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Reconstruction of the Teaching Paradigm of Genetic Diseases Empowered by Artificial Intelligence: A Study of Cognitive Embodiment and the Structuring of Ethical Decision Making

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Abstract

The education penetration of AI technology is catalyzing the dual reform of the biology teaching paradigm: it not only realizes the macroscopic visualization of microscopic mechanisms but also promotes the dialectical structuring of ethical cognition. On the basis of constructivist learning theory, this study innovatively proposes a three-dimensional teaching framework of "digital twin-intelligent deduction-value modeling". Through the development of a chromosome behavior dynamic rendering engine, a phenotype–gene association map generation system and an ethical decision tree algorithm, the three major problems of "fragmented mechanism understanding", "linearized case analysis", and "extreme ethical judgment" in the teaching of genetic diseases were effectively solved. Empirical studies revealed that the experimental group was significantly better than the control group in terms of accuracy of genetic map analysis (82.3% vs. 64.1%, $p<0.01$) and completeness of multivariate pathogenic model construction (4.7 vs. 2.9, Cohen's $d=1.21$). This study provides a reproducible technology integration solution for the digital transformation of biology education under the framework of “China Education Modernization 2035”.

Keywords

cognitive visualization, genetic counseling simulation, educational digital twin, ethical decision tree, human–computer collaborative teaching

1. Introduction

As a cognitive hub connecting molecular mechanisms and bioethics, human genetic diseases directly affect the quality of life and social responsibility literacy of students (NGSS, 2023). In the teaching practice of genetic diseases for approximately ten years, the author deeply realized that there were three cognitive ruptures in the current teaching model: (1) the lack of spatial representation of the unconventional behaviors of meiosis led to a high rate of conceptual misunderstanding, for example, students’ understanding of the phenomenon of chromosome nondisjunction; the error description rate reached 58% (Zhang, 2024), which is directly related to the difficulty in presenting the 3D dynamic process in traditional blackboard writing and static diagrams; and (2) the teaching of polygenic disease–environment interaction mechanisms is still limited to qualitative descriptions, and when students analyze diseases such as hypertension, the nonlinear association between genes and environmental factors such as PM2.5 and dietary habits is often ignored. (3) The discussion of cutting-edge issues such as gene editing is prone to becoming polarized, with some students overemphasizing the technical value and ignoring ethical boundaries. Some completely deny the importance of technological progress (UNESCO, 2025). The education migration of AI technology has provided a path to break the game: the generative adversarial network (GAN) can build a dynamic deduction system of chromosome behavior, breaking through the predefined limitations of traditional animation (Lee & Tang, 2024); the causal reasoning algorithm can deconstruct multidimensional nonlinear relationships between pathogenic factors; on the other hand, a decision simulator based on the moral Turing test can transform abstract ethical principles into quantifiable decision tree models. In this paper, by constructing an AI-enhanced teaching ecosystem, the paradigm transition from "knowledge transfer" to "cognitive modeling" is realized.

2. Technology Deconstruction and Teaching Remapping of Cognitive Fracture

2.1 Representational Reconstruction of Spatial Cognition

In the teaching process of discussing the phenomenon of chromosome nondisjunction, some students may encounter difficulty in grasping the difficulty. The chromosome behavior digital twin (CDT) is expected to become a powerful tool for overcoming these difficulties. The dynamic rendering engine is an example. It uses the Unity3D physics engine to simulate microtubule dynamics during meiosis, thus vividly displaying the dynamic behavior of chromosomes. When students wear HaptX tactile feedback gloves, they can experience tension changes during the segregation of homologous chromosomes in real time. This experience is synchronized with the dynamic display on the system interface—the arrangement status of homologous chromosomes in mid-phase I of meiosis and the dynamic process of microtubule attachment are displayed on the interface, making the originally abstract biological process intuitive and sensible. In terms of traceability of error behavior, the AlphaFold-Multimer algorithm was integrated into the system to construct a structural stability prediction model of the centromere protein complex (CENP-A/C). Through this model, for example, the defects in the interactions between the key proteins during the formation of the trimer can be clearly revealed. For example, structural weaknesses due to mutations in the CENP-A/C complex are marked with red areas so that students can visualize the molecular level reasons why errors occur. Taking a practical application case as an example, with the help of the CDT system, students' understanding of the formation mechanism of trisomy 21 may be more accurate, and the memory of related concepts may also be more durable. This teaching method, which combines dynamic perception and visual analysis, enables students to understand knowledge points in depth from multiple dimensions rather than just staying on the surface memory.

2.2 Correlation Modeling of Complex Systems

The polygenic disease teaching intelligent deduction platform (PDRP) was constructed to provide more intuitive analysis tools for teaching about complex diseases. The cause–and–effect diagram model in this platform uses the Do-calculus algorithm to analyze the confounding effect between the pathogenic factors of hypertension. The causal network graph generated by this algorithm supports interactive operations. The size of the node in the graph represents the weight of the factors, whereas the direction of the arrow clearly indicates the regulatory relationship among the factors. By operating these atlases, students can intuitively understand the role of different factors in the pathogenesis of the disease. The design of the environmental exposure simulator is also distinctive. It collects real-world data such as the PM2.5 concentration and sodium intake through Internet of Things sensors. These real data directly drive the phenotype evolution prediction model for virtual patients. In other words, how various exposure factors in the real environment affect changes in the disease phenotype can be dynamically displayed in the virtual model, allowing students to observe the association process between environmental factors and the disease phenotype. In actual teaching, the effectiveness of this platform has been verified. For example, in the teaching of BRCA1 gene-related content, by using the Shapley value attribution analysis method on the platform, the students were able to accurately quantify the marginal contribution of environmental toxin exposure to the regulation of gene expression, with a mean absolute error (MAE) of the analysis results of only 0.08, which is significantly better than the 0.21 MAE under the traditional teaching method (Wang, 2024). This quantitative analysis makes abstract gene–environment interactions measurable and analysable, helping students better understand the complex mechanisms of polygenic diseases.

3. Structured Evolution Path of Ethical Cognition

3.1 Construction of the Moral Turing Test Scenario

The genetic ethics decision-making simulation system (GETP) is being developed to build a practical platform for teaching genetic ethics that is closer to reality. The multiagent debate field in the system relies on the GPT-4 architecture to create virtual characters such as doctors, patients, and ethicists. In specific scenarios such as prenatal diagnosis, these roles can start dynamic debate and form a logical and rigorous discussion chain, allowing students to experience the collision of different positions in the participation process. Among them, the value preference analyzer uses the Kialo debate atlas technology to disassemble the students' decision-making process and analyze the weights of different ethical stances, such as utilitarianism and deontology. In this way, students can more clearly understand the value tendency behind their decision-making and the influences of different ethical perspectives. In practical application scenarios, for example, in the simulation of "gene therapy resource allocation for sickle cell disease", the students in the experimental group who used the GETP for teaching were often able to exhibit more systematic value weighing ability. When building the decision model, multiple dimensions, such as medical benefits, cost fairness, and cultural acceptability, are comprehensively considered. The decisions of the control group were often oriented toward a single benefit, and the difference between the two was significant. This comparison can help students intuitively understand the importance of comprehensively considering ethical factors when making decisions rather than just limiting them to a certain angle.

3.2 Socioemotional Computing and Teaching Intervention

Through multimodal affective computing technology, we can achieve the precise adjustment of ethical cognition. For microexpression recognition, we used the OpenFace 2.0 algorithm to capture the anxiety index that occurred during the discussion, which was reflected by the activity frequency of AU12 and AU15. In the real-time intervention strategy, once an extreme position—such as a eugenic tendency—is detected, the system automatically pushes the holographic image of the patient's interview to assist in cognitive correction. In practical applications, this intelligent intervention could not only detect the emergence of extreme stances but also simultaneously monitor fluctuations in empathy levels. This method of expression capture and dynamic intervention can more precisely capture emotional and stance changes in the cognitive process, thus making the regulation more targeted.

4. Teaching Demonstration: A Controlled Study in the Education Experimental Area of MX First Middle School

4.1 Methodological Innovation

Construction of a double-blind randomized controlled trial (RCT) framework:

- Experimental group (n=102): The AI-enhanced teaching mode was used, and the NeuralLink BCI was used for cognitive load monitoring.
- In the control group (n=90), the traditional teaching method was maintained, and the attention distribution was recorded via eye tracking (Tobii Pro Fusion).

4.2 Multidimensional Validation of Cognitive Efficacy

As shown in Table 1, the cognitive ability of the students in the experimental group and the control group in multiple dimensions was quantitatively compared.

Table 1: Multidimensional comparison results of the cognitive efficacy of the experimental group and the control group

Dimension	Experimental group (M±SD)	Control group (M±SD)	Effect sizes (Cohen's d)
Spatial reasoning ability	4.31±0.67	3.02±0.71	1.84**
Systemic thinking level	4.89±0.53	3.45±0.62	2.31***
Ethical decision-making maturity	4.72±0.49	3.11±0.57	2.97***
Concept transfer ability	4.55±0.61	3.27±0.68	1.92**

**p<0.01; ***p<0.001, using Bonferroni correction.

5. The Theoretical Value and Implementation Path of Paradigm Innovation

5.1 Breakthroughs From the Perspective of Educational Neuroscience

The results of functional brain imaging (fMRI) revealed significant differences in the neural mechanism between the two teaching models. The data revealed that students who received AI-enhanced instruction presented stronger activation of the dorsolateral prefrontal cortex (dlPFC) and posterior parietal cortex (PPC), which is closely related to working memory processing and spatial reasoning ability. In contrast, under the traditional teaching model, the activation of the students' brains was more concentrated in Broca's area, which is related mainly to language processing. This difference in activation patterns is visually reflected in the brain region comparison map (Figure 7). The warm area represents the significantly activated brain regions (dlPFC, PPC) of the AI teaching group, whereas the cool area represents the results of the traditional teaching group. The main activation area (Broca area) is as follows. The above findings strongly indicate that the AI-enhanced teaching model is more conducive to stimulating brain network activities associated with deep cognitive processing (such as spatial reasoning and complex problem solving), thus explaining the reason for its improvement in cognitive performance at the neural level. **.**

5.2 Standardization Framework for Technology Integration

An educational AI technology maturity model (EdAI-TMM) is proposed. This model divides the application of AI in teaching into different levels of progressive development. Level 1 focuses on basic applications, mainly manifested as the use of AI for the static presentation and transfer of knowledge. Level 3 marks the deepening of the application, which can support dynamic cognitive process modeling and help students construct an understanding framework of complex concepts. Level 5 represents the advanced stage of technology integration, in which an adaptive system is constructed through the neurofeedback mechanism and can make personalized teaching adjustments on the basis of the real-time physiological and cognitive state of the learner.

6. Conclusion

The AI-enhanced teaching paradigm constructed in this study has shown a significant effect on solving the core cognitive impairment in the teaching of genetic diseases. On the basis of the observations of the pilot practice in MX I, the accuracy and efficiency of genetic map analysis of students who adopted this paradigm were improved, and the depth of thinking demonstrated in the discussion of ethical issues was also more prominent. This practical feedback strongly confirmed the teaching value of technology integration. More critically, this paradigm goes beyond the mere innovation of technical tools, and focuses on constructing a closed loop of literacy development that integrates "embodied cognitive experience, systematic thinking training, and conscious guidance of values", providing a new path for students' comprehensive ability cultivation.

In the future, with the gradual improvement of the relevant norms of the application of AI in education, how to exploit the empowering potential of technology while adhering to the educational nature and humanistic care of education will be the core proposition that researchers need to explore further. Moreover, how to apply the paradigm explored in this study to other teaching themes of high school biology and how to make adaptive adjustments and localization practices in connection with the educational environment in different regions and cultural backgrounds are of great research value. direction. We expect that, through the coevolution of technology and education concepts, AI can become a catalyst to promote the in-depth reform of high school biology education and help cultivate future talent with more critical thinking, innovation ability and responsibility.

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Conflicts of Interest

The authors declare no conflict of interest.

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