games tend to focus on concepts in isolation, such as arms races within evolution, with players directly selecting traits. This characteristic often leads to teleological misconceptions regarding evolutionary theory (Muell et al., 2020). By contrast, *THE LIFE* incorporates genetic randomness, which prevents players from making deterministic choices regarding biological traits. This design addresses a common shortcoming of many games on evolution. Notably, game features related to aspects such as gene combination, reproduction, and mutations aid students' comprehension, helping them to recognise causal relationships between mutations, trait changes, and the effects on organism fitness. Therefore, these features were highly valued by many participants in this study, who reported that these features enabled them to learn key concepts in evolution and genetics.

The iterative processes and feedback mechanisms of the developed game offer players multiple opportunities to refine their knowledge by engaging with diverse scenarios (Yeh et al., 2016). In addition, when combined with features such as role-playing and a clearly defined game objectives, these elements form an integrated game structure that effectively represents abstract concepts and integrates microlevel genetics with macrolevel evolutionary content. This integrated approach helps students develop a more comprehensive understanding by reinforcing the connections between genetics and evolution, thereby promoting the integration of related knowledge.

CONCLUSION AND IMPLICATIONS

This study applied board game design to help students learn genetics and evolution concepts and foster their development of a comprehensive knowledge system. The research results showed that, after playing *THE LIFE* board game, the student participants' answers to open-ended questions were more logical. Concept map assessments showed a shift from a fragmented understanding to a more complete cognitive structure in the post-test; the students successfully made cross-scale links between genetic and evolutionary concepts. Moreover, the game scenarios encouraged students to engage with issues related to species survival and to reflect on topics aligned with core principles of evolutionary theory, such as natural selection and adaptation. Overall, *THE LIFE* proved to be effective in both enhancing scientific understanding of and fostering cross-scale concept on biology-related topics.

The developed game was designed on the basis of genetics and evolution content in the Taiwanese secondary school curriculum. Teachers can implement this game in the classroom when teaching related topics. Educators who wish to emphasise specific learning content or conceptual structures (e.g., single-scale or cross-scale reasoning) may refer to the concept maps developed in this study and adjust the game rules as needed to align the content with the corresponding game mechanisms. In addition, teachers should be aware that excessively simplified gameplay may lead to student misconceptions (e.g., a herbivore mutating directly into a carnivore). To address this, supplementary explanations can be incorporated during instruction to ensure that students develop accurate scientific understanding and to better support instructional goals.

Future studies may use video observations or conduct teacher–student interaction analyses to obtain enriched contextual insights into learning and engagement. Further development can include refining the mutation process to better reflect natural biological mechanisms and enhancing the developed game's adaptability across different learning contexts. A modular version of the game can be developed to allow teachers to adjust the complexity of the task on the basis of students' cognitive levels or prior knowledge. For instance, simplified modules derived from the developed game can support foundational understanding, whereas advanced versions can align with high school curricula by incorporating concepts such as regional, temporal, and reproductive isolation as well as genetic drift to introduce greater complexity. Furthermore, integrating socially controversial topics–such as genetically modified organisms, medical technologies, and genetic diseases–could broaden the game's scope, fostering students' issue-based thinking and enhancing their understanding of real-world applications of theory.

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CCK: writing – review & editing. All authors agreed with the results and conclusions.

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Ethical statement: The authors stated that, according to the Human Subjects Research Act in Taiwan at that time, this type of educational research did not require IRB approval; therefore, no approval code was issued. In compliance with IRB regulations, the researchers provided a thorough explanation of the study's purpose and procedures before initiating the research. The activities and surveys were designed to gather data for research purposes and to refine the game prior to its use. The participation was voluntary, and all students discussed the study with their parents before providing consent. Written informed consent was obtained from all participating students and their legal guardians. They signed an attendance sheet, then participated in the game, and completed the questionnaire.

AI statement: The authors stated that no generative AI or AI-based tools were used in any part of the study, including data analysis, writing, or editing.

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