



IMMERSION, EXPERIMENTATION, AND OBSERVATION: EFFECTS OF THREE LABORATORY ENVIRONMENTS ON GIFTED STUDENTS' CHEMICAL CHANGE KNOWLEDGE AND SCIENCE ATTITUDES

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Introduction

Effective science education for gifted students requires learning environments that meaningfully engage them with scientific ideas and practices while remaining responsive to their distinctive learning characteristics. Gifted students may differ from their peers in characteristics such as advanced reasoning, strong memory and attention, rapid learning, flexible thinking, high curiosity, intrinsic motivation, and self-regulation (Johnsen, 2021; Kuznetsova et al., 2024). However, these students do not constitute a homogeneous group in terms of their cognitive characteristics, interests, motivations, and educational needs (Davis et al., 2017; Joli et al., 2026). Their tendency to question scientific phenomena, seek out new experiences, and generate original ideas may support the development of a natural interest in science among gifted students (Gallagher, 2021). Indeed, it has been reported that these students' interest in and enjoyment of science classes can be higher than that of their peers, that they are more inclined to pursue careers in science-related fields, and that they place greater value on the societal role of science (Caleon & Subramaniam, 2008).

Science education for gifted students should not be reduced to accelerated pacing or additional tasks. Instead, it should match their readiness, interests, and learning profiles, supporting progression to advanced content and in-depth examination of topics through diverse evidence and perspectives (Stambaugh & Mofield, 2022; VanTassel-Baska, 2017). Students should also be involved in scientific practices like asking questions, planning investigations, conducting experiments, collecting data, and constructing evidence-based explanations (Cotabish, 2021; Erduran et al., 2026). Gifted students value hands-on work, laboratory activities, and learning connected to real life more than lecture-based teaching (Gómez-Arizaga et al., 2020; Kutlu Abu & Dal, 2025; Tanik Onal & Buyuk, 2021).

Abstract. *Laboratory environments offer varying degrees of physical interaction, immersion, control, and guidance, yet the impact of these differences on gifted students' knowledge and attitudes towards science classes and laboratories remains unclear. This study compared the effects of direct immersive virtual reality (IVR), a physical laboratory, and teacher-modelled observational virtual reality on gifted sixth-grade students' chemical change knowledge and attitudes towards science classes and laboratories. A three-group pretest-posttest quasi-experimental design was used with 66 gifted sixth-graders (39 girls, 27 boys). Gifted students learned through direct IVR, a physical laboratory, or observational IVR based on teacher modelling. All groups received the same content, procedures, worksheets, and teaching time. Data were collected using the Chemical Change Knowledge Test and the Attitude toward Science Course and Laboratories Scale, then analysed through a 3×2 mixed-design ANOVA. The interaction between learning environment and time was significant for all variables. The physical laboratory group showed greater gains in attitudes towards learning science at school, science self-concept, and overall attitudes towards science. Observational IVR produced knowledge gains comparable to those of the physical laboratory group, but smaller gains in attitudes. Overall, the findings indicate that different laboratory environments support different learning outcomes among gifted sixth-grade students.*

Keywords: *gifted students, immersive virtual reality, physical laboratory, observational learning, science attitudes*

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Chemical change is a key science topic in which students engage in scientific observation, measurement, data interpretation, and the construction of evidence-based explanations. During laboratory activities, students may observe indicators such as colour change, gas release, or solid formation, record their results, and evaluate these observations as evidence (National Research Council, 2012; Simon et al., 2026). However, students may have difficulty relating observable changes to the particulate nature of matter, distinguishing between physical and chemical changes, and determining whether the identity of a substance has changed. It has been found that lower-secondary students can confuse properties of matter with change processes and have difficulty scientifically justifying their answers (Simon et al., 2026). Similar difficulties appear to persist among upper-secondary students as well (Fitriani et al., 2025).

Following instructions during a science experiment, students must juggle apparatus, measurements, and multiple changes, straining their working memory (Johnstone, 1991). Gifted students, however, possess advanced working memory, observation, and scientific reasoning skills, making chemical change a suitable cognitive challenge (Kuznetsova et al., 2024; Yu et al., 2021). Nevertheless, advanced cognitive characteristics do not mean that students will automatically interpret every observed change correctly. Their observation and inference skills may still require support through domain knowledge, guiding questions, systematic recording, and teacher guidance (Yürümezoğlu et al., 2023). A supportive learning environment is crucial, engaging students in experimental processes while helping them transform observations into scientific evidence and explanations.

The physical laboratory, direct immersive virtual reality (IVR), and observational IVR based on teacher modelling provide opportunities to examine chemical change through different learning experiences. In the physical laboratory, students conduct experiments using real substances, tools, and measurement instruments, collect their own data, and directly encounter the observable outcomes of the reaction (de Jong et al., 2013; Gericke et al., 2023). In direct IVR, students enter a three-dimensional virtual laboratory via a head-mounted display (HMD) and motion controllers, individually operate the virtual tools, and have control over the actions within the experimental process (Makransky & Petersen, 2021; Wiedbusch et al., 2026). In teacher-modelled observational IVR, the teacher performs the experiment in the virtual laboratory while students watch the teacher's first-person view on a classroom screen and focus on critical stages of the experiment through the teacher's explanations. In similar observational arrangements, rather than operating the virtual environment themselves, students take part in the learning process by watching the actions and explanations of a teacher, an expert, or another user (Dubovi, 2023; Veitch et al., 2025). Thus, the three environments differ from one another in terms of the student's role, direct participation, sensory feedback, agency, teacher guidance, and the source of the experience.

The way these environments may support learning can be explained through different theoretical approaches. The experiential learning approach suggests that hands-on experiments in the physical laboratory alone do not guarantee conceptual learning. Meaningful learning occurs when students actively engage in a concrete experience, reflect on that experience, develop conceptual understandings from their observations, and apply those understandings to new situations (Kolb, 1984; Morris, 2020). Therefore, the educational value of the physical laboratory stems not merely from working with real substances, but from the educational support that enables students to interpret the data they collect and construct scientific explanations (Gericke et al., 2023).

The learning process in direct IVR can be understood through the Cognitive Affective Model of Immersive Learning (CAMIL). This model suggests that IVR's technical features can intensify presence, the feeling of being within the virtual environment, and agency, the ability to influence events through one's actions. These psychological experiences can affect learning outcomes through processes such as interest, motivation, self-efficacy, cognitive load, and self-regulation (Makransky & Petersen, 2021). Yet, high immersion does not guarantee greater knowledge gains. Studies have found that IVR can generate stronger presence, interest, and enjoyment than desktop simulations, videos, or presentations, although it does not consistently produce superior knowledge gains (Makransky et al., 2019, 2021; Parong & Mayer, 2018). In contrast, generative learning activities such as summarising, self-explaining, and drawing enhance IVR's educational effectiveness by helping students select and organise information and relate it to prior knowledge (Fiorella & Mayer, 2016; Makransky & Petersen, 2021). For chemistry topics that require students to relate observable phenomena to atomic, ionic, and molecular representations, such supports may facilitate connections between macroscopic observations and microscopic explanations (van Dinther et al., 2023).

Observational IVR based on teacher modelling can be understood through Bandura's (1977) observational learning theory. According to this theory, learning from a model depends on attending to the model's relevant actions, retaining the observed information, being able to reproduce what has been learned, and having sufficient motivation to do so. In the present context, the teacher's explanation of what is being done and why, emphasis on critical evidence, and prompts requiring students to compare their predictions with their observations may help

direct students' attention and support retention of the observed process (Bandura, 1977; Dubovi, 2023). Asking students to record the experimental steps, classify their observations, and construct scientific explanations may further encourage them to reorganise and express what they have observed rather than remain passive viewers (Fiorella & Mayer, 2016; Veitch et al., 2025).

Comparative studies have not demonstrated the consistent superiority of either physical or virtual laboratories across learning outcomes. Kapici et al. (2019) discovered that students who used both formats sequentially outperformed those who used only one, gaining more conceptual knowledge and inquiry skills. A follow-up study found that all three conditions (physical, virtual, and combined) improved students' attitudes towards science classes and laboratories, with no significant difference between them (Kapici et al., 2020). Kapici et al. (2022) found that physical and virtual laboratories produced similar outcomes for conceptual knowledge and inquiry skills, but guidance significantly impacted conceptual learning.

In a study comparing sixth-grade students under physical, virtual, and combined physical-virtual experimental conditions, all three environments improved conceptual knowledge and scientific process skills, but no statistically significant difference was found among the groups overall (Anam et al., 2025). However, different environments producing similar knowledge scores does not mean that students went through the same learning processes. Puntambekar et al. (2021) found that students in the physical laboratory talked more about setting up apparatus, taking measurements, and calculating results, whereas students in the virtual laboratory focused more on forming predictions, identifying relationships among variables, and interpreting scientific phenomena. This finding shows that physical and virtual laboratories can bring different scientific practices to the forefront.

Studies comparing direct IVR with physical laboratory settings in chemistry have reported broadly comparable learning outcomes. Hu-Au and Okita (2021) found that the physical laboratory and IVR groups achieved similar outcomes in terms of general chemistry knowledge, understanding of the experiment, and safety knowledge, while students in the physical laboratory group exhibited the cleaning and organising behaviours required by real equipment more frequently. This finding suggests that IVR can achieve a level of effectiveness close to the physical laboratory for certain knowledge and safety outcomes, while procedural behaviours associated with the use of real equipment are more prominent in the physical environment.

Studies comparing direct virtual interaction with observational learning suggest that student control may influence affective and procedural outcomes, although its effects are not consistently positive across all learning measures. Students who used a desktop-VR environment directly and those who watched another user's actions and dialogue with an expert achieved similar knowledge gains, but the direct interaction group showed more intense emotional engagement (Dubovi, 2023). In a VR-by-proxy study, broadcasting a teacher's HMD-based laboratory activity to students produced theoretical knowledge outcomes similar to those obtained through an interactive online laboratory manual, but supported greater confidence, enjoyment, and familiarity with the laboratory (Veitch et al., 2025). In a chemistry study with upper-secondary students, direct participation in IVR laboratory tasks produced higher overall knowledge gains, situational interest, and agency than watching the same tasks through a first-person video. However, statistical corrections revealed that not all differences in knowledge types remained significant, and a negative relationship between perceived agency and knowledge gain suggests that higher student control does not always lead to greater learning (Wiedbusch et al., 2026).

Comparative laboratory studies with gifted students are more limited. In their study conducted with gifted sixth-grade students, Kapici and Costu (2023a, 2023b) compared the physical laboratory with a desktop virtual laboratory. Both environments improved students' conceptual knowledge and inquiry or scientific process skills, with the virtual laboratory group achieving higher posttest scores. However, these studies did not examine direct HMD-based IVR or students' attitudes towards science classes and laboratories. Moreover, because the virtual laboratory group used online scaffolding tools whereas the physical laboratory groups used written counterparts, the observed differences cannot be attributed solely to laboratory type.

The importance of comparing the three laboratory environments among gifted students does not stem solely from the absence of a study examining these environments together. The physical laboratory foregrounds direct experience with real substances, sensory feedback, and the use of real equipment; direct IVR foregrounds immersive individual control and agency; and observational IVR based on teacher modelling foregrounds structured observation of an expert model's actions and decisions. Although gifted students' advanced cognitive characteristics suggest that they may benefit from direct and complex interactions, the fact that these students are not homogeneous and that they need guidance during scientific inquiry limits the assumption that higher student control will lead to greater learning in every case. Therefore, comparing the three environments can help clarify whether

directly conducting the experiment provides an additional contribution beyond structured observation, and how immersion, agency, sensory realism, and teacher guidance are reflected in knowledge and attitude outcomes.

The comparison also has practical implications. Whereas the physical laboratory requires chemical substances, equipment, safety infrastructure, and waste management, direct IVR requires hardware, software, maintenance, teacher training, and technical support (Jiang et al., 2025; van Dinther et al., 2023). Projecting the activity that a teacher carries out with a single HMD onto a classroom screen can reduce the need for a per-student HMD and the associated hardware costs, but it limits students' direct participation and individual control. This comparison can be particularly informative in showing how different laboratory environments support student learning. Schools vary greatly in their access to laboratory equipment and IVR technology, and gifted students may respond differently to different forms of laboratory activity. Some may engage more when conducting experiments first-hand, while others may respond more positively to immersive environments or structured observation through IVR. Understanding these differences can inform decisions about laboratory settings and resource allocation in gifted science education.

Previous studies have compared physical and desktop virtual laboratories, physical laboratory settings and direct IVR, and direct virtual interaction and observational learning in general student samples (Anam et al., 2025; Dubovi, 2023; Hu-Au & Okita, 2021; Kapici et al., 2019, 2020, 2022; Veitch et al., 2025; Wiedbusch et al., 2026). Research on gifted students has been limited to comparisons between physical and virtual laboratories (Kapici & Costu, 2023a, 2023b). To date, no study has compared a physical laboratory, direct HMD-based IVR, and teacher-modelled observational IVR among gifted students under equivalent conditions while examining both chemical change knowledge and attitudes towards science. This study compared the effects of three laboratory environments, namely a physical laboratory, direct IVR, and teacher-modelled observational IVR, on gifted sixth-grade students' chemical change knowledge and attitudes towards science course and laboratories. The study sought answers to the following research questions:

- How does the type of learning environment (physical laboratory, direct IVR, or teacher-modelled observational IVR) affect gifted sixth-grade students' knowledge of chemical change?
- How does the type of learning environment (physical laboratory, direct IVR, or teacher-modelled observational IVR) affect gifted sixth-grade students' attitudes towards science course and laboratories?

Research Methodology

Design

This study employed a three-group pretest-posttest quasi-experimental design to compare the effects of a physical laboratory, direct IVR, and teacher-modelled observational IVR on gifted students' chemical change knowledge and attitudes towards science course and laboratories (Fraenkel et al., 2012). Because participants were assigned to the three conditions within existing class structures without random assignment, the study was conducted as a quasi-experimental design with nonequivalent groups (Fraenkel et al., 2012).

Participants

Participants were 66 gifted sixth-graders at a Science and Art Center (BİLSEM) in Türkiye, identified in the general mental ability domain. The sample size was constrained by the number of eligible students available within the existing groups at the participating BİLSEM, as the study was conducted within intact groups rather than through recruitment from multiple institutions. Although all participants were identified in the same domain, this identification does not imply homogeneity in their cognitive, motivational, or learning characteristics. These individual differences were not examined as study variables. BİLSEMs offer free education in general mental ability, visual arts, or music. As of 2026, 362 BİLSEMs serve 106,370 students across Türkiye (Ministry of National Education [MoNE], 2026). Students in Grades 1–3 enter the identification process through teacher nomination, with no more than 20% of students per grade level nominated in up to two domains. Teachers complete observation forms; nominees then take a group screening test according to the MoNE schedule. Students meeting the cutoff score proceed to individual assessment in the relevant domain (MoNE, 2024, 2025). The direct IVR group consisted of 23 students (14 girls and 9 boys), the observational IVR group of 22 students (12 girls and 10 boys), and the physical laboratory group of 21 students (13 girls and 8 boys). Ethical approval was obtained prior to the start of data

collection. Written informed consent was obtained from the parents of all participating students, and assent was obtained from the students themselves.

Data Collection Instruments

Chemical Change Knowledge Test

Researchers developed the Chemical Change Knowledge Test to assess gifted sixth-graders' knowledge of chemical change. The test covered distinguishing physical and chemical changes, evaluating indicators, and applying knowledge to new situations. The general chemistry content test developed by Hu-Au and Okita (2021) was also reviewed before writing the draft items. A table of specifications ensured content validity. The 25-item multiple-choice draft was reviewed by two science education experts, two gifted education experts, a BİLSEM science teacher, and a measurement and evaluation expert. Revisions were made based on their feedback. Examples of items retained in the final form were "When a substance undergoes a chemical change, which property must change?" (distinguishing physical and chemical change), "When two liquids are mixed and a precipitate forms and the mixture changes colour, what do these observations most strongly suggest?" (evaluating indicators of chemical change), and "Carbon dioxide is exhaled as a result of which type of change occurring in the body?" (applying chemical change knowledge to a new context).

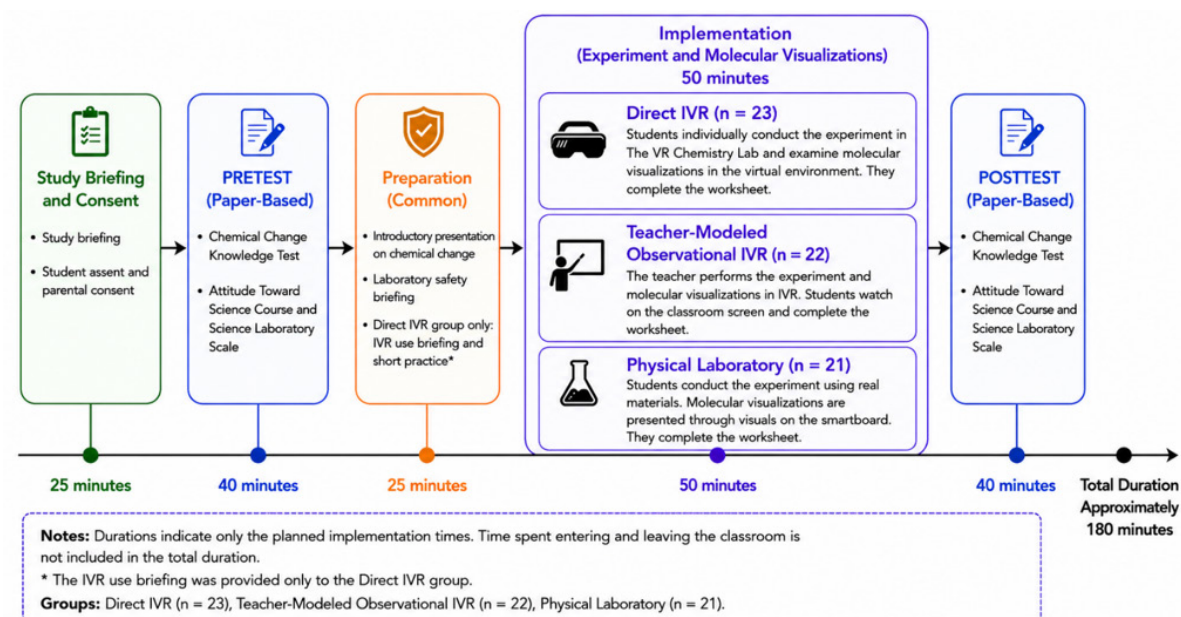
Item analysis was conducted with 180 gifted sixth-grade students, with correct responses scored as 1 and incorrect responses scored as 0. For the 25-item draft, KR-20 was .84, mean difficulty .48, item difficulty ranged from .200 to .839, and item-total correlations from $-.184$ to $.571$. Items 4, 11, 16, 22, and 24, with correlations below .30, were removed (Büyükoztürk, 2025). KR-20-if-item-deleted values (.841–.853) and low discrimination indices supported this decision (Ebel & Frisbie, 1991). The final 20-item test had KR-20 of .89, item difficulty from .200 to .839, item-total correlations from $.426$ to $.590$, and discrimination indices from $.449$ to $.878$, indicating good to very good discrimination (Crocker & Algina, 1986). Each correct response was worth 5 points, for a total possible score of 100 points.

Attitude toward Science Course and Laboratories Scale

The Attitude toward Science Course and Laboratories Scale measured gifted sixth-graders' attitudes towards science and laboratory work. Developed by Barmby et al. (2005) and adapted into Turkish by Kaya and Böyük (2011), the scale includes 21 items rated on a 5-point Likert scale. It has three subscales: learning science in school (6 items), practical work in science (8 items), and science self-concept (7 items). The first two measure students' attitudes towards learning science in classroom and laboratory settings, while the third assesses their perceived competence in learning school science. Items 6, 7, 8, and 12 in the science self-concept subscale and Item 21 in the practical work subscale were reverse-coded. Examples of items from the scale were "*I can't wait for science class*" (learning science in school), "*Science experiments are exciting*" (practical work in science), and "*I get good marks in science*" (science self-concept). Previous studies reported high reliability for the scale (Kapici et al., 2020; Kind et al., 2007). Cronbach's alpha was .81 at pretest and .79 at posttest, both exceeding the .70 criterion for acceptable reliability (Büyükoztürk, 2025).

Procedure and Data Collection

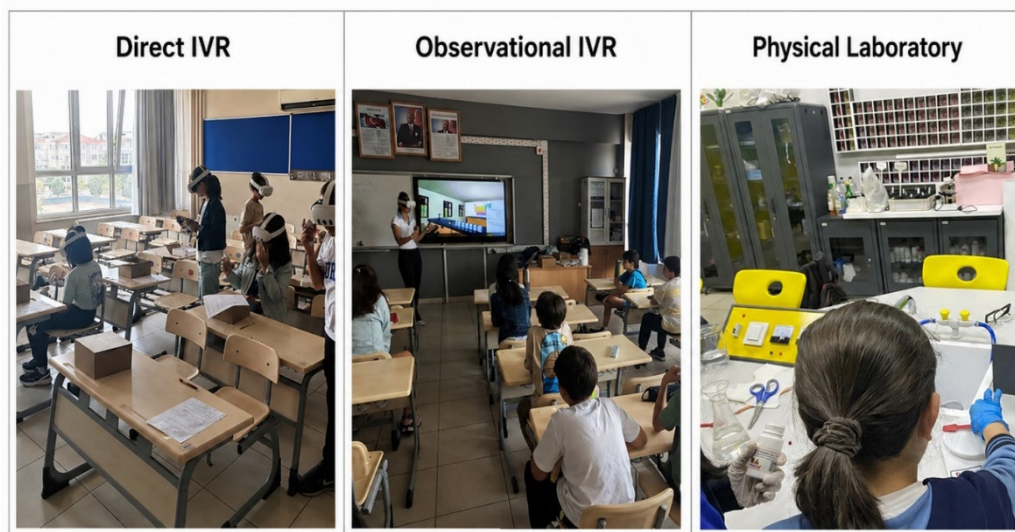
Before implementation, students were briefed on the study's purpose and procedures and provided voluntary assent, while their parents provided written consent. This stage lasted 25 minutes. Students then completed the Chemical Change Knowledge Test and the Attitude toward Science Course and Laboratories Scale in written form, which took approximately 40 minutes. The learning session is detailed in Figure 1. Next, all three groups received the same 25-minute preparatory lesson on the distinction between physical and chemical change. Students examined the initial substances, temperature changes, colour changes, gas formation, and the formation of a new solid, and learned to distinguish observation from inference. Laboratory safety teaching covered personal protective equipment, chemical handling, glassware use, and waste disposal.

Figure 1
Learning Session

The direct IVR group received additional teaching on using the IVR system. Students practised using the HMD and motion controllers, including moving within the virtual environment, selecting objects, and interacting with laboratory equipment. After a short practice session, they demonstrated independent use of the system. The study was based on the Single Mixture Exercise by Hu-Au and Okita (2021). Copper chloride was mixed with water, and aluminium foil was added to the resulting solution. Across all three groups, students examined initial substances, temperature changes, colour changes, gas formation, and new solid formation, recorded observations on the worksheet, and evaluated them as evidence of chemical change.

The students in the direct IVR group worked individually with The VR Chemistry Lab software (Hu-Au, n.d.). They used motion controllers to manipulate virtual equipment, complete the experimental steps, and examine molecular representations within the virtual environment. In the teacher-modelled observational IVR group, the teacher conducted the experiment in The VR Chemistry Lab and projected the first-person view onto the classroom screen. The teacher explained each step and directed students' attention to key observations. Students did not control the virtual environment; instead, they recorded predictions, observations, evidence, and explanations on a worksheet.

The students in the physical laboratory group conducted the experiment with real chemicals and equipment. They measured substances, prepared the solution, recorded temperature changes, examined molecular level changes through visuals on an interactive whiteboard, and recorded their findings on the worksheet. Visual comparisons of the three learning environments are presented in Figure 2.

Figure 2*Comparison of the Learning Environments*

The same content, experimental steps, worksheet, and time allocation were used across all three groups. Students applied the SOI model's selecting, organising, and integrating processes by selecting relevant information, organising measurements and observations, and connecting new information to prior knowledge. Generative learning strategies were also used consistently across all three groups. Students made predictions and recorded their observations. They also distinguished between observations and inferences and formulated evidence-based explanations. The teaching process included experiments and molecular representations and lasted approximately 50 minutes for each group. Immediately following the intervention, the Chemical Change Knowledge Test and Attitude toward Science Course and Laboratories Scale were administered as posttests. The posttest administration took approximately 40 minutes.

Data Analyses

The dataset was scrutinised for accuracy, with group codes, item responses, subscale scores, and total scores verified. Correct responses on the Chemical Change Knowledge Test earned 5 points each, producing scores from 0 to 100. On the Attitude toward Science Course and Laboratories Scale, positively worded items were scored directly, and negatively worded items 6, 7, 8, 12, and 21 were reverse-coded prior to analysis. Subscale and total scores were calculated by averaging relevant items. The total attitude score was obtained by averaging all 21 items after reverse coding. Scores ranged from 1 to 5, with higher scores indicating more positive attitudes.

Before analysis, the dataset was examined for missing data, data-entry errors, and univariate outliers. Outliers were evaluated using box plots and standardised scores. Normality of score distributions was examined separately for each group and measurement occasion using histograms, normal probability plots, skewness and kurtosis coefficients, and the Shapiro–Wilk test. Parametric procedures are generally robust to moderate departures from normality when group sizes are similar (Büyüköztürk, 2025). The homogeneity of variances was examined using Levene's test, and the equality of variance–covariance matrices across the three groups was evaluated using Box's M test. Because the within-subjects factor included only two measurement occasions, pretest and posttest, the sphericity assumption was automatically satisfied.

To determine group comparability before the intervention, pretest scores for the Chemical Change Knowledge Test, total attitude score, and the three attitude subscales were analysed separately using one-way analysis of variance. Following confirmation that pretest differences were statistically insignificant, a 3×2 mixed-design ANOVA was used to examine intervention effects for each dependent variable. This method allows researchers to track changes across repeated measurements and determine whether these changes differ across independent groups (Büyüköztürk, 2025; Fraenkel et al., 2012). The learning environment was treated as a three-level between-

subjects factor: direct IVR, teacher-modelled observational IVR, and physical laboratory conditions. Measurement occasion was treated as a two-level within-subjects factor: pretest and posttest. Five separate 3×2 mixed-design ANOVAs were conducted: one for chemical change knowledge and four for total attitude, learning science in school, practical work in science, and science self-concept.

Each analysis examined the main effect of measurement occasion, the main effect of learning environment, and their interaction. The main point of interest was the interaction effect, indicating whether the magnitude of change from pretest to posttest varied across the different learning environments. When the interaction was statistically significant, simple-effect analyses were conducted. Pretest and posttest scores were compared within each group, and posttest scores were compared pairwise across the three groups. To control the familywise Type I error rate, Bonferroni adjustment was applied to comparisons between direct IVR and physical laboratory, direct IVR and observational IVR, and physical laboratory and observational IVR. Pairwise comparisons were presented in terms of mean differences, standard errors, 95% confidence intervals, and p values adjusted using the Bonferroni correction.

In addition to statistical significance, effect sizes were calculated. Partial eta squared was reported for the main effects of group and measurement occasion and for their interaction. Cohen's d was calculated for pairwise between-group comparisons, and Cohen's d_z was used for within-group pretest-posttest changes (Cohen, 2013). The internal consistency of the attitude scale was evaluated using Cronbach's alpha, and the internal consistency of the Chemical Change Knowledge Test was evaluated using the Kuder-Richardson 20 coefficient. All analyses were two-tailed, with a statistical significance level set at .05. Data from the study were analysed using IBM SPSS Statistics 22.

Research Results

Findings for the Chemical Change Knowledge Test

A 3×2 mixed-design ANOVA was conducted to examine the effects of the learning environments on students' chemical change knowledge. Table 1 presents descriptive statistics for the pretest, posttest, and gain scores, while Figure 3 shows changes in mean scores across learning environments.

Table 1
Chemical Change Knowledge Test Scores

Measurement	Direct IVR ($n = 23$)	Physical laboratory ($n = 21$)	Observational IVR ($n = 22$)	Total ($N = 66$)
Pretest, M (SD)	54.35 (8.02)	53.33 (6.58)	52.50 (8.56)	53.41 (7.70)
Posttest, M (SD)	83.91 (6.73)	73.33 (7.47)	71.36 (7.90)	76.36 (9.18)
Gain, M (SD)	29.57 (10.33)	20.00 (10.25)	18.86 (12.14)	22.95 (11.83)

As shown in Table 1, chemical change knowledge scores increased in all three groups. The direct IVR group had the highest posttest mean and mean gain. Although the physical laboratory group had slightly higher posttest and gain scores than the observational IVR group, the two groups showed similar results.

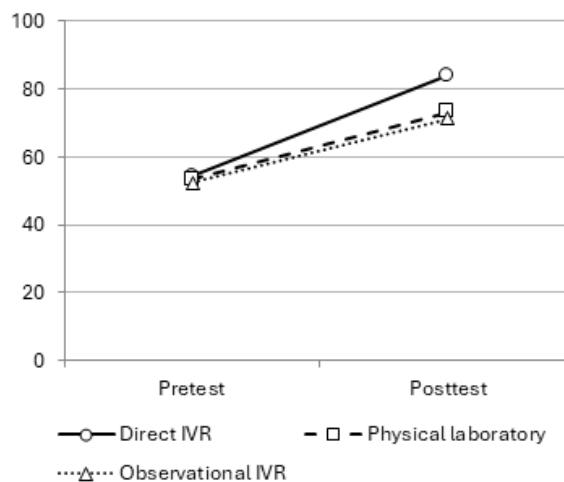
Figure 3*Pretest and Posttest Mean Scores on the Chemical Change Knowledge Test by Learning Environment*

Figure 3 shows that the groups had similar pretest means, whereas the direct IVR group achieved a higher posttest mean than the other groups. The increases in the physical laboratory and observational IVR groups were similar. Table 2 presents the main effects of learning environment and time and their interaction on chemical change knowledge scores.

Table 2*Results of the 3 × 2 Mixed-Design ANOVA for Chemical Change Knowledge Scores*

Effect	df	F	p	η_p^2
Learning environment	2, 63	11.92	< .001	.275
Time	1, 63	290.48	< .001	.822
Learning environment × time	2, 63	6.50	.003	.171

Note. η_p^2 = partial eta squared.

As shown in Table 2, the main effect of time was significant, $F(1, 63) = 290.48, p < .001, \eta_p^2 = .822$, indicating that chemical change knowledge generally increased from pretest to posttest. The effect size was large. The main effect of learning environment was also significant, $F(2, 63) = 11.92, p < .001, \eta_p^2 = .275$, with a large effect size. More importantly, the learning environment × time interaction was significant, $F(2, 63) = 6.50, p = .003, \eta_p^2 = .171$, and had a large effect. Thus, changes from pretest to posttest differed across learning environments.

Within-group comparisons showed significant increases in the direct IVR, $t(22) = 13.73, p < .001, d_z = 2.86$; physical laboratory, $t(20) = 8.94, p < .001, d_z = 1.95$; and observational IVR groups, $t(21) = 7.29, p < .001, d_z = 1.55$. All within-group effect sizes were large. Bonferroni-adjusted posttest comparisons showed that the direct IVR group scored significantly higher than the physical laboratory group (mean difference = 10.58, $p < .001, d = 1.49$) and the observational IVR group (mean difference = 12.55, $p < .001, d = 1.71$). Both differences had large effect sizes. Although the physical laboratory group scored 1.97 points higher than the observational IVR group, the difference was not significant ($p > .05, d = 0.26$) and had a small effect size. These findings indicate that all three environments improved chemical change knowledge, but the direct IVR group showed the greatest improvement.

Attitudes toward Science and Science Laboratories

Four 3 × 2 mixed-design ANOVAs examined the effects of learning environment on learning science in school, practical work in science, science self-concept, and overall attitude. Table 3 presents descriptive statistics for pretest, posttest, and gain scores, while Figure 4 shows changes in mean scores across learning environments.

Table 3
Descriptive Statistics for Attitude Scores

Variable and measurement	Direct IVR (n = 23)	Physical laboratory (n = 21)	Observational IVR (n = 22)	Total (N = 66)
Learning science in school				
Pretest, <i>M</i> (<i>SD</i>)	3.04 (0.38)	3.02 (0.52)	2.84 (0.49)	2.97 (0.47)
Posttest, <i>M</i> (<i>SD</i>)	3.77 (0.28)	4.40 (0.28)	3.45 (0.29)	3.87 (0.48)
Gain, <i>M</i> (<i>SD</i>)	0.73 (0.42)	1.38 (0.59)	0.61 (0.62)	0.90 (0.64)
Practical work in science				
Pretest, <i>M</i> (<i>SD</i>)	3.04 (0.37)	2.99 (0.43)	2.97 (0.46)	3.00 (0.41)
Posttest, <i>M</i> (<i>SD</i>)	4.29 (0.28)	4.03 (0.12)	3.50 (0.25)	3.95 (0.40)
Gain, <i>M</i> (<i>SD</i>)	1.25 (0.49)	1.04 (0.47)	0.53 (0.52)	0.94 (0.57)
Science self-concept				
Pretest, <i>M</i> (<i>SD</i>)	2.98 (0.50)	3.02 (0.38)	2.94 (0.47)	2.98 (0.45)
Posttest, <i>M</i> (<i>SD</i>)	3.84 (0.23)	4.32 (0.23)	3.40 (0.28)	3.84 (0.45)
Gain, <i>M</i> (<i>SD</i>)	0.86 (0.51)	1.30 (0.48)	0.45 (0.54)	0.86 (0.61)
Overall attitude				
Pretest, <i>M</i> (<i>SD</i>)	3.02 (0.33)	3.01 (0.34)	2.92 (0.40)	2.99 (0.36)
Posttest, <i>M</i> (<i>SD</i>)	3.99 (0.22)	4.23 (0.15)	3.45 (0.21)	3.89 (0.38)
Gain, <i>M</i> (<i>SD</i>)	0.97 (0.40)	1.22 (0.40)	0.53 (0.48)	0.90 (0.51)

As shown in Table 3, all attitude scores increased in all three environments. The physical laboratory group showed the largest gains in learning science in school, science self-concept, and overall attitude, whereas the direct IVR group showed the largest gain in practical work in science. Although all scores also increased in the observational IVR group, its gains were smaller than those of the other groups.

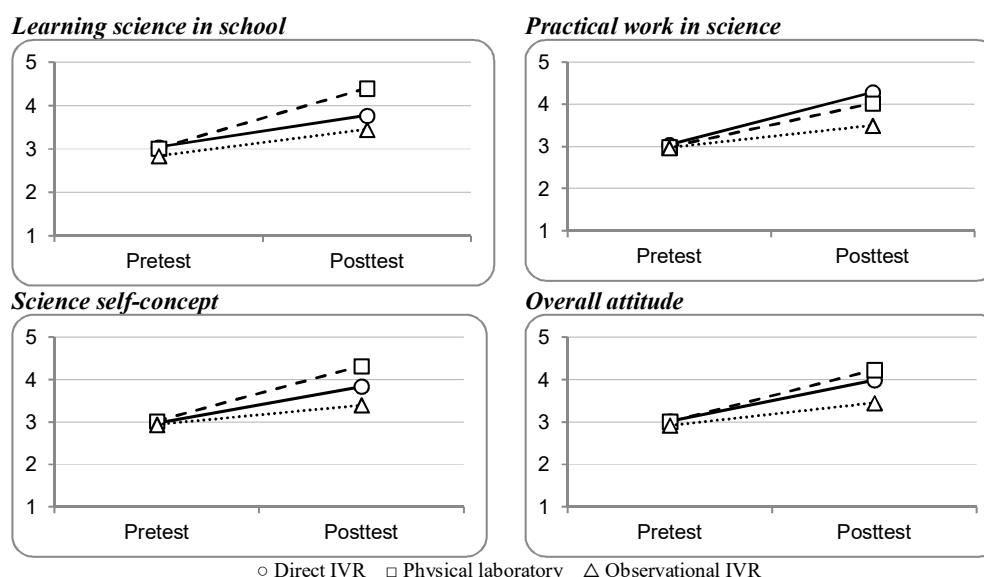
Figure 4
Pretest and Posttest Mean Attitude Scores by Learning Environment

Figure 4 shows that the groups had similar pretest means across all variables, whereas posttest means differed by learning environment. The physical laboratory group had the highest means for learning science in school, sci-

ence self-concept, and overall attitude. The direct IVR group had the highest posttest mean for practical work in science. The observational IVR group had the lowest posttest means across all variables. Table 4 presents the main effects of learning environment and time and their interactions for the four attitude variables.

Table 4
Results of the 3 × 2 Mixed-Design ANOVAs for Attitude Scores

Variable	Effect	df	F	p	η^2
Learning science in school	Learning environment	2, 63	23.25	< .001	.425
	Time	1, 63	177.24	< .001	.738
	Learning environment × time	2, 63	12.15	< .001	.278
Practical work in science	Learning environment	2, 63	19.87	< .001	.387
	Time	1, 63	240.07	< .001	.792
	Learning environment × time	2, 63	12.58	< .001	.285
Science self-concept	Learning environment	2, 63	20.22	< .001	.391
	Time	1, 63	188.76	< .001	.750
	Learning environment × time	2, 63	14.70	< .001	.318
Overall attitude	Learning environment	2, 63	28.12	< .001	.472
	Time	1, 63	293.04	< .001	.823
	Learning environment × time	2, 63	14.52	< .001	.316

The main effect of time was significant for learning science in school, $F(1, 63) = 177.24, p < .001, \eta_p^2 = .738$; practical work in science, $F(1, 63) = 240.07, p < .001, \eta_p^2 = .792$; science self-concept, $F(1, 63) = 188.76, p < .001, \eta_p^2 = .750$; and overall attitude, $F(1, 63) = 293.04, p < .001, \eta_p^2 = .823$. Thus, all scores increased from pretest to posttest. All effects were large. The main effect of learning environment was also significant and large for every variable. The learning environment × time interaction was significant for learning science in school, $F(2, 63) = 12.15, p < .001, \eta_p^2 = .278$; practical work in science, $F(2, 63) = 12.58, p < .001, \eta_p^2 = .285$; science self-concept, $F(2, 63) = 14.70, p < .001, \eta_p^2 = .318$; and overall attitude, $F(2, 63) = 14.52, p < .001, \eta_p^2 = .316$. All interaction effects were large, indicating that the magnitude of change differed across learning environments.

Within-group comparisons showed significant increases in all four variables in every condition. In the direct IVR group, scores increased for learning science in school, $t(22) = 8.36, p < .001, d_z = 1.74$; practical work in science, $t(22) = 12.13, p < .001, d_z = 2.53$; science self-concept, $t(22) = 8.09, p < .001, d_z = 1.69$; and overall attitude, $t(22) = 11.72, p < .001, d_z = 2.44$. Significant increases were also found in the physical laboratory group for learning science in school, $t(20) = 10.65, p < .001, d_z = 2.32$; practical work in science, $t(20) = 10.18, p < .001, d_z = 2.22$; science self-concept, $t(20) = 12.52, p < .001, d_z = 2.73$; and overall attitude, $t(20) = 14.06, p < .001, d_z = 3.07$. The observational IVR group likewise improved in learning science in school, $t(21) = 4.66, p < .001, d_z = 0.99$; practical work in science, $t(21) = 4.79, p < .001, d_z = 1.02$; science self-concept, $t(21) = 3.91, p < .001, d_z = 0.83$; and overall attitude, $t(21) = 5.11, p < .001, d_z = 1.09$. All within-group effects were large. The strongest effects occurred in the physical laboratory group for learning science in school, science self-concept, and overall attitude, and in the direct IVR group for practical work in science.

Bonferroni-adjusted posttest comparisons showed significant differences among all three groups for every variable. For learning science in school, the physical laboratory group scored higher than the direct IVR group (mean difference = 0.64, $p < .001, d = 2.27$) and the observational IVR group (mean difference = 0.95, $p < .001, d = 3.34$). The direct IVR group also scored higher than the observational IVR group (mean difference = 0.31, $p = .002, d = 1.11$). For practical work in science, the direct IVR group scored higher than the physical laboratory group (mean difference = 0.26, $p < .001, d = 1.20$) and the observational IVR group (mean difference = 0.79, $p < .001, d = 2.98$). The physical laboratory group also outperformed the observational IVR group (mean difference = 0.53, $p < .001, d = 2.64$). For science self-concept, the physical laboratory group scored higher than the direct IVR group (mean difference = 0.48, $p < .001, d = 2.10$) and the observational IVR group (mean difference = 0.92, $p < .001, d = 3.66$). The direct IVR group also scored higher than the observational IVR group (mean difference = 0.44, $p < .001, d = 1.74$). For overall attitude, the physical laboratory group scored higher than the direct IVR group (mean difference = 0.24, $p < .001$,

$d = 1.28$) and the observational IVR group (mean difference = 0.78, $p < .001$, $d = 4.21$). The direct IVR group also scored higher than the observational IVR group (mean difference = 0.54, $p < .001$, $d = 2.50$). All between-group effects were large. These findings suggest that direct experimentation particularly strengthened attitudes towards practical work in science, whereas the physical laboratory contributed more strongly to learning science in school, science self-concept, and overall attitude.

Discussion

This study compared the effects of direct IVR, physical laboratory, and observational IVR on gifted students' chemical change knowledge and science attitudes. The direct IVR group showed the greatest gain in chemical change knowledge and attitudes towards practical work in science. The physical laboratory group improved more in attitudes towards learning science in school, science self-concept, and overall science attitude. The observational IVR group also saw increased knowledge and attitude scores, though its attitudinal gains were smaller. The comparable knowledge gains in the observational IVR and physical laboratory groups suggest that observational IVR may be a viable option for teaching chemical change.

The direct IVR group's greater knowledge gain is consistent with previous virtual laboratory research involving gifted students. Kapici and Costu (2023b) found that gifted sixth-grade students improved their conceptual knowledge and science process skills in both physical and virtual laboratories, but gains were greater in the virtual laboratory group. They attributed this result to virtual hypothesis-generation and experiment-design tools that made inquiry more visible and manageable. This study extends that finding from desktop virtual laboratories to HMD-based direct IVR. Hu-Au and Okita (2021) reported a significant increase in general chemistry knowledge in the VR group but not in the physical laboratory group. However, gains did not differ significantly between the groups. Their findings do not establish the superiority of IVR but support its capacity to improve chemistry knowledge. Wiedbusch et al. (2026) found that perceived agency in IVR predicted declarative knowledge, procedural knowledge, and laboratory skills, and that IVR students later performed more accurately in a physical laboratory. Evidence suggests that IVR-based science education can improve achievement and science motivation compared with lecture-based education (Liu et al., 2022).

The direct IVR group's greater knowledge gain may be related to students' active control over experimental procedures and generative processing of information. According to CAMIL, technological affordances such as immersion and control produce psychological experiences such as presence and agency, which may then influence learning through interest, motivation, self-efficacy, embodiment, cognitive load, and self-regulation (Makransky & Petersen, 2021). Students in the direct IVR group performed the experiment's procedures themselves, connecting experimental actions, observed changes, and conceptual outcomes. The worksheets and generative tasks may have directed students to select relevant evidence, organise observations, and integrate new information with prior knowledge. Thus, the greater knowledge gain may reflect the combined contribution of embodied interaction and the processes of selecting, organising, and integrating information (Fiorella & Mayer, 2016; Makransky & Petersen, 2021).

However, IVR does not always produce superior learning. Makransky et al. (2021) found that IVR generated greater enjoyment and presence than video but did not independently yield higher learning. In the same study, students who reenacted the DNA analysis procedure with physical materials after IVR outperformed those who did not on procedural knowledge and transfer. Parong and Mayer (2018) reported greater interest but lower knowledge scores in IVR than in slide-based teaching. They also found that segmenting IVR content and requiring summaries after each segment improved knowledge. Makransky et al. (2019) found that IVR produced greater presence and cognitive load but lower learning than a desktop simulation. Anam et al. (2025) found no significant differences among physical, virtual, and combined physical–virtual experimentation in conceptual knowledge or science process skills. A systematic review by Poupard et al. (2025) showed that IVR may impose extraneous cognitive load, particularly on novices. These findings suggest that the knowledge gain observed in the present study cannot be attributed to immersion alone. Segmenting IVR content and requiring summaries may have limited IVR-related cognitive load.

Individual differences among gifted students should also be taken into account when interpreting the findings. Gifted students may exhibit distinct strengths in information processing, working memory, problem-solving, attentional control, intrinsic motivation, and self-efficacy. However, these characteristics vary considerably across individuals (Davis et al., 2017; Kuznetsova et al., 2024). This may influence how students respond to the cognitive

and interactive demands of IVR applications. The present study did not measure these characteristics, so they cannot explain the observed group differences. Lawson and Mayer (2024) found no significant difference in learning between IVR and slide groups, but executive functioning predicted learning within the IVR group. Students who regulate attention and behaviour more effectively may benefit more from IVR. Gifted students may also benefit from guidance during inquiry-based learning (Kapici & Costu, 2023a). High cognitive capacity does not eliminate the need for educational support. IVR activities for gifted students should balance learner autonomy with conceptual guidance.

Knowledge gains did not differ significantly between the physical laboratory and observational IVR groups. Previous research reported comparable outcomes for physical and virtual laboratories in conceptual knowledge and inquiry skills (Anam et al., 2025; Kapici et al., 2022). However, this does not mean the two environments are equivalent across all learning processes and skills. In the physical laboratory, students measured substances, prepared equipment, recorded temperature changes, and managed experimental uncertainty. They gained direct experience with laboratory tools and data collection. Meanwhile, part of their attention was devoted to apparatus setup, measurement, and safety. Puntambekar et al. (2021) found that students in physical laboratories talked more about setup, measurement, and calculation, whereas students in virtual laboratories focused more on prediction, variable relationships, and conceptual explanation. Students in the observational IVR group did not manipulate laboratory tools. However, the teacher explained the reasons for each procedure and directed attention to relevant changes while conducting the experiment. This may have helped students focus on the conceptual content of chemical change. Because science process skills and psychomotor laboratory skills were not measured, similar knowledge gains do not imply similar outcomes in other dimensions of laboratory learning (Gericke et al., 2023).

Greater gains in attitudes towards learning science in school, science self-concept, and overall science attitude in the physical laboratory group suggest that authentic laboratory experience supports students' evaluations of science learning and their own competence. Working with real substances, using equipment, taking measurements, solving problems, and completing an experiment provides direct evidence of scientific capability. Laboratory activities support conceptual learning and participation in scientific practices like observing, measuring, collecting data, and drawing evidence-based conclusions (Gericke et al., 2023). However, the attitudinal contribution of physical laboratories cannot be attributed solely to interaction with real objects. Lang et al. (2005) found significant relationships between gifted students' attitudes towards chemistry laboratories and their perceptions of openness, the material environment, and teacher-student interaction. Their study suggests that collaborative decision making, responsibility, immediate teacher feedback, and successful task completion strengthen science self-concept and attitudes towards school science.

The present attitudinal findings differ from those of Kapici et al. (2020), who compared physical, virtual, and combined laboratory conditions and found no differences in attitudes towards learning science in school, practical work in science, or science self-concept. In contrast, the physical laboratory produced greater gains in attitudes towards learning science in school and science self-concept, while direct IVR produced the greatest gain in attitudes towards practical work in science. This difference may reflect participant characteristics and the environments compared. Kapici et al. (2020) examined physical and desktop virtual laboratories used separately or sequentially, whereas the present study compared HMD-based direct IVR, physical laboratory, and teacher-led observational IVR. Nacaröğlu and Kızkapan (2020) found a moderate relationship between gifted students' academic risk-taking in laboratory work and their orientations towards science learning. Opportunities to test ideas, correct errors, consider alternatives, and make evidence-based decisions in a physical laboratory align with these tendencies.

The different attitudinal outcomes in the direct IVR and physical laboratory groups indicate that learning environments support distinct dimensions of attitude. Students in the direct IVR group individually controlled virtual tools, completed experimental steps, and observed immediate consequences. This ability to perform and repeat procedures without safety risks may have encouraged them to view IVR as practical science work. Gifted students learning chemical bonding through a haptic VR application reported more positive views of haptic interaction and VR than students receiving lecture-based education (Ucar et al., 2017). Dubovi (2023) also found that direct VR participants experienced stronger positive emotions than observational VR participants. However, positive evaluations of IVR do not automatically produce higher learning or more positive general science attitudes (Makransky et al., 2021). The present finding should be interpreted specifically in relation to attitudes towards practical work in science.

Attitude scores also increased in the observational IVR group, but less than in the direct IVR and physical laboratory groups. These results may reflect not only differences in learner control, but also differences in the nature of the learning experience itself. When students perform a task directly in IVR, they experience the consequences of their

own actions as part of the task. In observational IVR, students instead follow the teacher's actions and explanations and focus on the parts of the procedure highlighted by the teacher. From Bandura's (1977) perspective, this form of observation may support attention and retention, although students in this condition did not reproduce the observed actions themselves. This may partly explain why observational IVR supported knowledge gains, while changes in attitudes were smaller than in direct IVR. In Dubovi's (2023) study, observational learners did not simply watch a successful performance. They observed a novice's errors and an explanatory dialogue between the novice and an expert, achieving knowledge gains comparable to direct VR learners. Luo et al. (2021) found no difference in knowledge or performance between students who used VR directly and those who observed another student, but structured debriefing improved both groups' outcomes. Students observing a teacher conduct an HMD-based lab activity achieved theoretical knowledge scores comparable to those using written lab materials (Veitch et al., 2025). The effectiveness of observational IVR may therefore also depend on how observation is supported through explanation, discussion, reflection, and opportunities to apply the observed procedures. In the present study, students completed generative worksheets but did not make experimental decisions or perform the procedures they observed. This may have limited some of the experiential and affective benefits of direct participation. To strengthen observational IVR, prediction, error analysis, teacher think alouds, structured debriefing, and practice after observation may be added.

Conclusion and Implications

The findings showed that direct IVR produced the greatest gains in students' chemical change knowledge and attitudes towards practical work in science. In contrast, students in the physical laboratory showed the largest gains in attitudes towards learning science, science self-concept, and overall attitudes towards science. No single laboratory environment produced the strongest outcomes across all measures. These findings suggest that the intended learning outcome should guide the choice of laboratory environment for gifted students. Direct IVR may be particularly suitable when the aim is to improve chemical change knowledge and attitudes towards practical work in science through individual control of experimental procedures. A physical laboratory may be more appropriate when the aim is to strengthen attitudes towards school science and science self-concept. Observational IVR and the physical laboratory produced similar gains in chemical change knowledge, suggesting that observational IVR may support learning when opportunities for direct experimentation are limited. However, the smaller attitudinal gains observed in this condition suggest that observation may not provide the same affective benefits as direct participation. Although the study was conducted in the Turkish BİLSEM context, the findings may also be relevant to other gifted education settings facing similar circumstances. These findings can help schools make informed decisions about the use of physical laboratories, direct IVR, and observational IVR in relation to their learning goals and available resources. They may also inform decisions about investment in laboratory infrastructure and IVR technology.

Limitations and Recommendations for Future Research

The study involved 66 gifted sixth-grade students from a single BİLSEM and used existing groups without random assignment. Although the measured pretest scores did not differ significantly, unmeasured baseline differences cannot be ruled out, and the observed group differences should therefore not be interpreted as definitive causal effects of the learning environments. Accordingly, non-random assignment may have introduced selection bias despite the absence of statistically significant pretest differences. The relatively small sample drawn from a single institution also limits the strength and generalisability of the conclusions. In addition, because the intervention was brief and the posttest was administered immediately afterwards, the findings mainly reflect immediate outcomes rather than longer-term change. This limitation is particularly relevant to the attitude measures, which relied on self-report and may not fully capture behavioural or lasting attitudinal change. The use of identical instruments at pretest and posttest may also have introduced testing effects. Future research could address these limitations by incorporating delayed posttests and performance-based laboratory tasks to examine retention, transfer, and hands-on laboratory skills. It would also be worthwhile to compare conditions that combine physical laboratories and IVR, or that employ them in different sequences. Such studies might further benefit from measuring agency, cognitive load, and presence to shed light on how these factors relate to learning outcomes.

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Declaration of Interests

The author declared no conflicts of interests.

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