

Effectiveness of Interactive Punnett Square Simulations on Students' Learning Performance in Non-Mendelian Genetics

Aurielyn B. Mangawa  **Maria Theresa A. Estrada** 

University of Luzon Dagupan City, Pangasinan

Corresponding Author: aureejm73@gmail.com

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Abstract: Interactive simulations offer students the chance to visualize and delve into intricate genetic concepts. This research investigated how effective interactive Punnett square simulation-based teaching is in enhancing high school students' understanding of non-Mendelian genetics. A quantitative experimental action research design was utilized, employing a pretest–posttest control group methodology. The study involved 45 biology students, with 26 in the control group and 19 in the experimental group. While the control group received conventional genetics instruction, the experimental group engaged with interactive Punnett square simulations over a three-week period. To assess learning outcomes, researcher-created parallel-form pretests and posttests were administered. Data analysis involved descriptive statistics, independent samples and paired-samples t-tests, and Cohen's d. Findings revealed that both groups showed significant improvement from pretest to posttest. Nonetheless, the experimental group achieved a higher posttest average ($M = 21.84$, $SD = 4.992$) than the control group ($M = 17.46$, $SD = 6.376$), with a notable difference between the groups ($p = .017$). Additionally, the experimental group exhibited a significantly larger mean gain (10.789) than the control group (6.346), $p = .006$, with a substantial effect size ($d = 0.87$). These results suggest that interactive Punnett square simulation-based instruction can be an effective supplementary method for enhancing students' learning in non-Mendelian genetics. The study advocates for the integration of interactive simulations alongside teacher-led instruction to aid in understanding complex inheritance concepts.

Keywords: *Interactive Punnett Square, Non-Mendelian Genetics, interactive simulation, learning performance, Biology education*

INTRODUCTION

Biology education is all about building scientific literacy, which helps students think critically about scientific ideas and tackle real-world issues. Take genetics, for example. It's a key part of biology that helps students get a grip on heredity, genetic variation, gene expression, and how traits are passed down. This understanding is crucial for making sense of advances in health, biotechnology, agriculture, and environmental sciences. Nowadays, science education focuses on applying biological concepts through inquiry-based learning, encouraging students to reason and explain rather than just memorize facts or do hands-on activities without deeper understanding (Dian et al., 2024; Morris, 2025; Mulyono et al., 2024; Romli et al., 2024). But genetics can be tough. Students often find it hard to link genes and chromosomes, genotypes and phenotypes, and meiosis and inheritance. Misunderstandings about dominant and recessive traits can make things even more confusing. Many students go through the motions with Punnett squares without really getting the principles of heredity, which leads to ongoing confusion and poorer learning outcomes (Herak et al., 2025; Kyriazis et al., 2025; Potvin et al., 2024). Tackling these challenges is key to improving genetics education and helping students engage more deeply with the material (Herak et al., 2025). Non-Mendelian genetics adds another layer of complexity

with concepts like incomplete dominance, codominance, multiple alleles, polygenic inheritance, and sex-linked inheritance. These topics require students to think probabilistically and recognize variability beyond just dominant-recessive patterns. Traditional lecture and paper-based Punnett square instruction might not cut it for all learners, highlighting the need for innovative, interactive teaching methods.

Boosting science achievement in the United States is still a big focus because students aren't quite hitting the mark yet. The Next Generation Science Standards (NGSS) are all about getting students to use inquiry skills, scientific modeling, evidence-based reasoning, and applying what they learn to real-world situations. Instead of just memorizing facts, this approach gets students involved in scientific practices to really understand concepts and think critically (Morris, 2025). These goals encourage questioning, explaining, and exploring to build up scientific literacy and reasoning skills. California's adoption of NGSS (CA NGSS) is still facing some hurdles. For instance, in the Los Angeles Unified School District (LAUSD), only 27.28% of students met or exceeded the state science standards on the 2024–2025 California Science Test, which shows there's a need for better teaching methods to boost achievement and engagement (Haverly et al., 2022). Research backs up the idea that inquiry-based learning, which actively involves students with concepts, modeling, data analysis, and reasoning in different contexts, is effective (Clark et al., 2025). Using technology in teaching, especially interactive simulations, seems like a promising way forward. These tools let students play around with variables, visualize complex biological ideas, make predictions, and test scenarios with immediate feedback, helping them understand concepts and link theory with practice (Masbukhin & Kusmawan, 2025; Tarigan et al., 2021). In biology, they're particularly handy for understanding things like genetic inheritance and cellular mechanisms, which can be tough to grasp with just static diagrams or text. Interactive Punnett Square Simulations take this approach to genetics by letting students manipulate parental genotypes and see offspring genotypes and phenotypes in real time. Unlike paper-based Punnett squares, these simulations encourage active learning, immediate hypothesis testing, and repeated exploration, which strengthens understanding of inheritance mechanisms through evidence and experimentation (Williams et al., 2021).

Research shows digital simulations can help students grasp science concepts, like genetics. But technology alone isn't enough. It works best when teachers guide and give feedback alongside these simulations (Ali et al., 2022; Alvarez, 2021; Masbukhin & Kusmawan, 2025). The key is to tie these tools to methods encouraging students to ask questions, analyze evidence, explain findings, and reflect on what they learned. According to Constructivist Learning Theory, interactive simulations are valuable because they help students build knowledge by connecting new experiences with what they already know. Exploring inheritance patterns and seeing results helps them learn. Inquiry-Based Learning fits here, framing simulation activities around questioning, investigating, and reflecting, which boosts scientific reasoning and understanding of genetics (Clark et al., 2025; Morris, 2025). These approaches make interactive simulations a tool that aligns with NGSS objectives. Past research in science education has shown they boost engagement and understanding, especially in Mendelian Genetics and among college students (Farida & Clark, 2025; Kuta et al., 2024; Thomas & S, 2024). However, most studies focus on genetics or Mendelian inheritance, not non-Mendelian topics or high school settings. There's a gap in Interactive Punnett Square Simulations for high schoolers learning Non-Mendelian Genetics. Plus, little evidence from California high school biology classes compares simulation-based learning to traditional methods (Haryanto et al., 2024; Win & Nyunt, 2021). So, this study examines Interactive Punnett Square Simulation-Based Instruction for high school students learning Non-Mendelian Genetics by analyzing pre-, post-, and mean gain scores.

RESEARCH QUESTIONS

This study aimed to determine the effectiveness of Interactive Punnett Square Simulation-Based Instruction in improving students' learning performance in non-Mendelian genetics. Specifically, it

sought to answer the following questions:

1. What was the learning performance of the control and experimental groups in non-Mendelian genetics based on their pre- and post-test scores?
2. Is there a significant difference between the control and experimental groups in terms of the following variables?
 - a. pretest scores;
 - b. posttest scores; and
 - c. means gain scores?
3. Was there a significant difference between the pretest and post test scores of the control group?
4. Was there a significant difference between the pretest and posttest scores of the experimental group?

METHODS

Research Design

This study employed a quantitative experimental action research design using a pretest–posttest control group approach to determine the effectiveness of interactive Punnett square simulation-based instruction in improving students' learning performance in non-Mendelian genetics. Two intact biology classes were assigned at the class level to control and experimental conditions. The control group received traditional genetics instruction, while the experimental group received interactive Punnett square simulation-based instruction. This design allowed the researcher to compare students' learning performance before and after the intervention and between the two instructional approaches.

Participants and Sampling Technique

The participants were 45 high school biology students from two intact classes at William Howard Taft Charter High School, California. The control group consisted of 26 students, while the experimental group consisted of 19 students. Purposive sampling was used to select classes that met the study requirements, after which the two classes were randomly assigned to the instructional conditions. Students were included if they were enrolled in the selected biology classes and had not yet received formal instruction in non-Mendelian genetics.

Research Instrument

The study used researcher-developed parallel-form pretest and posttest assessments, each consisting of 30 multiple-choice items covering incomplete dominance, codominance, multiple alleles, polygenic inheritance, and sex-linked inheritance. The instruments were aligned with the biology learning competencies through Tables of Specifications. Content validity was evaluated by four Biology and science education experts, resulting in mean validity ratings of 3.65 for the pretest and 3.67 for the posttest, both interpreted as *highly valid*. Pilot testing yielded KR-20 reliability coefficients of 0.669 and 0.667, respectively. Item analysis was conducted, and the identified items were revised before the actual administration.

Data Gathering Procedure

After securing the necessary school approval, parental consent, and student assent, both groups were administered a pretest to establish their baseline learning performance. The intervention was then conducted face-to-face for three weeks during regular 54-minute Biology classes. The experimental group received Interactive Punnett Square Simulation-Based Instruction using digital genetics resources, while the control group received traditional instruction through lectures, discussions, demonstrations, and paper-based activities. Both groups covered the same non-Mendelian genetics content and learning competencies. After the intervention, a parallel-form posttest was administered, and the students' pretest, posttest, and gain scores were recorded for analysis.

Data Analysis Procedure

The data were analyzed using IBM SPSS Statistics Version 32. Mean and standard deviation were used to describe students' pretest and posttest performance. Normality was examined using the Kolmogorov–Smirnov and Shapiro–Wilk tests and graphical procedures. Independent-samples t-tests were used to compare the control and experimental groups, while paired-samples t-tests were used to determine changes from pretest to posttest within each group. Cohen's d was calculated to determine effect size. All statistical tests were evaluated at the .05 level of significance.

RESULTS AND DISCUSSION

Table 1. Pretest and Posttest Learning Performance of the Control and Experimental Groups

Group	n	Pretest M	Pretest SD	Posttest M	Posttest SD	Mean Gain
Control	26	11.12	4.255	17.46	6.376	6.346
Experimental	19	11.05	4.720	21.84	4.992	10.789

In Table 1, a comparison of the control and experimental groups' learning uses pre- and post-test assessments. Both groups started with similar pretest scores. The control group had an average of 11.12 (SD = 4.255), while the experimental group was at 11.05 (SD = 4.720). This tells us they were at a similar level before the intervention. After the treatment, the control group's posttest average jumped to 17.46 (SD = 6.376), a gain of 6.346. But the experimental group stood out, with their posttest average climbing to 21.84 (SD = 4.992), a bigger gain of 10.789 points. This shows that the experimental group improved more than the control group. The bigger gain in the experimental group suggests that the intervention, probably skills-based learning material, was effective in boosting student outcomes beyond what the control group achieved. This conclusion is in line with other research using pretest-posttest non-equivalent control group designs, which also found significant differences between the groups. The experimental interventions showed large effect sizes (like Cohen's $d = 1.16$) compared to smaller effect sizes in the control groups (like Cohen's $d = 0.31$) (Lumanog & Medrano, 2021). So, innovative learning materials or approaches can enhance learners' performance compared to traditional methods.

Table 2. Difference Between the Pretest Learning Performance of the Control and Experimental Groups

Group	n	M	SD	t	df	p	d	Decision
Control	26	11.12	4.255	0.047	43	.963	0.02	Fail to reject H_0
Experimental	19	11.05	4.720					

The data in Table 2 show how the control and experimental groups performed on the pretest before any intervention was applied. Both groups had almost the same average scores: the control group scored an average (M) of 11.12 (SD = 4.255), while the experimental group scored 11.05 (SD = 4.720). A t-test was done to see if there were any significant differences between these pretest scores. The test gave a t-value of 0.047 with 43 degrees of freedom, and the p-value was 0.963, which is way above the usual alpha level of 0.05. This means there wasn't a statistically significant difference in pretest scores between the groups. The effect size calculated ($d = 0.02$) also showed a negligible difference, confirming that the groups were pretty much the same at the start. The decision to "fail to reject H_0 " (the null hypothesis that there's no difference) confirms that both the control and experimental groups began with similar learning performance before the treatment. Establishing this baseline equivalence is crucial in experimental and quasi-experimental designs to make sure that any differences seen in posttest outcomes can be confidently linked to the intervention, rather than any pre-existing differences between the groups (Herlambang et al., 2024; Ismail, 2022; Lumanog & Medrano, 2021). This kind of rigor supports the internal validity of the study and strengthens claims about how effective the intervention is.

Table 3. Difference Between the Posttest Learning Performance of the Control and Experimental Groups

Group	n	M	SD	t	df	p	d	Decision
Control	26	17.46	6.376	-2.487	43	.017	0.75	Reject H_0
Experimental	19	21.84	4.992					

The data in Table 3 show there's a clear difference in post-test learning performance between the control and experimental groups. The control group had an average score of 17.46 (SD = 6.376), while the experimental group did much better, with an average of 21.84 (SD = 4.992). The independent samples t-test gave us a t-value of -2.487 with 43 degrees of freedom and a p-value of .017, which is below the usual significance level of 0.05. This means we can reject the null hypothesis (H_0), suggesting that the difference in post-test scores between the groups probably isn't just by chance. An effect size of 0.75 indicates that the intervention had a moderate to large practical impact on learning outcomes. These results are in line with previous experimental studies using pretest-posttest control group designs, showing that educational interventions, like e-learning supported by social reality videos or skills-based learning materials, significantly boost student performance compared to traditional methods (Ismail, 2022; Lumanog & Medrano, 2021). Such research often reports not only statistically significant differences but also substantial effect sizes, highlighting the positive impact of innovative teaching strategies on improving students' cognitive outcomes.

Table 4. Pretest–Posttest Difference in the Control Group

Comparison	Pretest M (SD)	Posttest M (SD)	Mean Gain	t	df	p	d	Decision
Control group	11.12 (4.255)	17.46 (6.376)	6.346	-5.862	25	< .001	1.15	Reject H_0

The data in Table 4 demonstrate a significant improvement in learning performance within the control group from the pretest to the posttest. The control group's mean score increased from 11.12 (SD = 4.255) in the pretest to 17.46 (SD = 6.376) in the posttest, resulting in a mean gain of 6.346. A paired t-test analysis yielded a t-value of -5.862 with 25 degrees of freedom and a p-value less than .001, indicating that this improvement was statistically significant. The calculated effect size (Cohen's d) of 1.15 suggests a large practical impact of the learning experience on the control group performance. This significant pretest-posttest improvement aligns with the findings of multiple quasi-experimental and experimental studies employing similar pretest-posttest designs in educational settings. Such designs consistently reveal that learning interventions or instructional exposure, even under control conditions, can lead to notable gains in knowledge or skills (Ismail, 2022; Lumanog & Medrano, 2021). The effect size here is comparable to that observed in interventions utilizing e-learning with social reality videos and skills-based learning materials, emphasizing the efficacy of structured educational programs in improving knowledge.

Table 5. Pretest–Posttest Difference in the Experimental Group

Comparison	Pretest M (SD)	Posttest M (SD)	Mean Gain	t	df	p	d	Decision
Experimental group	11.05 (4.720)	21.84 (4.992)	10.789	-10.499	18	< .001	2.41	Reject H_0

Table 5 shows how much the experimental group's learning performance improved after the intervention. The average score jumped from 11.05 (SD = 4.720) in the pretest to 21.84 (SD = 4.992) in the post-test, which means there was a gain of 10.789 points. The paired-sample t-test results showed a big difference ($t(18) = -10.499$, $p < .001$), so we rejected the null hypothesis. Plus, the effect size (Cohen's d) of 2.41 suggests the intervention had a huge impact on students' learning outcomes in this study. This

result is similar to what other studies have found when looking at educational interventions with pretest-posttest designs. For example, significant gains with large effect sizes have been seen in studies using active learning strategies like the Quiz Team Learning Model (Sitio & Habeahan, 2023), PowerPoint-assisted Think-Pair-Write models (Muis & Priawasana, 2022), and educational media like Word Wall learning media (Sitepu & Pulungan, 2024). In these studies, students showed significant improvements in learning outcomes, proving the effectiveness of the instructional methods used. The large effect size here highlights the strong influence of the intervention, aligning with findings that effective teaching strategies supported by innovative materials or methods can significantly boost students' academic performance. So, the experimental treatment in Table 5 clearly shows educational effectiveness, supporting its use for improving learning achievement.

Table 6. Difference Between the Mean Gain Scores of the Control and Experimental Groups

Group	n	Pretest M	Posttest M	Mean Gain	SD	t	df	p	d	Decision
Control	26	11.12	17.46	6.346	5.520	-2.881	43	.006	0.87	Reject H ₀
Experimental	19	11.05	21.84	10.789	4.479					

Table 6 highlights a difference in average gain scores between the control and experimental groups. The control group, with 26 participants, had a gain of 6.346 (SD = 5.520). The experimental group, with 19 participants, showed a higher gain of 10.789 (SD = 4.479). An independent samples t-test gave a t-value of -2.881, with 43 degrees of freedom and a p-value of .006, below the significance level of 0.05. This means we can reject the null hypothesis (H₀), showing that the experimental group improved significantly more than the control group. The effect size, Cohen's d = 0.87, indicates a large impact of the intervention. These results are consistent with educational studies, both quasi-experimental and experimental. For instance, pretest-posttest non-equivalent control group designs often report significant mean gain differences favoring experimental groups, with large effect sizes showing how effective educational interventions can be in boosting learning outcomes (Lumanog & Medrano, 2021). Similarly, this effect size is comparable to findings in medical education research, where effect sizes between 0.53 and 0.9 indicate meaningful learning gains from targeted educational strategies (Görllich & Friederichs, 2021). Overall, the data in Table 6 confirm that the experimental method led to better learning gains than the control, supporting its effectiveness in enhancing student performance.

CONCLUSION

The study found that using Interactive Punnett Square Simulation-Based Instruction really helped students do better in non-Mendelian genetics. Both the control and experimental groups showed a lot of improvement from the pretest to the posttest. However, the students who used the interactive simulation scored higher on the posttest and had bigger learning gains compared to those who learned through traditional genetics instruction. The noticeable difference in the average gain scores, along with the large effect size, shows that adding interactive simulations can really help in understanding complex inheritance patterns. These results suggest that Interactive Punnett Square Simulations can be a great extra tool for helping students grasp and perform better in non-Mendelian genetics. But it's important to keep in mind that these findings are based on a small sample and just two biology classes.

RECOMMENDATIONS

From what we've found, biology teachers should think about adding interactive Punnett square simulations to their toolkit, especially when tackling non-Mendelian genetics. These tools can really help students get a grip on those tricky inheritance patterns. Schools can pitch in by making sure

teachers have the tech they need and chances to beef up their skills in using simulations and inquiry-based teaching. Both groups of students showed progress, so it's clear that while these simulations are great, they should work alongside teacher guidance, class discussions, and other tried-and-true teaching methods. For future research, it'd be great to see this study done again with bigger and more varied groups, across different schools and classes, over longer periods, and with better randomization. Researchers might also want to look into other outcomes like how well students understand the concepts, remember the information, reason scientifically, solve problems, and stay engaged and motivated. This could give us a fuller picture of how effective simulation-based genetics teaching really is.

LIMITATIONS OF THE STUDY

When looking at the results of this study, there are a few limitations to keep in mind. First off, we only had 45 students from two biology classes at one high school, so it's hard to say if these findings apply to other students or schools. Also, the intervention was just three weeks long, so we couldn't see if the learning improvements stuck around over time. Plus, the two classes were put into different teaching setups, which might have affected the outcomes. Lastly, we only looked at learning performance through pretest and posttest scores, without considering things like student engagement, motivation, retention, or their attitudes toward genetics. So, it's important to view these findings within the specific context and conditions of this study.

FUTURE RESEARCH DIRECTIONS

In the future, researchers might want to look into how well Interactive Punnett Square Simulation-Based Instruction works by involving larger and more varied groups of students from different schools. They could also try longer teaching sessions and use delayed posttests to see if students remember what they've learned over time. It would be interesting to explore other outcomes too, like how well students understand concepts, their scientific reasoning, problem-solving skills, engagement, motivation, and attitudes toward genetics. Studies that include multiple class sections, different teachers, and better randomization methods are also suggested to give stronger evidence on how effective interactive simulations are for teaching non-Mendelian genetics.

ETHICS STATEMENT

In this study, we adhered to the ethical principles for research with human participants. Before data collection, we secured permissions from the administration of William Howard Taft Charter High School and the Biology Department. Because our participants were high school students, we obtained written informed consent from their parents or legal guardians and the students' assent before participation. Participation was voluntary, with students clearly informed about the study's purpose and procedures and their right to opt out at any time without penalty or negative impact on their academic standing. Whether or not they participated, students' grades and classroom status remained unaffected. Throughout the study, we safeguarded participant privacy and confidentiality by using identification codes instead of names during data recording, analysis, and reporting. Research data were securely managed and used only for the study's stated objectives. Every step of the research process was carried out with awareness of the participants' rights, welfare, privacy, and educational interests.

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AI DISCLOSURE STATEMENT

During the preparation of this manuscript, the author used Google Search AI Mode, Perplexity AI, and Claude to assist with the refinement of manuscript sections, academic language and grammar, consistency of presentation, and verification and correction of in-text citations against the reference list. These tools were not used to generate, manipulate, or analyze the research data or to determine the study findings. Following the use of these tools, the author reviewed, verified, and edited all AI-assisted content to ensure accuracy, consistency with the original research, and appropriate scholarly presentation. The author takes full responsibility for the content, interpretations, conclusions, and integrity of the published work.