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# Effect of *Virtual Reality* (VR)–Based Learning Media on Grade XI Students' Learning Outcomes in the Human Respiratory System

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**Abstract:** This study aimed to examine the effect of Virtual Reality (VR)-based instructional media on students' learning outcomes in the respiratory system topic among Grade XI students at SMA Has Sepakat. A quantitative approach was employed using a quasi-experimental pretest–posttest control group design. The study involved 40 students, comprising 20 students in the experimental group and 20 students in the control group, selected through cluster random sampling. The experimental group received instruction using three-dimensional VR simulations that visualized respiratory organ structures, inspiration–expiration mechanisms, and gas exchange processes, whereas the control group received conventional instruction. Data were collected using a validated and reliable multiple-choice achievement test. Statistical analyses were performed using an independent-samples *t*-test and effect size calculation with SPSS version 22. The mean pretest score was 30.90 in the control group (SD = 9.049; 95% CI = 26.66–35.14) and 25.40 in the experimental group (SD = 8.708; 95% CI = 21.32–29.48). After the intervention, the mean posttest score increased to 60.00 in the control group (SD = 15.681; 95% CI = 52.66–67.34) and 77.80 in the experimental group (SD = 12.068; 95% CI = 72.15–83.45). The independent-samples *t*-test indicated a significant difference in posttest learning outcomes between the two groups ($t = -4.023$, $p < 0.001$), with a mean difference of −17.800. The effect size was 1.27, indicating a large difference between the groups. These findings suggest that VR-based instruction was associated with higher learning outcomes in the respiratory system topic. However, the results should be interpreted cautiously because the two groups differed in their initial pretest performance.
**Keywords:** Virtual Reality (VR); learning outcomes; instructional media; respiratory system; Grade XI students

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## INTRODUCTION

Education is a fundamental component of human resource development because it plays a crucial role in fostering the knowledge, skills, and attitudes required to address the challenges of the twenty-first century. Beyond academic competence, education is expected to cultivate critical thinking, creativity, communication, and collaboration skills that enable students to respond effectively to advances in science and technology (Halimah et al., 2024). Within this context, biology education plays a strategic role in developing students' scientific literacy through conceptual understanding and science process skills (Sriatun et al., 2024). Biology education also promotes scientific thinking by engaging students in science process skills that enable them to solve problems and make decisions based on scientific evidence (Imtihana & Restiana, 2023; Wulandari et al., 2020). Thus, biology learning is intended not only to strengthen conceptual mastery but also to foster scientific reasoning and awareness of health and environmental issues (Akinwumi, 2023; Sari et al., 2022).

One biology topic that requires substantial conceptual understanding is the human respiratory system. Learning this topic requires students not only to identify the structures and functions of respiratory organs but also to understand the mechanisms of inspiration and expiration, gas exchange in the alveoli, and the transport of oxygen and carbon dioxide in the blood. Most of these physiological processes occur within the human body and therefore cannot be observed directly (Rini et al., 2024). Because of this abstract nature, students often encounter difficulties in constructing mental representations of the relationships between anatomical structures and physiological processes when instruction relies primarily on verbal explanations or two-dimensional visual media (Gafur et al., 2024). Consequently, learning the respiratory system requires instructional media capable of presenting anatomical structures and physiological mechanisms in concrete, dynamic, and interactive forms to facilitate students' conceptual understanding (Zulia & Alimah, 2023). Evidence from extended-reality research also suggests that three-dimensional and immersive representations can support the acquisition of anatomical knowledge by enabling learners to examine spatial relationships that are difficult to represent through conventional instructional materials (García-Robles et al., 2024).

These challenges remain evident in biology instruction at the school level. Advances in digital technology have created opportunities to provide more interactive, contextualized, and meaningful learning experiences that can support students in understanding complex and abstract concepts (Murtini & Cintamulya, 2026). However, the integration of digital technologies into biology education has not yet been fully optimized. Topics characterized by extensive scientific terminology, abstract concepts, and physiological processes that cannot be directly observed are still frequently taught using conventional instructional media, which may limit students' ability to develop a comprehensive understanding of the subject matter. This situation highlights the need for instructional technologies that do more than present information visually; they should also allow learners to interact with representations of biological structures and processes in ways that support active exploration and conceptual integration.

Observations conducted by the researchers in collaboration with the biology teacher at SMA Has Sepakat Labuhanbatu indicated that instruction on the respiratory system primarily relied on PowerPoint presentations. Although PowerPoint facilitates the presentation of information through text and two-dimensional images, it provides limited opportunities to visualize respiratory structures and physiological mechanisms dynamically. Classroom observations further showed that students' learning activities were predominantly characterized by listening to the teacher's explanations and taking notes, while opportunities to independently explore learning objects remained limited.

Documentation of daily assessment scores for the Grade XI respiratory system unit during the second semester of the 2025/2026 academic year, obtained from the biology teacher at SMA Has Sepakat Labuhanbatu, showed that only 20 of 40 students (50%) achieved a score of ≥75, corresponding to the Minimum Mastery Criterion (KKM), whereas the remaining 20 students had not achieved mastery. These results indicate that students' understanding of the respiratory system requires further improvement. This finding does not imply that the use of PowerPoint was the primary cause of the relatively low learning outcomes; rather, it highlights the need for alternative instructional media capable of providing more comprehensive visualization of biological concepts.

Virtual Reality (VR) is a technology with considerable potential to address these instructional challenges because it can provide three-dimensional virtual environments in which students interact directly with learning objects. Immersive visualization may facilitate the understanding of abstract concepts by providing more concrete representations than conventional two-dimensional media (Zhang et al., 2024). In biology education, VR enables students to explore anatomical structures, observe physiological mechanisms, and examine relationships among biological components in a more comprehensive manner, thereby supporting the development of stronger conceptual representations (Luo et al., 2024). Beyond visualization, immersive environments may support learning by increasing spatial presence, enabling active exploration, and providing experiential access to phenomena that are otherwise difficult or impossible to observe directly. However, the educational benefits of VR are not uniform across contexts and depend on factors such as instructional design, educational level, subject domain, and the type of comparison condition used (Coban et al., 2022).

Previous studies have reported positive outcomes associated with Virtual Reality in science education. Radianti et al. (2020) demonstrated that Virtual Reality can enhance the quality of learning experiences through immersive learning environments. Wuisan and Purba (2024) found that the use of Virtual Reality increased student engagement during the learning process, whereas Rahmawati et al. (2024) reported that Virtual Reality had a positive effect on conceptual understanding in science learning. At a broader level, meta-analytic evidence indicates that immersive VR has a positive effect on learning outcomes, although the magnitude of this effect varies substantially across educational settings. Coban et al. (2022), for example, reported an overall positive but relatively small effect of immersive VR on learning and found that its effects differed according to educational level and instructional context. Similarly, a meta-analysis of immersive VR in science education found an overall positive effect on science learning outcomes, while emphasizing the moderating roles of instructional approaches, learning stages, and assessment methods (Zhang et al., 2024). These findings indicate that VR should not be assumed to be universally superior to conventional instruction; rather, its effectiveness needs to be examined within specific subject areas, learner populations, and classroom conditions.

Despite the growing evidence supporting immersive technologies, an important gap remains in the context of senior high school biology. Previous research has frequently addressed general science learning, student engagement, motivation, conceptual understanding, or applications in higher education and health sciences, whereas empirical evidence concerning cognitive achievement in specific secondary-school biology topics remains comparatively limited. In particular, few studies have examined the use of interactive three-dimensional VR for teaching the human respiratory system under authentic senior high school classroom conditions while comparing students' cognitive achievement with that obtained through conventional teacher-led instruction. This gap is important because the effectiveness of VR may vary according to both the abstract nature of the biological content and the developmental characteristics of the learners.

Accordingly, the contribution of the present study lies in its context-specific empirical evaluation rather than in the novelty of VR technology itself. First, this study implements an existing Virtual Reality application to visualize the anatomical structures and physiological mechanisms of the human respiratory system as three-dimensional objects that students can explore interactively during instruction. Second, the study was conducted in an authentic Grade XI classroom at SMA Has Sepakat Labuhanbatu using a quasi-experimental design, thereby providing evidence regarding the effectiveness of VR under actual classroom conditions. Third, the study evaluates students' overall cognitive achievement through learning-achievement test scores, extending previous work that has often emphasized engagement, motivation, or specific measures of conceptual understanding. Fourth, the study specifically addresses the human respiratory system, a topic characterized by abstract and internally occurring physiological processes for which three-dimensional visualization may be particularly relevant. By integrating these elements, the study provides context-specific evidence on whether VR-supported instruction is associated with better cognitive learning outcomes than conventional PowerPoint-assisted instruction in senior high school biology.

Based on these considerations, this study aimed to examine the effect of Virtual Reality-supported instruction on Grade XI students' cognitive learning outcomes in the human respiratory system and to determine whether students taught using VR achieved different learning outcomes from those taught through conventional instruction supported by PowerPoint at SMA Has Sepakat Labuhanbatu.

## METHOD

### Research Design

This study employed a quasi-experimental design with a pretest–posttest control group design to examine the effect of Virtual Reality (VR)-based instruction on students' learning outcomes in the Human Respiratory System topic. A quasi-experimental approach was used because the study involved intact classroom groups and did not permit full randomization of individual students. According to Arib et al. (2024), this design involves an experimental group and a control group that are assessed before and after the intervention.

Both groups completed a pretest to assess their initial knowledge before instruction. The experimental group subsequently received instruction using VR media, whereas the control group received lecture-based instruction supported by PowerPoint. At the end of the intervention, both groups completed a posttest to assess their learning outcomes. The research design is presented in Table 1.

**Table 1.** Pretest–posttest control group design

| Group | Pretest | Treatment | Posttest |
|---|---|---|---|
| Experimental | O1 | X | O2 |
| Control | O3 | – | O4 |

**Notes:**
O1 = Pretest administered to the experimental group before VR-based instruction
O2 = Posttest administered to the experimental group after VR-based instruction
O3 = Pretest administered to the control group before conventional instruction
O4 = Posttest administered to the control group after conventional instruction
X = VR-based instructional treatment
– = No VR-based treatment

### Participants and Sampling

The population comprised all Grade XI students at SMA Has Sepakat Labuhanbatu during the 2025/2026 academic year. The population consisted of two intact classes with a total of 40 students. Cluster random sampling was used because sampling was conducted at the class level rather than at the level of individual students (Sugiyono, 2019).

Through random selection of the two existing classes, Class XI-1 was assigned as the experimental group and Class XI-2 as the control group. Each class consisted of 20 students, resulting in a total sample of 40 students. The selection of the two classes also considered their relative academic comparability based on preliminary observations and recommendations from the Biology teacher.

### Instructional Procedures

The study was conducted in three stages: pretesting, instructional treatment, and posttesting. During the first stage, both groups completed a pretest to determine their initial knowledge of the Human Respiratory System. During the treatment stage, the experimental group received instruction using VR media, whereas the control group received lecture-based instruction supported by PowerPoint.

In the experimental group, the VR media provided interactive three-dimensional representations of respiratory organs, respiratory mechanisms, and respiratory system disorders. Students used the media to explore the structure of respiratory organs and observe processes that are difficult to visualize directly, including respiratory mechanisms. The teacher acted as a facilitator by providing instructions for using the VR media, guiding students during exploration, facilitating discussions, and reinforcing the relevant biological concepts.

In the control group, the same content was delivered through lecture-based instruction supported by PowerPoint slides containing images, illustrations, and key concepts related to the Human Respiratory System. The teacher also facilitated question-and-answer sessions and discussions to reinforce students' understanding of the material.

Both groups were taught by the same Biology teacher and received the same instructional content, learning objectives, instructional duration, and assessment instruments. Therefore, the principal difference between the groups was the instructional medium used. The instructional procedures are summarized in Table 2.

**Table 2.** Instructional procedures

| Instructional Stage | Experimental Group | Control Group |
|---|---|---|
| Introduction | The teacher opened the lesson, communicated the learning objectives, motivated the students, and administered the pretest. | The teacher opened the lesson, communicated the learning objectives, motivated the students, and administered the pretest. |
| Presentation of Material | The teacher introduced the basic concepts of the respiratory system and guided students in using VR media to interactively explore respiratory organs and mechanisms. | The teacher explained the respiratory system through lecture-based instruction supported by PowerPoint slides containing images and illustrations. |
| Main Learning Activities | Students explored the VR environment, observed respiratory structures and processes, participated in discussions, and formulated conclusions based on their observations. | Students listened to the teacher's explanations, examined the material presented in PowerPoint, asked questions, participated in discussions, and completed practice exercises. |
| Closing | The teacher and students summarized the lesson, the teacher provided feedback, and students completed the posttest. | The teacher and students summarized the lesson, the teacher provided feedback, and students completed the posttest. |

## Treatment Fidelity

Treatment fidelity was maintained to ensure that the instructional procedures in both groups were implemented consistently with the research protocol. Both groups followed lesson plans prepared before the study and were taught by the same teacher using identical instructional content, learning objectives, instructional duration, and assessment procedures.

The only systematic difference between the groups was the instructional medium: VR media were used in the experimental group, whereas lecture-based instruction supported by PowerPoint was used in the control group. These controls were implemented to minimize the influence of extraneous instructional variables and to strengthen the interpretation of differences in learning outcomes between the two groups.

**Research Instrument**

Students' cognitive learning outcomes were measured using a multiple-choice achievement test on the Human Respiratory System. The initial instrument consisted of 30 items developed based on the relevant learning outcomes and instructional indicators. The test covered the structure and function of respiratory organs, mechanisms of human respiration, and respiratory system disorders.

The test blueprint was developed with reference to the Revised Bloom's Taxonomy, encompassing C1 (remembering), C2 (understanding), C3 (applying), C4 (analyzing), C5 (evaluating), and C6 (creating). The items were distributed according to the learning indicators and intended cognitive levels to provide broad coverage of students' cognitive learning outcomes.

**Instrument Validation and Reliability**

Before the main study, the initial 30-item test was pilot-tested with 60 students at SMA Has Sepakat who had previously studied the Human Respiratory System. Students who participated in the pilot test were not included in the main study sample. The pilot-test data were analyzed using IBM SPSS Statistics version 22.

Empirical item validity was assessed using the Pearson Product–Moment correlation at a significance level of 5% ($\alpha = 0.05$). With 60 respondents (df = 58), the critical correlation coefficient was 0.254. Of the 30 items tested, 20 met the validity criterion ($r$calculated > 0.254), whereas 10 items did not meet the criterion and were excluded from the final instrument.

The internal consistency of the 20 retained items was evaluated using Cronbach's alpha. The analysis yielded a coefficient of 0.768, indicating acceptable internal consistency and supporting the use of the instrument in the main study. For dichotomously scored multiple-choice items, Cronbach's alpha is mathematically equivalent to the Kuder–Richardson Formula 20 (KR-20) under appropriate measurement assumptions.

Item difficulty and item discrimination were also examined as supporting indicators of item quality. Of the 20 retained items, 14 were classified as moderately difficult, one as easy, and five as difficult. The corrected item–total correlations ranged from 0.102 to 0.715, indicating variability in the discriminatory performance of the items from poor to very good. These analyses were used to evaluate the overall measurement characteristics of the instrument before its administration in the main study.

**Data Analysis**

Data from the main study were analyzed using IBM SPSS Statistics version 22. Descriptive statistics were first used to summarize students' pretest and posttest scores. The assumptions required for parametric analysis were subsequently examined through tests of normality and homogeneity of variance.

The normality of the pretest and posttest scores in both the experimental and control groups was assessed using the Shapiro–Wilk test at a significance level of 5% ($\alpha = 0.05$). Data were considered normally distributed when $p > 0.05$. Homogeneity of variance between the two groups was assessed using Levene's test, with $p > 0.05$ indicating homogeneous variances.

After these assumptions were satisfied, an independent-samples $t$-test was used to determine whether posttest learning outcomes differed significantly between the experimental and control groups. The analysis was conducted at a significance level of 5% ($\alpha = 0.05$). The null hypothesis was rejected when the two-tailed *p*-value was < 0.05.

The statistical hypotheses were formulated as follows:
$H_0$: $\mu_e = \mu_k$
$H_1$: $\mu_e \neq \mu_k$
where:
$\boldsymbol{\mu_e}$ = mean learning outcome score of the experimental group receiving VR-based instruction
$\boldsymbol{\mu_k}$ = mean learning outcome score of the control group receiving conventional instruction
$\mathbf{H_0}$ stated that there was no statistically significant difference in mean learning outcomes between the experimental and control groups, whereas $\mathbf{H_1}$ stated that a statistically significant difference existed between the two groups.

## RESULTS AND DISCUSSION

This study examined the effect of Virtual Reality (VR)-based instruction on students' learning outcomes in the Respiratory System topic among Grade XI students at SMA Has Sepakat Labuhanbatu. The results are presented sequentially through descriptive statistics, assumption testing, hypothesis testing, effect size analysis, and learning mastery. The findings are subsequently interpreted in relation to relevant previous studies, the pedagogical characteristics of VR, and the methodological limitations of the present study.

### Descriptive Statistics of Students' Learning Outcomes

Descriptive statistical analysis was conducted to characterize students' learning outcomes in the control and experimental groups before and after the intervention. The statistics included the mean, standard deviation (SD), minimum and maximum scores, and 95% confidence interval (CI).

**Table 3.** Descriptive statistics of students' learning outcomes

| Group and Test | Mean | SD | Min | Max | 95% CI |
|---|---|---|---|---|---|
| Control Group Pretest | 30.90 | 9.049 | 18 | 48 | 26.66–35.14 |
| Control Group Posttest | 60.00 | 15.681 | 40 | 88 | 52.66–67.34 |
| Experimental Group Pretest | 25.40 | 8.708 | 12 | 40 | 21.32–29.48 |
| Experimental Group Posttest | 77.80 | 12.068 | 60 | 100 | 72.15–83.45 |

As shown in Table 3, the mean pretest score was 30.90 in the control group and 25.40 in the experimental group, indicating a descriptive difference in baseline performance between the two groups. Following instruction, the mean posttest score increased to 60.00 in the control group and 77.80 in the experimental group. Thus, both groups demonstrated improvement after instruction, although the experimental group achieved a substantially higher posttest mean. The experimental group also showed a narrower posttest standard deviation (SD = 12.068) than the control group (SD = 15.681), indicating somewhat less variability in post-intervention scores. Inferential statistical analyses were subsequently conducted to determine whether the observed posttest difference between the groups was statistically significant.

### Normality Test

Normality was assessed using the Shapiro–Wilk test in IBM SPSS Statistics version 22 at a significance level of 0.05. The results are presented in Table 4.

**Table 4.** Normality test results

| Group | Shapiro–Wilk Statistic | df | Sig. | Interpretation |
|---|---|---|---|---|
| Pretest, Control Group | 0.926 | 20 | 0.130 | Normal |
| Posttest, Control Group | 0.928 | 20 | 0.143 | Normal |
| Pretest, Experimental Group | 0.948 | 20 | 0.340 | Normal |
| Posttest, Experimental Group | 0.958 | 20 | 0.503 | Normal |

As presented in Table 4, the significance values for all pretest and posttest scores were greater than 0.05. Therefore, the distributions of scores in both groups did not significantly deviate from normality, supporting the use of parametric statistical procedures.

**Homogeneity of Variance Test**

Homogeneity of variance was assessed using Levene's test at a significance level of 0.05. The results are presented in Table 5.

**Table 5.** Homogeneity of variance test results

| Test | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|
| Pretest | 0.003 | 1 | 38 | 0.959 |
| Posttest | 2.160 | 1 | 38 | 0.150 |

Levene's test yielded significance values of 0.959 for the pretest and 0.150 for the posttest. Because both values were greater than 0.05, the variances of the experimental and control groups were considered homogeneous. Together with the normality results, these findings supported the use of an independent-samples *t*-test for comparing posttest scores between the two groups.

**Hypothesis Testing and Effect Size**

An independent-samples *t*-test was conducted to determine whether posttest learning outcomes differed significantly between students who received VR-based instruction and those who received conventional instruction.

**Table 6.** Independent-samples *t*-test results

| Variable | Levene's *F* | Sig. | *t* | df | *p* (2-tailed) |
|---|---|---|---|---|---|
| Learning Outcomes | 2.160 | 0.150 | −4.023 | 38 | <0.001 |

As shown in Table 6, the independent-samples *t*-test revealed a statistically significant difference in posttest learning outcomes between the experimental and control groups, $t(38) = -4.023$, $p < 0.001$. Thus, the null hypothesis was rejected and the research hypothesis was supported. The absolute difference between the posttest means was 17.80 points, with the experimental group obtaining the higher mean score.

Nevertheless, this result should be interpreted cautiously because the two groups differed descriptively at baseline. The control group had a higher mean pretest score (30.90) than the experimental group (25.40). Because the present analysis compared posttest scores without statistically adjusting for baseline performance, the significant posttest difference cannot be considered completely independent of possible pre-existing differences between the groups.

To estimate the magnitude of the difference in posttest learning outcomes between the experimental and control groups, Cohen's *d* was calculated using the pooled standard deviation. The calculation was based on the mean posttest score of the experimental group ($M$ = 77.80), the mean posttest score of the control group ($M$ = 60.00), and the pooled standard deviation ($SD$pooled = 13.99), resulting in a Cohen's $d$ of 1.27. According to Cohen's criteria, this value represents a large effect size, indicating a substantial difference in posttest learning outcomes between students who received VR-based instruction and those who received conventional instruction. However, because the two groups showed a descriptive difference in pretest performance, this effect size should be interpreted as the magnitude of the posttest difference rather than as a fully adjusted estimate of the causal effect of VR-based instruction.

**Learning Mastery**

In addition to mean scores, students' achievement was descriptively examined using the Minimum Mastery Criterion (*Kriteria Ketuntasan Minimal*, KKM), which was set at ≥75. The mastery results for both groups are summarized in Table 7 to facilitate direct comparison.

**Table 7.** Learning mastery in the control and experimental groups

| Group | Pretest ≥75, *n* (%) | Posttest ≥75, *n* (%) | Pretest <75, *n* (%) | Posttest <75, *n* (%) |
|---|---|---|---|---|
| Control | 0 (0%) | 5 (25%) | 20 (100%) | 15 (75%) |
| Experimental | 0 (0%) | 12 (60%) | 20 (100%) | 8 (40%) |

At pretest, none of the students in either group achieved the mastery criterion. Following instruction, 5 students (25%) in the control group achieved scores of ≥75, compared with 12 students (60%) in the experimental group. Thus, a greater proportion of students receiving VR-based instruction achieved the predetermined mastery criterion after the intervention. These percentages are descriptive and are presented to complement, rather than replace, the inferential statistical analysis.

Overall, the findings indicate that students who received VR-based instruction achieved higher posttest learning outcomes than those who received conventional instruction. The experimental group obtained a mean posttest score of 77.80, compared with 60.00 in the control group, while the proportion of students achieving the mastery criterion was 60% and 25%, respectively. The significant between-group difference ($p < 0.001$) and large effect size ($d$ = 1.27) further indicate a substantial post-intervention difference between the instructional conditions. Within the context of this study, these findings suggest that VR-based instruction was associated with higher cognitive learning outcomes in the Respiratory System topic.

The higher learning outcomes observed in the experimental group may be related to the capacity of VR to transform abstract biological structures and physiological processes into interactive three-dimensional representations. In the present study, students could explore respiratory organ structures, observe the mechanisms of inspiration and expiration, and examine gas-exchange processes through virtual simulations. These representations may facilitate the construction of more concrete mental models by making spatial relationships and dynamic physiological processes more accessible to learners. Such affordances are particularly relevant to the Respiratory System, in which several physiological processes occur internally and therefore cannot be directly observed during conventional classroom instruction.

The present findings are consistent with previous evidence demonstrating the educational potential of VR. Dhanil & Mufit (2024) reported in their meta-analysis that VR-based science learning improved learning outcomes compared with conventional instruction, while also showing that the magnitude of its effectiveness varied according to factors such as immersion level and study characteristics. Similarly, Liu et al. (2025) reported that desktop virtual reality generally enhanced academic achievement compared with conventional learning. These findings support the potential of VR to improve learning outcomes while indicating that its effectiveness should be understood in relation to the characteristics of the instructional context rather than as an inherent effect of the technology itself.

Evidence from broader meta-analytical research also supports a positive, although heterogeneous, effect of VR. Yang et al. (2024), based on 37 empirical studies and 72 effect sizes, found a significant moderate positive effect of VR on practical skills in science and engineering education ($g$ = 0.477). Their moderator analyses further demonstrated that disciplinary context and instructional approach influenced the magnitude of the effect. This evidence is important because it suggests that the effectiveness of VR depends not only on technological immersion but also on how VR activities are pedagogically integrated into instruction.

The characteristics of the Respiratory System topic may have contributed to the comparatively strong result observed in the present study. Concepts such as respiratory organ structure, inspiration and expiration mechanisms, and alveolar gas exchange require students to understand spatial relationships and dynamic processes. When these concepts are presented primarily through verbal explanations and static images, students may find it difficult to construct accurate representations of how structures and physiological processes interact. VR can provide dynamic and spatially organized representations that allow learners to explore these relationships more directly. Mehra (2024) similarly explained that VR-based learning can provide immersive experiences that support conceptual understanding by enabling learners to interact with representations that are difficult to observe directly.

The findings also align with Jindal et al. (2024), who suggested that Virtual Reality can facilitate the understanding of abstract concepts through simulation-based learning experiences. However, VR should not be considered an instructional solution that automatically produces superior learning. Its educational value depends on the way students interact with virtual content and how teachers integrate that interaction into the learning process. In the present study, VR use was accompanied by teacher guidance, student exploration, discussion, and conceptual reinforcement. Therefore, the observed learning outcomes may reflect the interaction between the technological affordances of VR and the instructional activities surrounding its use rather than the technology alone.

This more cautious interpretation is supported by recent comparative evidence. Koç & Kanadlı (2025), in a network meta-analysis of 53 studies examining interactive learning environments in science education, found that the effect of VR on cognitive outcomes was not significantly different from conventional instruction, although VR showed a significant advantage for affective outcomes. Their results also indicated variation among VR, augmented reality, mixed reality, and interactive digital games. These findings demonstrate that the educational effectiveness of VR is heterogeneous and that positive results may depend on learning objectives, instructional design, content characteristics, and the outcome being measured. Consequently, the large effect observed in the present study should be interpreted within the specific context of Respiratory System instruction rather than generalized to all applications of VR in education.

The magnitude of the effect observed in the present study also warrants careful consideration. The Cohen's $d$ of 1.27 is substantially larger than the average effects reported in several broader syntheses of VR research. For example, Yang et al. (2024)

reported an overall moderate effect of $g$ = 0.477 for practical skills, while previous meta-analytical evidence has also demonstrated that average VR effects may be small to moderate across heterogeneous educational contexts. Therefore, the relatively large effect observed in this study may partly reflect the characteristics of the sample, the specific biological topic, instructional procedures, duration of the intervention, or students' previous familiarity with VR. It may also reflect a novelty effect, whereby students respond more positively because the instructional technology is new to them. Accordingly, replication across different schools, populations, and instructional periods is necessary before assuming that an effect of similar magnitude would occur in other contexts.

Another important methodological consideration is the baseline difference between the two groups. The control group had a higher mean pretest score (30.90) than the experimental group (25.40). Such differences may occur in quasi-experimental studies because intact classes are used rather than participants being individually randomized. Although the experimental group subsequently achieved a substantially higher posttest mean, the statistical procedure used in this study did not explicitly adjust the posttest comparison for baseline performance. Therefore, the findings demonstrate a significant post-intervention difference associated with the instructional conditions, but the magnitude of the causal contribution of VR cannot be established conclusively from the current analysis. Future studies could strengthen causal inference by using analytical approaches that statistically adjust for baseline performance, such as analysis of covariance (ANCOVA), provided that the relevant statistical assumptions are satisfied.

Despite its educational potential, VR also presents practical challenges that should be considered when translating these findings into classroom practice. VR-based instruction requires appropriate technological resources, including smartphones with adequate technical specifications, VR headsets, compatible applications, and reliable infrastructure. These requirements may restrict implementation in schools with limited financial or technological resources. Marougkas et al. (2023) similarly identified hardware requirements, implementation costs, infrastructure readiness, and appropriate instructional design as important considerations in the educational implementation of immersive VR. Therefore, the pedagogical benefits of VR should be considered alongside its accessibility, sustainability, and feasibility in actual school settings.

The instructional design of VR environments is equally important. Although immersive environments can provide rich visual and interactive information, excessive visual complexity may increase cognitive load rather than facilitate learning. Students may need to simultaneously process scientific information, navigate the virtual environment, and adapt to unfamiliar technological interfaces. Hamilton et al. (2021) emphasized that immersive VR can support learning but that its effectiveness depends considerably on experimental and instructional design. Therefore, VR content should be aligned with specific learning objectives, presented at an appropriate level of complexity, and accompanied by sufficient teacher guidance to ensure that technological immersion supports rather than distracts from conceptual learning.

Physical comfort also needs to be considered when VR is implemented in classroom settings. Some users may experience cybersickness, including dizziness, nausea, eye discomfort, or disorientation during or after exposure to immersive virtual environments. Caserman et al. (2021) identified cybersickness as a persistent challenge associated with current-generation VR head-mounted displays. Consequently, VR-based learning should consider exposure duration, equipment characteristics, individual differences among students, and opportunities for rest. These considerations are particularly important when VR is used repeatedly or for extended instructional periods.

Several limitations should be acknowledged when interpreting the present findings. First, the study involved only 40 students from two intact classes, which limits the representativeness of the sample. Second, the research was conducted at a single school; therefore, the findings may not be directly generalizable to schools with different student characteristics, instructional environments, or technological resources. Third, the VR intervention was implemented over a relatively short period, preventing conclusions about the persistence of the observed learning gains or long-term knowledge retention. Fourth, students' responses may have been influenced by a novelty effect because VR represented a relatively new instructional technology. Finally, although a significant posttest difference was observed, the analysis did not statistically adjust for the descriptive baseline difference between the experimental and control groups.

Taken together, these limitations indicate that the higher learning outcomes observed in the experimental group should not be attributed exclusively to VR itself. Rather, the findings provide evidence that VR-based instruction, as implemented within the specific instructional conditions of this study, was associated with higher posttest achievement in the Respiratory System topic. Future studies should involve larger and more diverse samples, include multiple schools, extend the duration of VR-based interventions, and employ analytical approaches that control for baseline differences. Further research should also examine knowledge retention, conceptual understanding, motivation, cognitive load, student engagement, and learning experiences to clarify not only whether VR supports biology learning but also how, for whom, and under what instructional conditions it is most effective.

## CONCLUSION

Based on the findings and data analysis, the use of Virtual Reality (VR) as a learning medium was associated with significantly higher cognitive learning outcomes among Grade XI students studying the human respiratory system at SMA Has Sepakat Labuhanbatu. The independent-samples *t*-test revealed a statistically significant difference in posttest scores between the experimental and control groups (Sig. [2-tailed] = 0.000; $p < 0.05$). However, this finding should be interpreted with consideration of the differences in students' initial abilities, as indicated by their pretest scores.

The experimental group achieved a mean posttest score of 77.80, compared with 60.00 in the control group. Within the context of this study, these findings indicate that students who learned using VR achieved higher cognitive learning outcomes than those who received conventional instruction without VR. Nevertheless, the findings are limited to the human respiratory system topic, the characteristics of the study sample, and the learning conditions at SMA Has Sepakat Labuhanbatu. Therefore, caution should be exercised when generalizing these findings to other schools, biological topics, or student populations.

## RECOMMENDATION

Based on the findings, biology teachers may consider VR as an alternative instructional medium for facilitating the learning of abstract biological concepts, particularly those related to the human respiratory system. Schools are encouraged to support the effective implementation of VR-based learning by providing appropriate infrastructure, including VR-compatible devices and technology-based learning resources.

Future studies should involve larger and more diverse samples, include multiple schools, and investigate the application of VR to other biology topics to improve the generalizability of the findings. Further research should also examine additional learning variables, such as student motivation, critical-thinking skills, engagement, and knowledge retention. Studies employing longer intervention periods and analytical approaches that account for differences in students' baseline abilities are also recommended to provide more robust evidence regarding the effectiveness of VR in biology education.

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