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Modeling the Invisible: Effects of a Blender-Designed Interactive 3D DNA Model on Technology-Enhanced Biology Learning in Moroccan Secondary Schools.

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Abstract

Digital visualization tools are increasingly used in science education for concepts that are abstract, microscopic, and spatially complex. This study examines the effect of a Blender-designed interactive three-dimensional DNA model, integrated into the BioStrato web platform, on Moroccan secondary students' conceptual understanding of DNA structure. A quasi-experimental pre-test/post-test control-group design was conducted with sixty second-year Baccalaureate students majoring in Life and Earth Sciences, assigned to conditions at the intact-class level. The experimental group of thirty students learned DNA structure through a teacher-guided lesson supported by the interactive model, while the control group of thirty students received conventional instruction using teacher explanation and static two-dimensional diagrams. Learning outcomes were measured with a twenty-item achievement test, and experimental-group perceptions were explored through a post-intervention questionnaire and structured classroom observation. The two groups did not differ at pre-test. Both groups improved after instruction, but the experimental group achieved a higher mean learning gain than the control group. An analysis of covariance on post-test scores, controlling for pre-test scores, confirmed a significant group effect with a medium effect size. Questionnaire responses and classroom observations indicated that students perceived the model as clear, motivating, and useful for visualizing molecular structure. The findings suggest that accessible open-source three-dimensional modeling tools, when integrated into a structured teaching sequence, can enhance technology-supported biology learning in resource-constrained secondary-school contexts.

Keywords

Technology-enhanced learning; 3D modeling; Blender; interactive visualization; biology education; DNA structure; secondary education; Morocco

Introduction

Molecular biology requires students to reason about structures that are invisible, three-dimensional, and spatially organized. DNA is a representative case: learners must coordinate nucleotide composition, complementary base pairing, antiparallel strand orientation, and double-helix geometry, none of which can be observed directly. These demands make DNA structure conceptually difficult, and research consistently reports that secondary students confuse the related concepts of gene, DNA, and chromosome and struggle to connect molecular structure to biological function (Machová & Ehler, 2023). Conventional two-dimensional textbook diagrams often leave students to reconstruct the spatial organization on their own. Interactive three-dimensional models and animations offer a promising response to these difficulties. Unlike static diagrams, they allow learners to observe, rotate, zoom, and inspect molecular structures from different perspectives, which can help them build more accurate mental models. Research on multimedia learning suggests that combining verbal explanation with visual representation supports understanding when the material is coherent, segmented, and pedagogically guided (Mayer, 2009), and a meta-analysis found that animations can enhance learning compared with static graphics, although their effectiveness depends on instructional design (Berney & Bétrancourt, 2016).

Empirical studies increasingly support the educational value of 3D models and animations. Three-dimensional models and animations can positively affect students' learning outcomes and intrinsic motivation in natural science education, particularly when integrated into meaningful teaching scenarios (Teplá et al., 2022). In molecular biology, interactive 3D learning modules can improve students' understanding of DNA structure-function relationships (Howell et al., 2019). More recent syntheses of immersive and three-dimensional visualization in biology classrooms similarly report positive effects on achievement and motivation, while cautioning that effect sizes vary with instructional design and intervention duration (Faria & Lobato Miranda, 2024). These findings suggest that 3D visualization may be especially useful for teaching abstract and spatially demanding molecular concepts such as DNA.

In the Moroccan secondary-school context, the teaching of genetics faces additional practical and didactic challenges. Teachers often work with dense curricula, limited digital resources, and classroom conditions where traditional explanation and two-dimensional textbook diagrams remain dominant; surveys of Moroccan science classrooms repeatedly identify inadequate equipment, limited teacher training, and weak technical support as barriers to integrating educational technology (Ait Hammou & Elfatihi, 2021). Where such barriers are addressed, locally designed digital resources can be effective: a pre-test/post-test study with two hundred Moroccan secondary students found that integrating interactive 3D animation into nuclear-physics instruction significantly improved conceptual modeling, motivation, and autonomy relative to conventional teaching (Taoussi et al., 2026). These constraints make it important to explore accessible, low-cost digital tools that can be realistically integrated into ordinary biology lessons. Blender, an open-source 3D modeling software, offers a practical opportunity to design educational molecular models without requiring expensive commercial tools, and when integrated into a web-based platform such models may provide a more interactive and visually meaningful learning experience.

Within this perspective, the present study investigates the effect of a Blender-designed interactive 3D DNA model, integrated into the BioStrato platform, on Moroccan secondary students' conceptual understanding of DNA structure, and explores students' perceptions of the model in terms of clarity, motivation, retention, and perceived learning support. The study is guided by two research questions. First, does the use of an interactive 3D DNA model improve secondary students' conceptual understanding of DNA structure compared with conventional 2D instruction? Second, how do students perceive the use of the interactive 3D DNA model in terms of clarity, motivation, retention, and learning support?

The remainder of this article is organized as follows. The next section presents the materials and methods, including the epistemological positioning and research design, the participants and study context, the Blender-designed 3D DNA model and the control condition, the measurement instruments, and the data-analysis procedures. The following section reports the results, covering baseline equivalence, learning gains, students' perceptions of the model, and classroom observations. The discussion then interprets these findings in light of prior research on multimedia learning and molecular visualization, and the conclusion summarizes the study's main contributions, limitations, and implications for teaching abstract molecular concepts in resource-constrained secondary-school contexts.

1. Materials and Methods

1.1. Research Design

This study adopted a quasi-experimental pre-test/post-test control-group design to examine the effect of an interactive 3D DNA model on secondary students' conceptual understanding. This design was selected because the intervention was implemented in a real classroom setting, where strict individual randomization was not compatible with normal school organization. Quasi-experimental designs are commonly used in educational intervention research when researchers compare instructional conditions while preserving ecological validity (Shadish et al., 2002). Two groups participated: an experimental group that learned DNA structure using the Blender-designed interactive 3D model integrated into the BioStrato platform, and a control group that received conventional instruction based on teacher explanation and static two-dimensional diagrams. Both groups completed the same achievement test before and after the instructional sequence.

The choice of this design reflects an explicit epistemological and methodological positioning. The study is situated within a post-positivist paradigm, which assumes that educational phenomena can be investigated objectively through measurable indicators while acknowledging that such measurement remains approximate and context-dependent. Consistent with this stance, the research follows a hypothetico-deductive mode of reasoning: a testable expectation that learning supported by an interactive 3D model would produce greater conceptual gains than conventional two-dimensional instruction was derived from the literature and then examined empirically by comparing an experimental and a control group under equivalent conditions. A quantitative quasi-experimental approach was therefore considered the most appropriate way to answer the research questions, and it was complemented by descriptive questionnaire and observation data in order to interpret the measured effects within their real classroom context.

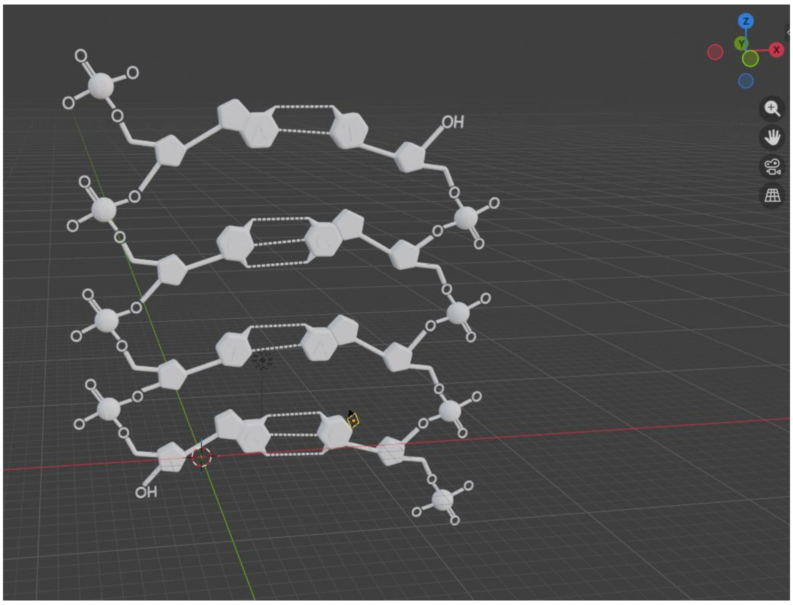
1.2. Participants and Study Context

The participants were sixty Moroccan second-year Baccalaureate students majoring in Life and Earth Sciences. Assignment to conditions was carried out at the level of intact class groups rather than by individual randomization: two pre-existing class groups of thirty students each were assigned, one to the experimental condition and one to the control condition. Group-level assignment of intact classes is the reason the design is quasi-experimental rather than a true experiment, and baseline equivalence was therefore tested empirically (Section 2.1). The two groups were taught by the same teacher, followed the same curricular objectives, and received the same lesson duration, in order to reduce variation related to teacher effect, instructional time, and curricular content. The main difference between the two groups was the type of visual instructional support used during the lesson.

1.3. Instructional Material: Blender-Designed 3D DNA Model

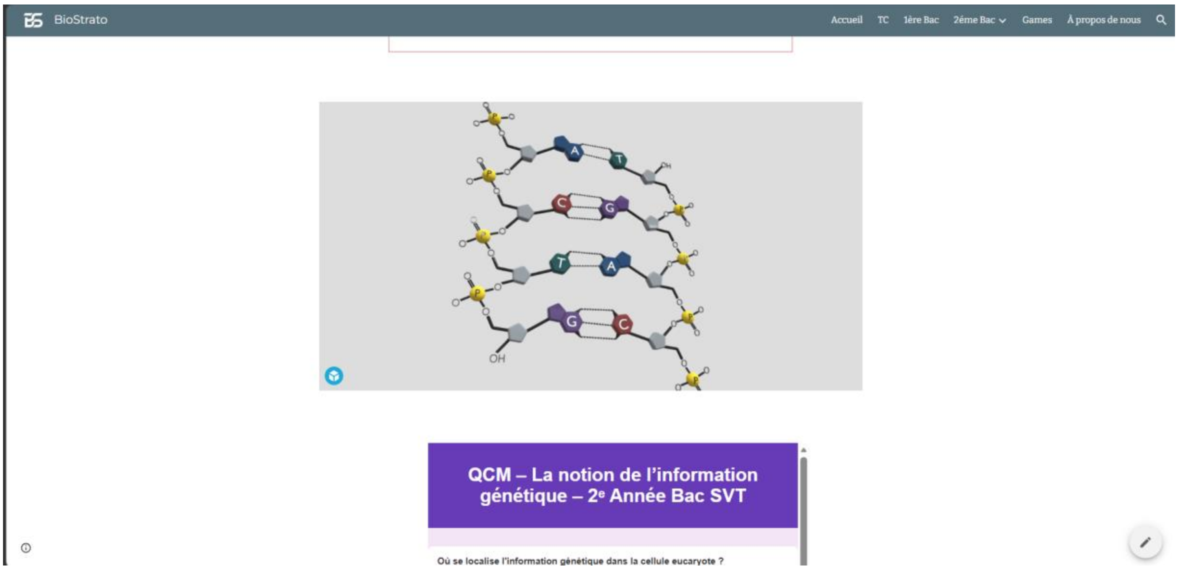
The main instructional material in the experimental condition was an interactive 3D model of DNA developed with Blender and integrated into the BioStrato platform. The model represented the B-DNA double helix and was built from nucleotide units showing the phosphate group, deoxyribose sugar, and nitrogenous bases. Adenine-thymine and cytosine-guanine base pairs were represented with visible hydrogen-bond links, while the sugar-phosphate backbone and helix organization were made accessible through rotation, zooming, and guided inspection. The model drew on the canonical structural description of DNA as a double helix (Watson & Crick, 1953). During the lesson, the teacher projected the model and manipulated it in real time to illustrate helix rotation, strand arrangement, nucleotide organization, and complementary base pairing, and students were given guided opportunities to interact with it. The instructional use of the model followed multimedia and cognitive-load principles by combining oral explanation with visual manipulation, focusing attention on relevant molecular features, and segmenting the explanation into manageable steps (Mayer, 2009; Sweller, 1988).

Figure N°1 : The Blender-designed interactive 3D DNA model.



Source : Authors' own work (modeled in Blender).

Figure N°2 : The 3D DNA model integrated into the BioStrato web platform.



Source : Authors' own work (BioStrato web platform).

1.4. Control Condition

The control group received the same curricular content, lesson duration, and teacher explanation as the experimental group. Instruction relied on textbook diagrams, board explanation, and verbal guidance, and no interactive digital 3D model was used. This clarification is important because the comparison concerns the added value of interactive 3D visualization relative to conventional 2D diagram-based instruction.

1.5. Instruments

Students' conceptual understanding of DNA structure was assessed using a twenty-item achievement test administered before and after the intervention. The test included multiple-choice and short-answer questions covering nucleotide composition, complementary base pairing, double-helix organization, strand arrangement, and the relationship between DNA structure and biological function. It was aligned with the Moroccan biology curriculum and reviewed by biology teachers to support content validity. Multiple-choice items were scored as one (correct) or zero (incorrect); short-answer items used a partial-credit rubric. Internal consistency was acceptable for classroom-based research (Cronbach's alpha = 0.78). Cronbach's alpha is widely used to estimate internal consistency, but it should not be interpreted as evidence of validity by itself and should be understood in relation to the purpose and structure of the instrument (Tavakol & Dennick, 2011).

Students in the experimental group completed a post-intervention questionnaire exploring their perceptions of the model in terms of clarity, motivation, understanding, retention, and willingness to use similar tools in future lessons. All items concerned aspects of DNA structure addressed in the lesson. Items used a Likert-type response format, and internal consistency was good (Cronbach's alpha = 0.85). Because the questionnaire was administered only to the experimental group, responses are reported as counts and percentages out of thirty. A structured classroom observation grid documented visible indicators of student engagement, including attention, spontaneous questioning, participation, visible confusion, interaction with instructional materials, and willingness to discuss the model. Structured observation grids of this kind are recommended for documenting classroom behaviors and instructional interactions when the categories are clearly defined (Anwar & Menekse, 2021; Birdwell et al., 2016). No inter-rater reliability was calculated because the observation was conducted by a single observer; the observation results are therefore treated as contextual information rather than independent quantitative evidence.

1.6. Procedure

The study was conducted in three stages. First, both groups completed the achievement pre-test under the same classroom conditions, to assess prior knowledge of DNA structure. Second, both groups received a two-hour lesson on DNA structure; the experimental group learned with the support of the interactive 3D model, while the control group learned through conventional explanation and 2D visual supports, with the same teacher delivering both lessons using the same objectives and duration. Third, both groups completed the post-test immediately after instruction; the experimental group also completed the perception questionnaire, and classroom observations were recorded during the sessions.

1.7. Data Analysis

Means and standard deviations were computed for pre-test, post-test, and gain scores, where gain was the post-test score minus the pre-test score for each student. Baseline equivalence was tested with an independent-samples t-test on pre-test scores. The primary analysis of the intervention effect was an analysis of covariance on post-test scores, with group as the fixed factor and pre-test score as the covariate; this approach was preferred over a t-test on gain scores because it adjusts for residual pre-test differences and provides greater statistical power in pre-test/post-test designs. For comparability with prior studies, an independent-samples t-test on gain scores and Cohen's d are also reported. Reporting both significance and effect size is recommended in educational intervention research because p-values alone do not indicate the practical magnitude of an effect (Upsher et al., 2025). Questionnaire responses were summarized as frequencies and percentages; observation notes were analyzed thematically.

2. Results

2.1. Baseline Equivalence and Descriptive Statistics

An independent-samples t-test on pre-test scores indicated no significant difference between the experimental and control groups, $t(58) = 0.35$, $p = .73$, confirming comparable prior knowledge before the intervention. Table 1 summarizes the pre-test, post-test, and gain scores.

Table N°1 : Descriptive statistics of pre-test and post-test scores.

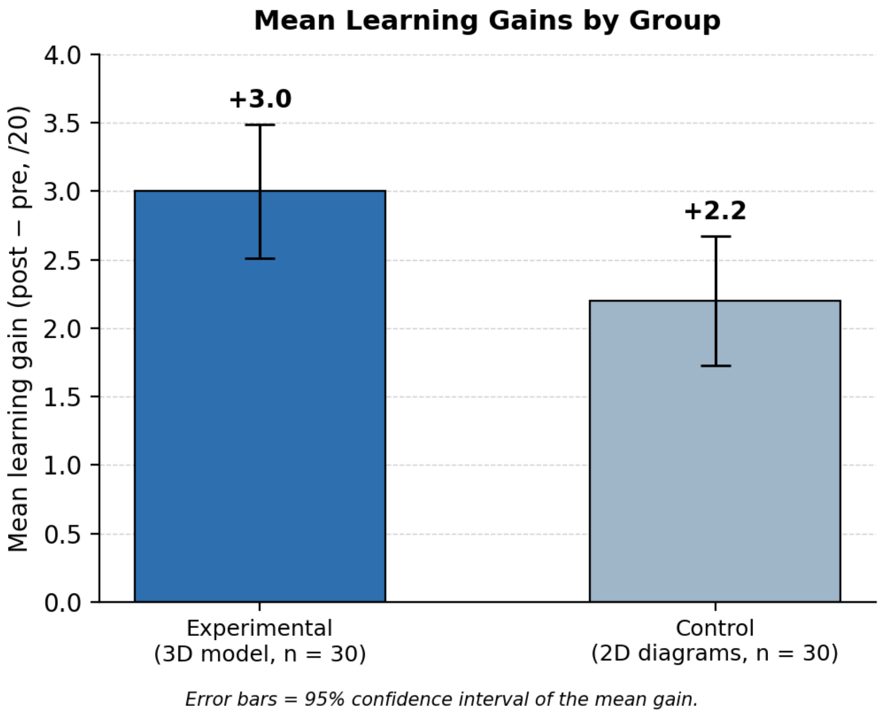
Group	n	Pre-test (M ± SD)	Post-test (M ± SD)	Gain (M ± SD)
Experimental	30	12.1 ± 2.3	15.1 ± 2.5	+3.0 ± 1.31
Control	30	11.9 ± 2.1	14.1 ± 2.4	+2.2 ± 1.27

Source : Authors.

2.2. Learning Gains

Both groups improved significantly from pre-test to post-test. Paired-samples t-tests showed significant within-group progress in the experimental group, $t(29) = 12.54$, $p < .001$, and in the control group, $t(29) = 9.49$, $p < .001$. The primary between-group analysis, an analysis of covariance on post-test scores with pre-test score as the covariate, showed a significant effect of group, $F(1, 57) = 5.81$, $p = .019$, partial eta squared = .09, with adjusted post-test means of 15.08 (experimental) and 14.12 (control). The independent-samples t-test on gain scores was consistent, $t(58) = 2.41$, $p = .019$, Cohen's $d = 0.62$, a medium and educationally meaningful effect. These results answer the first research question by showing that the interactive 3D model was associated with greater conceptual learning gains than conventional 2D instruction (Figure 3).

Figure N°3 : Comparison of mean learning gains between the experimental and control groups.

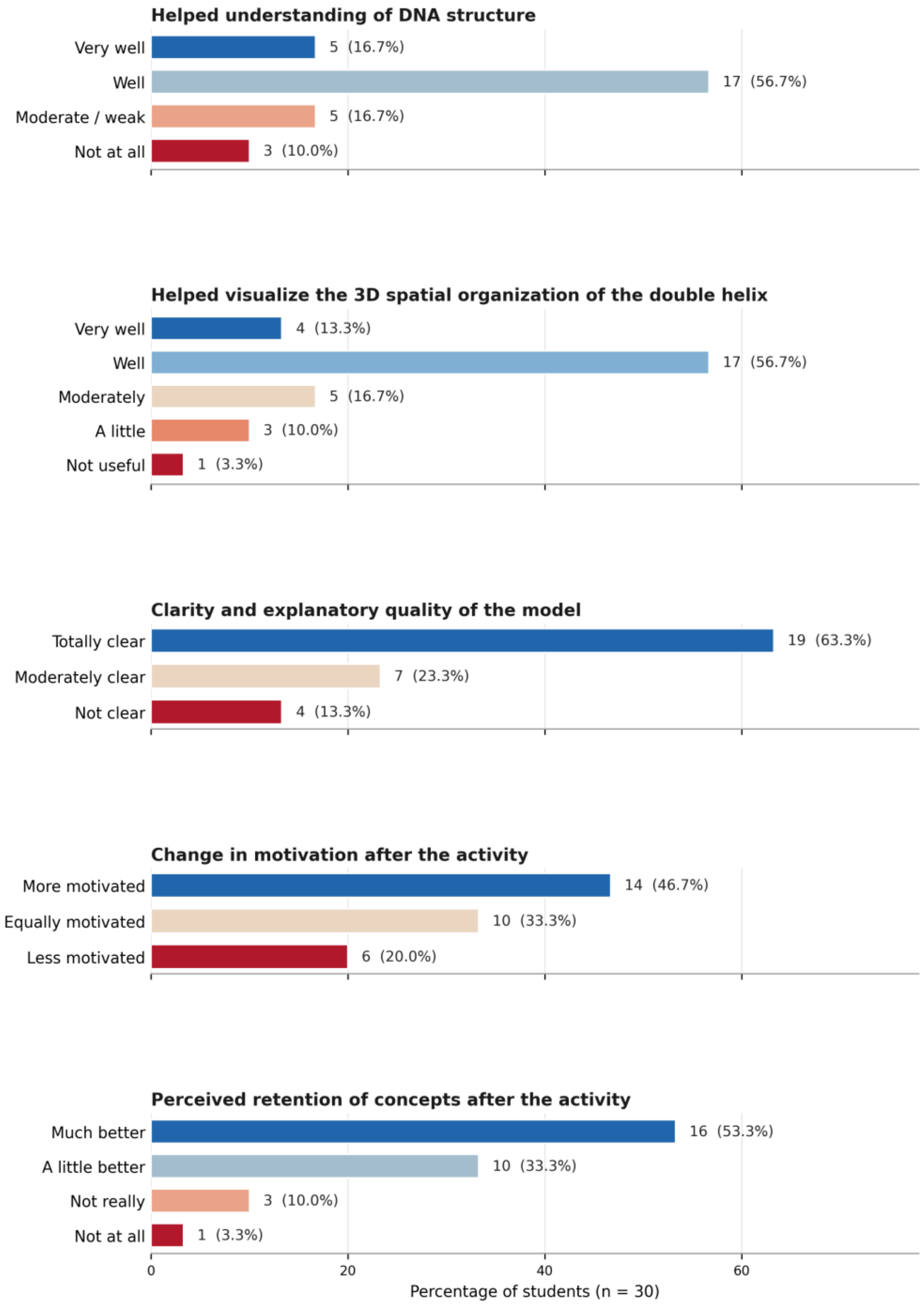


Source : Authors. Error bars represent 95% confidence intervals of the mean gain.

2.3. Students' Perceptions of the 3D Model

Overall, questionnaire responses suggested that students perceived the model as helpful for visualizing DNA structure, clarifying the relationship between bases and strands, increasing interest, and supporting memorization (Figure 4). Because the questionnaire was exploratory and not statistically compared with the control group, these findings are interpreted as descriptive evidence only. Notably, six of thirty students (20.0%) reported feeling less motivated after the activity; this minority response is considered further in the discussion.

Figure N°4 : Students' perceptions of the 3D DNA model (post-intervention questionnaire, n = 30).



Source : Authors. Each panel shows one questionnaire item; response options are ordered from most positive (top) to most negative (bottom).

2.4. Classroom Observations

Observation notes indicated differences in the quality of classroom participation (Table 2). In the experimental group, students more frequently asked spontaneous questions, requested clarification about base pairing, and volunteered to interact with the visual model. In the control group, engagement was more conventional and centered on note-taking and responses to teacher prompts. These observations support the interpretation that the 3D model encouraged exploratory participation, but they remain qualitative because the observation process did not include multiple raters or inter-rater reliability.

Table N°2 : Qualitative classroom observation summary.

Observation dimension	Experimental group pattern	Control group pattern
Attention	Sustained visual attention during model manipulation	Sustained but mostly passive attention
Spontaneous questioning	More frequent questions about DNA structure and base pairing	Mostly responses to teacher questions
Participation	Voluntary interaction with the model and peer discussion	Mainly note-taking and guided answers
Confusion / scaffolding	Some students needed slower pacing and clearer segmentation	Confusion addressed mainly through teacher explanation
Interaction with material	Direct exploration of rotation, zoom, and visual features	Interaction limited to static diagrams and verbal explanation

Source : Authors.

3. Discussion

This study examined whether a Blender-designed interactive 3D DNA model could improve Moroccan secondary students' conceptual understanding of DNA structure compared with conventional 2D instruction. Both groups improved after instruction, but the experimental group achieved a higher learning gain, suggesting that the interactive model provided added instructional value beyond teacher explanation and static diagrams. The medium effect size indicates that the difference was not only statistically significant but also educationally meaningful for a classroom-based intervention.

One possible explanation is that the model helped students overcome the representational difficulty of DNA structure. Learning DNA requires coordinating several elements at once: nucleotide composition, complementary base pairing, sugar-phosphate backbones, strand orientation, and double-helix organization. When these are presented only through static 2D diagrams, learners must mentally reconstruct the spatial structure themselves, which is difficult for students with limited visuospatial reasoning skills. Research on multiple representations shows that visual supports improve learning when they help students connect different forms of representation and when their design is aligned with the learning task (Ainsworth, 2006). The ability to interpret external representations in biochemistry depends jointly on conceptual knowledge, reasoning, and the mode of representation itself, which helps explain why an explicit 3D representation may reduce the interpretive load that static diagrams place on novices (Schönborn & Anderson, 2009); visual representations support understanding only when learners' prior knowledge and cognitive load are managed (Cook, 2006).

The findings are consistent with research on molecular visualization and structure-function learning. Students' understanding of DNA structure-function relationships improved after using dynamic 3D learning modules (Howell et al., 2019), and such models can be designed specifically to address common misconceptions about molecular structure (Howell et al., 2018). These studies show that the value of 3D models is not limited to visual appeal; it lies in helping students inspect molecular features, relate structure to function, and correct incomplete mental models. The positive learning gains can also be interpreted through the broader literature on animation and 3D visualization, which shows that 3D illustration, animation, and interactive animation contribute to learning when combined with appropriate narration and text (Berney & Bétrancourt, 2016; Korakakis et al., 2009). Recent syntheses focused specifically on biology likewise report consistent positive effects on achievement and motivation while underscoring that benefits depend on pedagogical structure rather than the technology alone (Faria & Lobato Miranda, 2024).

Students' questionnaire responses suggest that the model was perceived as clear, motivating, and useful for retention, aligning with reports that 3D models and animations increase intrinsic motivation in natural science education (Teplá et al., 2022), and with research on biology animations arguing that animation helps novice learners visualize complex processes difficult to infer from static representations alone (McClean et al., 2005). These findings should be interpreted cautiously, however. Because the questionnaire was administered only to the experimental group, the results cannot prove that the model produced statistically higher motivation than conventional instruction; they describe how students experienced the lesson, and positive perceptions may also reflect novelty or curiosity. Moreover, the finding that twenty percent of students felt less motivated indicates that the tool was not uniformly experienced as beneficial and is consistent with reports that some students found the animation too rapid or technical. This reinforces the view that technology-enhanced representations are most effective when pedagogically structured rather than used as attractive add-ons (Ainsworth, 2006; Berney & Bétrancourt, 2016; Cook, 2006).

The classroom observations also support the interpretation that the model encouraged more active engagement, functioning as a shared visual object around which teacher explanation and student inquiry could be organized. Nevertheless, these data remain illustrative because no systematic counting or inter-rater reliability procedure was applied; future studies should strengthen this component using two trained observers, predefined behavioral indicators, and inter-rater agreement measures (Anwar & Menekse, 2021; Birdwell et al., 2016). Spatial learning is another important consideration. Visuospatial thinking plays an important role in learning molecular representations, especially when students must connect symbolic or two-dimensional representations to three-dimensional forms (Wu & Shah, 2004), and 3D virtual representations can support spatial reasoning for abstract submicroscopic concepts (Rahmawati et al., 2021).

An important implication is that accessible 3D modeling tools can provide meaningful support even without expensive immersive devices. The results suggest that a desktop-based, teacher-guided model may improve the teaching of abstract molecular concepts in ordinary classroom conditions, which is particularly relevant in resource-constrained contexts where advanced virtual or augmented reality equipment may be unavailable; this echoes Moroccan evidence that locally designed 3D digital resources can raise achievement and motivation in abstract science topics (Taoussi et al., 2026). Reviews of molecular visualization in immersive environments show that such systems are promising for spatially demanding content but face challenges of usability, access, and classroom implementation (Kuťák et al., 2023). Systematic reviews of virtual field experiences in the earth sciences reach comparable conclusions, documenting diverse technological approaches and beneficial learning outcomes alongside recurring barriers to classroom implementation (Youlyouz et al., 2026). The present study should therefore be positioned as evidence for accessible interactive 3D visualization, not for virtual or augmented reality effectiveness. Finally, the teacher's role remains central: consistent with cognitive load theory (Sweller, 1988) and multimedia learning principles (Mayer, 2009), the model is most useful when embedded in a structured instructional scenario rather than presented as a self-sufficient digital resource.

This study has several limitations. The sample was relatively small and drawn from a single school, which limits generalizability; the study measured immediate learning gains only, so a delayed post-test would be needed to determine whether gains persist; the achievement test showed acceptable but modest reliability; the questionnaire findings are exploratory and were not statistically compared with the control group; classroom observations were conducted by a single observer; and a novelty effect may have contributed to positive perceptions. Future research should involve larger and more diverse samples, delayed post-tests, item-level analysis of the instrument, validated motivation scales administered to both groups, multiple trained observers reporting inter-rater agreement, and designs that isolate the specific contribution of 3D visualization from novelty effects.

Conclusion

This study examined the effect of a Blender-designed interactive 3D DNA model on Moroccan secondary students' conceptual understanding of DNA structure. Students who learned with the interactive model achieved significantly greater learning gains than students who received conventional 2D diagram-based instruction, suggesting that accessible 3D visualization can support learning of abstract molecular concepts when embedded in a guided instructional sequence. Students' perceptions and classroom observations further suggested that the model may enhance clarity, interest, and exploratory participation, although these findings remain descriptive. Within the limits of a single two-hour intervention in one school, the study supports the pedagogical value of locally designed 3D models for biology education and provides a foundation for future research on long-term retention, motivation, and adaptation to immersive learning environments.

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