



GIFTED FIFTH-GRADE STUDENTS' ATTITUDES, MOTIVATION, AND MEANING- MAKING REGARDING IMMERSIVE VIRTUAL REALITY IN SCIENCE EDUCATION

Leyla Ayverdi

Abstract. *Research examining gifted students' attitudes, motivation, and meaning-making regarding immersive virtual reality (IVR) in science education remains limited. This study examined gifted fifth-grade students' attitudes and motivation towards virtual reality (VR), together with their metaphorical meanings and free word associations related to IVR, before and after IVR-supported science teaching. The participants were 73 students attending a Science and Art Centre in Türkiye. The study followed a convergent mixed-methods design. During six lessons, students received theoretical preparation, guided IVR observation and exploration, and post-activity discussion. Attitude and motivation scales provided quantitative data; metaphors and free word associations provided qualitative data. At post-test, higher scores were found for attitudes towards VR, total motivation, intrinsic motivation, integrated regulation, and the reverse-scored external regulation subscale. Higher scores on the latter reflected lower endorsement of externally regulated reasons. Individual patterns varied. Reality and virtuality remained central in the qualitative findings, while learning, education, knowledge, and enjoyable learning became more prominent and technology-related meanings less prominent. Considered together, the findings showed partial convergence and expansion. Because the study involved a single group, the observed pre-post differences are not interpreted as evidence of causal effects or academic learning.*

Keywords: *convergent mixed methods, gifted students, immersive virtual reality (IVR), science education*

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Introduction

Students may struggle to learn abstract science topics that cannot be directly observed or experienced. Microscopic and molecular processes, such as bacteria and mechanisms of antibiotic action, can pose conceptual difficulties and contribute to misconceptions (Molan et al., 2025). Likewise, space, atoms, and subatomic particles are often interpreted through two-dimensional visuals and explanations because they cannot be directly observed (Ayverdi & Avcu, 2025; Girón-Gamero & Franco-Mariscal, 2023; Pinto et al., 2023). Science topics spanning micro, nano, and macroscales require spatial reasoning, mental visualisation, and conceptual integration. Presenting these processes mainly through two-dimensional representations may hinder understanding of three-dimensional, dynamic relationships and connections across scales (Claußnitzer & Paul, 2025; Hamerská et al., 2024).

Given their potential to address these limitations, virtual technologies have received growing attention in science education research (Radianti et al., 2020). Among them, immersive virtual reality (IVR) uses a head-mounted display and motion tracking to immerse users in and enable interaction with a three-dimensional virtual environment. Its sensory immersion, representational fidelity, and interactivity may foster a sense of presence and perceived control over actions in the virtual environment (Matovu et al., 2023). These affordances may enable students to examine difficult-to-observe scientific structures and processes in three dimensions and explore them interactively.

In science education, IVR may allow students to examine microscopic structures and invisible processes in three dimensions (Chen et al., 2024; Mokmin & Apandi, 2025). Its motion-tracking features can support embodied interaction and, when combined with interactive interfaces, may enable students to conduct experiments that would be hazardous or ethically problematic in real life within a virtual environment (Matovu et al., 2023; Ye et al., 2022). In addition, IVR may allow students to manipulate elements in the virtual environment and observe the consequences of their actions. It may



also provide an alternative environment for conducting science activities when direct access to physical equipment, materials, or specialised settings is limited (Matovu et al., 2023). However, IVR's technological affordances should not be assumed to produce positive learning outcomes or experiences in every context. Despite its advantages in science education, IVR use has been associated with greater cognitive load and emotional arousal, while some comparisons have reported lower engagement or learning performance (Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2021). IVR use may also be accompanied by simulator sickness symptoms such as dizziness, nausea, and difficulties with focus and concentration (Hsin et al., 2023). Practical challenges may include device purchase and maintenance, software updates, user account management, sharing devices among students, managing lesson time, and finding curriculum-aligned content (Fransson et al., 2020). Therefore, the role of IVR in science education should be evaluated not only in terms of immersion but also in relation to instructional design, learner characteristics, and implementation conditions.

Research Problem

Reviews indicate that IVR research has concentrated particularly on biology and physics (Hamilton et al., 2021). In the broader VR/AR-supported K–12 science education literature, inquiry-based learning has been reported as the most frequently adopted approach (Zhang & Wang, 2021). IVR studies have generally involved short-term or one-time interventions (Hamilton et al., 2021; Matovu et al., 2023; Won et al., 2023), and information retention has rarely been examined (Hamilton et al., 2021). IVR has commonly been used to visualise abstract concepts and enhance learning experiences (Matovu et al., 2023), while technological features have received more attention than pedagogical features that structure learners' engagement with learning (Won et al., 2023). These findings suggest that interest in IVR is closely related to its visualisation, immersion, and interaction affordances, but how these affordances are integrated with pedagogical tasks and activities also warrants attention.

Studies across science contexts have examined outcomes including knowledge acquisition, conceptual learning, motivation, attitudes, interest, engagement, self-efficacy, cognitive load, and learning performance (Ayverdi, 2026; Huang et al., 2021; Liu et al., 2022; Makransky et al., 2020; Makransky, Terkildsen, et al., 2019; Parong & Mayer, 2018; Petersen et al., 2023). However, the reported patterns are not consistent. Some studies found higher interest and self-efficacy (Makransky et al., 2020), whereas others reported greater cognitive load and lower learning performance alongside higher presence (Makransky, Terkildsen, et al., 2019). Parong and Mayer (2018) found higher motivation and engagement in the IVR group but higher learning scores in the slideshow group. IVR applications incorporating structured generative activities further highlight the importance of pedagogical design (Petersen et al., 2023). Overall, these patterns suggest that IVR outcomes should be considered in relation to educational design and implementation conditions rather than immersion alone.

Caution is needed when generalising these findings to gifted students. Enrichment for these students is expected to provide challenging, open-ended, and creative learning opportunities responsive to individual characteristics and interests (García-Martínez et al., 2021; Reis et al., 2021). Although IVR affordances for interactive exploration, learner control, and examining complex scientific representations may align theoretically with these principles, this does not mean that IVR is inherently suitable or effective for gifted students. Design studies in gifted science education have integrated IVR with inquiry, creative thinking, the 5E model, collaboration, and design activities (Avcu & Yaman, 2024; Ayverdi & Avcu, 2025). Empirical studies have examined environmental attitudes and nature relatedness (Avcu & Yaman, 2025), science engagement, self-regulation, and scientific creativity (Avcu & Yaman, 2026), as well as conceptual understanding (Ayverdi, 2026). Notably, Avcu and Yaman (2025) assessed attitudes towards the environment rather than towards IVR itself. Despite this emerging literature, studies combining complementary data sources to examine gifted students' attitudes and motivation towards VR, the metaphorical meanings they attribute to IVR, and their spontaneous associations appear limited.

Research Focus

One theoretical model of immersive learning is the Cognitive Affective Model of Immersive Learning (CAMIL). CAMIL proposes that, through the interaction of IVR features and instructional design, psychological affordances such as presence and agency may be associated with cognitive and affective processes. These processes include motivation, self-efficacy, embodiment, cognitive load, and self-regulation. Rather than assuming that IVR itself produces superior learning outcomes, CAMIL emphasises that IVR experiences emerge through interactions with instructional methods and may vary across learners (Makransky & Petersen, 2021).

This perspective is particularly relevant for gifted students, whose cognitive characteristics and learning needs may differ. Despite individual variation, gifted students may differ from their peers in information processing, reasoning, and problem solving. They may also differ in tendencies towards intrinsic motivation, curiosity, exploration, and engagement with complex cognitive tasks (Kuznetsova et al., 2024; Mohseni & Abedi, 2025; Renzulli, 2021). Enrichment programmes for these students are recommended to provide depth, complexity, flexibility, active interaction, and opportunities for exploration (Kutlu Abu & Dal, 2025; Sternberg et al., 2022; World Council for Gifted and Talented Children, 2021). Integrating theoretical preparation, observation and exploration in IVR, and post-activity discussion may align with these principles. However, such alignment does not establish that IVR is inherently suitable or effective for gifted students.

Attitudes and motivation towards VR can be systematically examined using psychometric scales. Educational VR research has generally reported positive patterns in these outcomes (Acevedo et al., 2024; Cheng & Tsai, 2020; Jiang & Fryer, 2024; Makransky & Lilleholt, 2018). Alongside structured data on predefined constructs, metaphors and word association tasks can provide insight into how students frame concepts and experiences and the associations they form with them. Metaphors may support the conceptualisation of new, abstract, or complex phenomena through familiar domains and related mental images (Norscini & Daniela, 2024), while their analysis can identify different ways participants make sense of concepts and experiences (Ahlgren et al., 2021). Whereas metaphors focus on framing through analogies and their rationales, word association tasks elicit words or ideas prompted by a stimulus concept and allow related associations to be examined (Hovardas & Korfiatis, 2006; Playfoot et al., 2018). Such tasks are also used to examine conceptual associations in science education (Nakiboğlu, 2024). However, these data should not be assumed to directly represent students' entire conceptual knowledge or level of learning; they should be interpreted as associations and association patterns linked to the stimulus concept. Together, these four data sources were used to examine complementary dimensions of students' IVR-related experiences. The attitude and motivation scales assessed predefined affective constructs, whereas the metaphor and free word association tasks were used to examine how students conceptualised IVR and the spontaneous associations they formed with it. These data sources were integrated not as measures of the same construct, but to examine patterns of convergence, expansion, and divergence across related but distinct dimensions.

Research Aim and Research Questions

This study aimed to examine pre–post differences in gifted fifth-grade students' attitudes and motivation towards VR, as well as their metaphorical meanings and associative patterns related to IVR, following IVR-supported science teaching. It also aimed to integrate the quantitative and qualitative findings to identify patterns of convergence, expansion, and divergence across data sources. Accordingly, the following research questions were addressed:

1. Do gifted fifth-grade students' attitudes towards VR differ before and after IVR-supported science teaching?
2. Do gifted fifth-grade students' total motivation towards VR and the dimensions of integrated regulation, intrinsic motivation, and external regulation differ before and after IVR-supported science teaching?
3. How do gifted fifth-grade students' metaphorical meanings related to IVR differ before and after IVR-supported science teaching?
4. How do gifted fifth-grade students' associative patterns related to IVR differ before and after IVR-supported science teaching?
5. When the pre–post findings on attitudes and motivation towards VR, metaphorical meanings related to IVR, and associative patterns are integrated, what patterns of convergence, expansion, and divergence emerge across the data sources?

Research Methodology

General Background

This study employed a convergent mixed methods design, in which quantitative and qualitative data are collected during similar time periods, analysed separately, and integrated during interpretation (Fetters et al., 2013). In this study, both types of data were collected from the same group before and after IVR-supported science teaching. Findings from the separate analyses were compared side by side to examine patterns of convergence, expansion, and divergence across data sources (Creswell & Plano Clark, 2018; Fetters et al., 2013). Integration did not assume

that the data sources measured the same construct; rather, they were used to provide complementary interpretations of affective, metaphorical, and associative patterns across the two measurement points.

Participants

The participants were 73 gifted fifth-grade students attending a Science and Art Centre (BİLSEM) in northwestern Türkiye. The sample size was determined by the number of fifth-grade students who volunteered to participate in the study during the data-collection period. Of these, 34 were girls (46.6%) and 39 were boys (53.4%). The students had been identified as gifted through the Ministry of National Education's identification process and admitted to BİLSEM, which provides supplementary education outside regular school hours (Ministry of National Education, 2022). Participants were selected through convenience sampling based on accessibility and willingness to participate (Etikan et al., 2016). The study was approved by the relevant university's Social and Human Sciences Ethics Committee. Parents received an information form describing the study's purpose, scope, duration, and content. All 73 students participated with parental consent and provided assent after the study procedures were explained in age-appropriate language.

Instruments and Procedures

Educational Virtual Reality Applications Attitude Scale (EdVR-AS)

Students' attitudes towards educational virtual reality applications were assessed using the Educational Virtual Reality Applications Attitude Scale (EdVR-AS) developed by Akçelik and Baran (2022). The unidimensional scale for lower-secondary students consists of 18 items, three of which are reverse scored, rated from 1 ("Strongly disagree") to 5 ("Strongly agree"). Total scores range from 18 to 90, with higher scores indicating more positive attitudes. In the development study with 850 lower-secondary students, the single-factor structure explained 54.96% of the variance, with Cronbach's alpha coefficients of .95 and .94. An alpha of .90 was also reported for 26 sixth-grade students who individually experienced an educational VR application (Akçelik & Baran, 2022). In the present study, alpha coefficients were .91 at pretest and .92 at posttest. A sample item is "I like using EdVR apps."

Motivation toward Virtual Reality Scale (MVR Scale)

Students' motivation towards VR was assessed using the Motivation toward Virtual Reality Scale (MVR Scale) developed by Kayar and Umdü Topsakal (2026). The 14-item, 5-point Likert scale comprises three dimensions: integrated regulation, intrinsic motivation, and external regulation, with the external regulation items reverse-scored so that higher scores indicate lower endorsement of externally regulated reasons. The scale's three-factor structure was established through exploratory factor analysis with 301 lower-secondary students and subsequently examined through confirmatory factor analysis with a second sample of 292 students. Additional evidence was obtained from internal consistency, Item Response Theory, measurement invariance, and criterion-related validity analyses (Kayar & Umdü Topsakal, 2026). In the present study, alpha coefficients were .70 at pretest and .74 at posttest. A sample item is "I feel more confident in my learning when I use a virtual reality app to study a topic."

Metaphor Generation Task for IVR

An open-ended metaphor generation task was used to examine the meanings students attributed to IVR and the mental images through which they conceptualised it. Metaphors are used in educational research as cognitive tools for exploring how individuals think about and conceptualise phenomena (Saban, 2010; Saban et al., 2007). Students completed the statement, "Immersive virtual reality (IVR) is like ... because ...," adapted from the "... is like ... because ..." structure used to examine conceptualisations of educational phenomena (Saban, 2010; Saban et al., 2007). The same prompt structure has also been used to examine metaphors about educational technologies across measurement points (Andić et al., 2024). The task was administered with identical instructions before and after IVR-supported science teaching. The entire response, rather than only the metaphor term, was treated as data, allowing the metaphor to be interpreted together with its rationale and accounting for different meanings attached to the same metaphor (Andić et al., 2024).

Free Word Association Task for the IVR Stimulus Concept

A free word association task was used to examine students' spontaneous associations with IVR. In such tasks, participants are presented with a stimulus word or concept and asked to generate related words that come to mind (Playfoot et al., 2018). These tasks have been used in educational research to examine associations with particular concepts and compare associative patterns across measurement points (Hovardas & Korfiatis, 2006). In the present study, the same instructions and the stimulus concept "immersive virtual reality (IVR)" were used before and after IVR-supported science teaching. Students were asked to write words or short phrases that came to mind without predefined response options. Unlike the metaphor task, they were not asked to compare IVR with another concept or phenomenon or explain their associations. Responses were treated as data reflecting associations with the IVR stimulus rather than as direct indicators of students' complete conceptual knowledge or learning level. Accordingly, the instrument was termed a "free word association task" rather than a "test."

Implementation and Data Collection Procedure

The study was conducted through six lesson hours (240 min) of IVR-supported science teaching. The attitude and motivation scales, metaphor task, and free word association task were administered with identical instructions before and after the teaching. The post-test measures were administered immediately after completion of the final IVR-supported science teaching activity. Students completed the teaching in five groups of 14–15 on different days. Ten-minute breaks after each 40-minute lesson were excluded from the total duration.

The teaching comprised three phases: theoretical preparation, observation and exploration in IVR, and post-IVR discussion and conceptualisation. The theoretical phase activated prior knowledge and introduced key concepts and structures, consistent with the pre-training principle of multimedia learning, which recommends introducing essential concepts before complex visual content (Mayer & Fiorella, 2022). In IVR contexts, pre-training has also been associated with positive outcomes in knowledge, transfer, and self-efficacy (Meyer et al., 2019). The teaching sequence is presented in Table 1.

Table 1
Phases of the IVR-Supported Science Teaching

Discipline/Topic	Phase	Duration	Activity
General	Orientation	30 min	Introduction to the IVR system, headset and controllers, and safe-use guidelines
	Theoretical preparation	20 min	Activation of prior knowledge; introduction to bacterial structure, disease development, and antibiotic effects on bacterial ribosomes and protein synthesis
Biology: Bacteria and antibiotic mechanisms	IVR observation and exploration — <i>10k.science: Trouble in Sunshine Creek</i>	30 min	Observation of diseased plants; comparison of healthy and diseased tissues; examination of <i>Xylella fastidiosa</i> ; simulation of antibiotic treatment
	Discussion and conceptualisation	20 min	Linking IVR observations to xylem blockage, bacterial structure, and antibiotic mechanisms
Chemistry: Atom	Theoretical preparation	20 min	Activation of prior knowledge; historical development of atomic models, atomic structure, and subatomic particles
	IVR observation and exploration — <i>VR Lab Academy Junior: Introduction to Atomic Models</i>	30 min	Examination of changes in atomic models, atomic structure, and subatomic particles in different atoms
	Discussion and conceptualisation	20 min	Connecting changes in atomic models with atomic structure and subatomic particles

Discipline/Topic	Phase	Duration	Activity
Physics/Astronomy: Solar System	Theoretical preparation	20 min	Activation of prior knowledge; introduction to the Solar System, planets, asteroids, and natural satellites
	IVR observation and exploration — <i>VR School: Solar System</i>	30 min	Virtual movement around the Sun and other celestial bodies; examination of their size, position, and spatial relationships from different perspectives
	Discussion and conceptualisation	20 min	Discussion of the Solar System, celestial bodies, and their spatial relationships
Total		240 min	Six lesson hours

The IVR content was selected to allow three-dimensional examination of difficult-to-observe structures and spatial relationships across micro, nano, and macroscales in biology, chemistry, and physics/astronomy (Laohapornchaiphan & Chenprakhon, 2024; Wilhelm et al., 2018; Wollmuth et al., 2023). IVR was not treated as a stand-alone tool assumed to ensure learning, but as a teaching environment integrated with theoretical preparation and post-experience activities.

Following theoretical preparation, students used 15 Meta Quest 2 and 3 headsets simultaneously and retained the same device throughout the day. During IVR, they examined virtual structures from different perspectives, observed spatial relationships, and completed interactive tasks. The teacher directed attention to scientifically relevant features while allowing students to explore and complete the tasks. The same teacher led all groups, while two additional instructors provided technical support with the headsets and controllers. Safe-use procedures were explained beforehand, and students were told they could remove the headset, rest, or discontinue the activity if they experienced discomfort. One student experienced nausea, removed the headset to rest, and therefore had a shorter IVR exposure than the other students. Classroom examples of students’ participation in the IVR observation and exploration phase across the three science topics are presented in Figure 1.

Figure 1
IVR Observation and Exploration in (a) Chemistry, (b) Physics/Astronomy, and (c) Biology



After each IVR experience, students were asked to explain and compare their observations and relate them to scientific concepts. These discussions were consistent with active processing involving selecting, organising,

explaining, and connecting information with prior knowledge (Mayer, 2014). Post-VR group discussions have also been associated with positive outcomes in knowledge acquisition and behavioural performance (Luo et al., 2021). Rather than labelling students' responses as simply correct or incorrect, the teacher encouraged them to justify their ideas, compare alternative views, and reconstruct their IVR observations through scientific explanations.

Data Analysis

Quantitative Data Analysis

Reverse-scored items on the attitude and motivation scales were recoded before total and subscale scores were calculated. Normality was assessed separately for each quantitative outcome using posttest–pretest difference scores because, for paired-samples *t* tests, the normality assumption concerns the distribution of the paired differences rather than the pretest and posttest distributions separately (Xu et al., 2017). The assessment was based on the Shapiro–Wilk test, histograms, normal Q–Q plots, and skewness and kurtosis (Kim, 2013). Potential outliers for integrated regulation and intrinsic motivation were systematically examined using boxplots of the posttest–pretest difference scores. Observations below the first quartile minus 1.5 times the interquartile range (IQR) or above the third quartile plus 1.5 times the IQR were flagged as potential outliers (Hoaglin et al., 1986). To assess their influence, the paired-samples *t* tests were repeated with and without the flagged observations as sensitivity analyses (Thabane et al., 2013). The direction and statistical significance of the results remained unchanged in both analyses; therefore, all observations were retained in the main analyses. Attitude, total motivation, and external regulation were analysed using sign tests. In these analyses, extreme difference magnitudes do not exert the same influence because the sign test is based on the direction rather than the magnitude of paired differences (Nahm, 2016). Because difference scores for integrated regulation and intrinsic motivation were approximately normally distributed, pre–post comparisons were conducted using paired-samples *t* tests. An a priori power analysis was not conducted. However, a sensitivity analysis was performed using G*Power 3.1.9.7 to evaluate the statistical sensitivity of the available sample for the paired-samples *t* tests. With $N = 73$, a two-sided $\alpha = .05$, and power of .80, the minimum detectable effect size was $d_z = .33$. This sensitivity analysis applies only to the integrated regulation and intrinsic motivation outcomes analysed using paired-samples *t* tests. Attitude, total motivation, and external regulation difference scores showed marked asymmetry and were therefore analysed using two-sided paired-samples sign tests. The Wilcoxon signed-rank test was not used because it assumes symmetry of difference scores (Thas et al., 2005). Total motivation and the three theoretically defined subscales were analysed as complementary indicators of the motivation construct, without treating them as hierarchically ordered primary and supplementary outcomes. Holm correction was applied to subscale comparisons within the same hypothesis family (Holm, 1979). Statistical significance was set at two-sided $p < .05$. Cohen's d_z was reported for *t* tests (Lakens, 2013). For variables analysed using the sign test, numbers of positive, negative, and unchanged differences and the proportion of students with higher posttest scores among nonzero differences were reported. Because no comparison group was included, the results were interpreted as observed pre–post differences within the same students rather than evidence of a causal effect of IVR-supported science teaching.

Metaphor Data Analysis

Metaphor data were analysed using inductive content analysis without a predetermined category system (Elo & Kyngäs, 2008). The unit of analysis was the complete “IVR is like ... because ...” response, including both the metaphor and its rationale. Blank responses, responses merely repeating IVR/VR, responses without a rationale, and those lacking an interpretable relationship between the metaphor and rationale in the IVR context were excluded (Anđić et al., 2024; Saban et al., 2007). Based on these criteria, 64 pre-activity and 66 post-activity responses were considered valid. Valid responses were organised so that each student's pre-activity and post-activity responses could be viewed side by side, although each was coded independently as a metaphor–rationale unit. Short, data-near codes were generated to capture the dominant meaning in each rationale. The same metaphor could be assigned to different categories when supported by different rationales, whereas different metaphors could be grouped together when they reflected a common meaning. Codes with similar meanings were then grouped into broader categories. The category system was developed inductively from the combined pretest and posttest data and applied consistently across both measurement points. The coders were aware of the measurement time to which each response belonged. Categories were iteratively reviewed, overlapping categories were merged, and

labels were refined to better represent their constituent codes. Secondary meanings in multidimensional responses were retained in coding notes, but each response was assigned to one category based on its dominant rationale (Andić et al., 2024; Saban et al., 2007). Category frequencies and percentages were calculated using the number of valid responses at each administration. Responses from the 60 students who produced valid metaphors at both measurement points were paired, and patterns of remaining within or moving between categories were described at the individual level. No inferential test of category differences was conducted. After inductive coding and category development, CAMIL was used only as a secondary interpretive framework during integration. Categories without a clear connection to CAMIL were retained as independent findings, and the categories were not treated as direct measures of CAMIL components.

Free Word Association Data Analysis

Free word association data were analysed using descriptive frequencies and inductive content analysis. Because students could provide multiple responses to the IVR stimulus, each word or meaningful short phrase constituted a unit of analysis. Frequencies represented the total number of occurrences. Capitalisation, spelling errors, singular/plural forms, and grammatical variants clearly referring to the same concept were standardised. The pre-activity administration yielded 255 associations representing 92 distinct expressions, whereas the post-activity administration yielded 387 associations representing 130 distinct expressions. For each standardised expression, frequency and percentage of all associations at the corresponding administration were calculated. Because the total number of associations differed across measurement points, comparisons considered relative proportions as well as raw frequencies (Hovardas & Korfiatis, 2006). Expressions were coded inductively, grouped into themes reflecting similar associative meanings, and assigned to a single theme. Theme frequencies were calculated by summing the frequencies of their constituent expressions, and percentages were based on the total number of associations at each administration. Percentage-point change was calculated as the posttest percentage minus the pretest percentage. Because the data were aggregated and individual students could contribute multiple associations, associations were not treated as independent observations; therefore, no inferential test was conducted. Results were described using frequencies, percentages, and percentage-point changes. Observed differences were not interpreted as conceptual change caused by IVR-supported science teaching or as indicators of students' complete conceptual knowledge or learning level. After inductive coding and theme development, CAMIL was used only as a secondary interpretive framework. Themes without a clear connection to CAMIL were retained as independent findings, and the themes were not treated as direct measures of CAMIL components.

Integration of Quantitative and Qualitative Findings

Consistent with the convergent mixed methods design, quantitative and qualitative findings were analysed separately and integrated during interpretation and reporting (Fetters et al., 2013). Integration was conducted through a joint display presenting quantitative results alongside related metaphor categories, category transitions, word association themes, and integrated interpretations (Guetterman et al., 2015). Relationships across data sources were examined for patterns of convergence, expansion, and divergence (Fetters et al., 2013). In this study, convergence was identified when different data sources showed conceptually compatible patterns regarding students' IVR experiences; expansion when one data source added dimensions not captured by another; and divergence when the data sources showed incompatible patterns. Partial convergence referred not to direct confirmation of the same construct by quantitative and qualitative findings, but to complementary or compatible patterns concerning related aspects of students' experiences. Comparisons were based on conceptual relationships rather than lexical similarity. Qualitative categories were not assumed to directly measure the constructs assessed by the quantitative scales. CAMIL (Makransky & Petersen, 2021) was used only as a secondary interpretive framework after the inductive analyses were completed.

Reliability of Qualitative Coding

To examine coding consistency, a coding guide containing category and theme definitions, inclusion and exclusion criteria, boundary cases, and example responses was provided to a second coder. The second coder independently coded all metaphor responses, including decisions regarding response validity, and all distinct expressions in the free word association data (92 at pretest and 130 at posttest). Inter-coder Cohen's kappa was

$\kappa = .68$ for metaphors (146 responses) and $\kappa = .846$ for word association expressions (222 expressions). According to Landis and Koch (1977), agreement for the metaphor data was substantial, while agreement for the word association data was almost perfect. Kappa values were based on independent coding, and disagreements were resolved through discussion using the raw data and coding guide. The coding guide, category revisions, and consensus decisions were retained as an audit trail, with representative student responses supporting the findings (Elo et al., 2014; O'Connor & Joffe, 2020).

Statement on the Use of AI-Assisted Tools

ChatGPT (OpenAI) and Grammarly were used in earlier stages of manuscript preparation to support the review of linguistic expression and consistency. Suggestions generated by these tools were critically reviewed by the author, and the final manuscript was additionally reviewed by a human for language, clarity of expression, and academic readability.

Research Results

Gifted Students' Attitudes towards VR Before and After IVR-Supported Science Teaching

Results of the two-sided sign test for attitude scores are presented in Table 2.

Table 2

Sign Test Results for Attitude Scores at Pretest and Posttest

Outcome	Pretest Median [Q1–Q3]	Posttest Median [Q1–Q3]	Positive differences, <i>n</i>	Negative differences, <i>n</i>	Ties, <i>n</i>	Post > Pre, % ^a	Exact <i>p</i>
Attitude	75.00 [69.00–82.00]	84.00 [75.50–90.00]	53	8	12	86.9	< .001

Note. *N* = 73. ^aPercentage was calculated from nonzero differences.

As shown in Table 2, attitude scores were higher at posttest in 86.9% of nonzero differences (exact $p < .001$). Eight students had lower scores, while 12 showed no change.

Gifted Students' Motivation towards VR Before and After the IVR-Supported Science Teaching

Results of the two-sided sign test for total motivation scores are presented in Table 3.

Table 3

Sign Test Results for Total Motivation Scores at Pretest and Posttest

Outcome	Pretest Median [Q1–Q3]	Posttest Median [Q1–Q3]	Positive differences, <i>n</i>	Negative differences, <i>n</i>	Ties, <i>n</i>	Post > Pre, % ^a	Exact <i>p</i>
Total motivation	57.00 [52.00–61.00]	61.00 [56.00–66.50]	52	13	8	80.0	< .001

Note. *N* = 73. ^aPercentage was calculated from nonzero differences.

As shown in Table 3, total motivation scores were higher at posttest in 80.0% of nonzero differences (exact $p < .001$). Thirteen students had lower scores, while eight showed no change. Pre–post differences in the three theoretically defined motivation subscales were also examined, with Holm-adjusted comparisons presented in Table 4.

Table 4
Pretest–Posttest Comparisons of Motivation Subscale Scores

Subscale	Pretest	Posttest	Test result	Unadjusted <i>p</i>	Holm-adjusted <i>p</i>	Effect size / descriptive indicator
Integrated regulation	23.49 (4.04)	25.08 (4.38)	$t(72) = 3.79$; mean difference = 1.59, 95% CI [0.75, 2.42]	< .001	< .001	$d_z = 0.44$
External regulation (reverse-scored)	19.00 [17.50–20.00]	20.00 [19.00–20.00]	28 positive, 10 negative, 35 tied differences	.005	.005	Post > Pre = 73.7%
Intrinsic motivation	15.40 (2.62)	16.78 (2.59)	$t(72) = 4.69$; mean difference = 1.38, 95% CI [0.80, 1.97]	< .001	< .001	$d_z = 0.55$

Note. $N = 73$. Integrated regulation and intrinsic motivation are reported as $M (SD)$, and external regulation as $Mdn [Q1–Q3]$. Both unadjusted and Holm-adjusted p values are reported. ^{||}Calculated from nonzero differences.

At posttest, integrated regulation ($d_z = 0.44$), intrinsic motivation ($d_z = 0.55$), and reverse-scored external regulation scores were higher, with all differences remaining significant after Holm adjustment. For external regulation, 10 students had lower scores and 35 showed no change.

Gifted Students' Metaphorical Meanings of IVR Before and After IVR-Supported Science Teaching

Sixty-four responses before teaching and 66 after teaching were considered valid. Inductive analysis grouped the valid metaphors into eight conceptual categories. Their distributions are presented in Table 5.

Table 5
Distribution of Metaphor Categories Before and After IVR-Supported Science Teaching

Metaphor category	Before teaching, n (%)	After teaching, n (%)	Change, percentage points
Real and virtual world experience	20 (31.2)	20 (30.3)	–0.9
Transition to other worlds and environments	13 (20.3)	8 (12.1)	–8.2
Imagination, creativity, and limitless possibilities	8 (12.5)	10 (15.2)	+2.7
Technology and digital tools	8 (12.5)	2 (3.0)	–9.5
Entertainment and games	9 (14.1)	5 (7.6)	–6.5
Learning with enjoyment	3 (4.7)	8 (12.1)	+7.4
Learning, educational value, and access to information	2 (3.1)	10 (15.2)	+12.1
Embodied and temporal experience	1 (1.6)	3 (4.5)	+2.9
Total	64 (100.0)	66 (100.0)	—

“Real and virtual world experience” was the most frequent category at both measurement points and largely retained its relative weight. Students conceptualised IVR as an experience resembling the real world, appearing realistic, or blurring the boundary between real and virtual. For example, S9’s initial metaphor, “*It is like an abstract world because it allows us to see things that do not exist in reality for a while,*” became “*It is like the world because it gives us the opportunity to experience anything, whether real or not.*” The largest proportional difference following IVR-supported science teaching occurred in “Learning, educational value, and access to information,” where students associated IVR with learning resources such as teachers, books, libraries, and microscopes. “Learning with enjoyment” also became more prominent. For example, S69’s initial response, “*It is like a game because it is fun,*” became “*It is like entertainment and games because I have fun while learning.*” In contrast, meanings centred on general technology, games alone, and transition to other environments had lower relative representation, whereas learning, educational value, and learning with enjoyment had higher representation following IVR-supported science teaching.

Among the 60 students who produced valid metaphors at both measurement points, 39 (65.0%) remained in the same category and 21 (35.0%) shifted to another. Remaining in the same category did not imply that all features of a metaphor were unchanged, but that its dominant meaning remained within the same category. Of the 18 students initially classified under “Real and virtual world experience,” 16 remained in this category. Shifts were most evident from “Technology and digital tools” and “Entertainment and games.” Four of the seven students in the technology category shifted to “Learning, educational value, and access to information.” For example, S65’s initial response, “*It is like a computer because it has a screen and you can play games*,” became “*It is like a teacher because it teaches*.” Some responses initially categorised as “Entertainment and games” also retained the entertainment dimension while expanding to include learning. A small number of metaphors reflected embodied experiences. S29’s statement, “*It is like a roller coaster because it is fun but dizzying*,” combined positive affective and negative bodily aspects. Overall, the reality–virtuality dimension remained central, while meanings related to learning, educational value, access to information, and learning with enjoyment became more prominent following IVR-supported science teaching. These findings were interpreted as descriptive patterns in the same students’ metaphorical meanings before and after IVR-supported science teaching, rather than as evidence of a causal effect of the teaching.

Gifted Students’ Associative Patterns Related to IVR Before and After IVR-Supported Science Teaching

Standardised responses from the free word association task were inductively grouped into ten themes. Students generated 255 associations before teaching and 387 after teaching. Frequencies, percentages, and percentage-point changes are presented in Table 6.

Table 6

Distribution of Free Word Associations by Theme Before and After IVR-Supported Science Teaching

Theme	Before teaching, f (%)	After teaching, f (%)	Change, percentage points
Technology and digital tools	100 (39.2)	89 (23.0)	–16.2
Entertainment and games	49 (19.2)	77 (19.9)	+0.7
Learning, education, and knowledge	26 (10.2)	57 (14.7)	+4.5
Science and experimentation	9 (3.5)	41 (10.6)	+7.1
Virtuality, reality, and different worlds	29 (11.4)	42 (10.9)	–0.5
Imagination, creativity, and expanding possibilities	13 (5.1)	18 (4.7)	–0.4
Affective and embodied experience	11 (4.3)	28 (7.2)	+2.9
Social interaction and collaboration	4 (1.6)	6 (1.5)	–0.1
Exploration and access to different places	8 (3.1)	15 (3.9)	+0.8
Use characteristics, benefits, and limitations	6 (2.4)	14 (3.6)	+1.2
Total	255 (100.0)	387 (100.0)	—

Note. *f* indicates association frequency. Percentages were calculated from the total number of associations at each administration. Because individual students could generate multiple associations, observations were not treated as independent and no inferential test was conducted.

As shown in Table 6, the largest increase was observed for “Science and experimentation.” The relative shares of “Learning, education, and knowledge,” “Affective and embodied experience,” and “Use characteristics, benefits, and limitations” also increased. Associations such as “*experiment*,” “*bacteria*,” “*learning*,” “*dizzying*,” and “*expensive*” illustrated these patterns following IVR-supported science teaching. The largest decrease occurred for “Technology and digital tools.” Because “*technology*” and “*VR headset*” remained frequent associations following IVR-supported science teaching, this pattern indicates a decline in their relative share of all associations rather than their disappearance. The relative shares of the other themes remained largely stable. Although the raw frequency of “Entertainment and games” increased, its relative share was nearly unchanged, reflecting the different total numbers of associations across the two administrations. The findings were interpreted as descriptive differences in the associative distributions of the same student group before and after IVR-supported science teaching, rather than as evidence of conceptual learning or a causal effect of the teaching.

Integration of Quantitative and Qualitative Findings

Quantitative findings and results from the metaphor and free word association tasks were integrated in a joint display to identify patterns of partial convergence and expansion. The data sources were treated as complementary rather than equivalent. CAMIL was used only as a secondary interpretive framework; because presence, agency, and embodiment were not directly measured, related links remained conceptual. Patterns outside CAMIL, including entertainment, creativity, social interaction, and use-related features and limitations, were also retained.

Table 7 shows partial convergence and expansion across the findings. Higher posttest scores for attitude, total motivation, intrinsic motivation, and integrated regulation were accompanied by more prominent learning- and education-related qualitative meanings. However, these patterns cannot explain the total-score differences because individual scale items were not analysed separately. Qualitative findings also revealed dimensions not captured by the scales, including reality–virtuality, exploration, embodied experience, creativity, social interaction, and use-related limitations. Higher reverse-scored external regulation scores indicated lower endorsement of externally regulated reasons, while no prominent qualitative pattern of reward, pressure, or obligation emerged, suggesting partial convergence. Given the absence of a comparison group, these integrated patterns were not interpreted causally.

Table 7
Integration of Quantitative and Qualitative Findings

Integration focus	Quantitative pattern	Related qualitative patterns	Integrative meta-inference
Positive attitudes and motivation accompanied by learning-related meanings	Attitude, total motivation, intrinsic motivation, and integrated regulation scores were higher at posttest. The scales include learning-related items, but individual items were not analysed separately.	M: Learning, educational value, access to information, and learning with enjoyment became more prominent. WA: The relative shares of learning, education, knowledge, science, and experimentation increased.	Partial convergence and expansion: Qualitative findings extended the learning-related evaluations represented in the scales by providing more specific meanings. However, the total-score differences cannot be attributed to particular items. Links to CAMIL are indirect and primarily concern motivation.
Reality and exploration	Presence and agency were not directly measured.	M: Reality–virtuality remained central. WA: Associations with reality, different worlds, exploration, and access to different places persisted.	Expansion: Qualitative findings revealed experiences of realism, being elsewhere, and exploration that were not captured by the scales. Their links to CAMIL constructs such as presence and agency are conceptual rather than directly measured.
Embodied experience and individual differences	Although group-level scores were higher at posttest, some students had lower or unchanged scores. Embodiment was not directly measured.	M: Bodily experiences such as dizziness and difficulty with movement appeared. WA: Affective–embodied experiences and use-related benefits and limitations became more prominent.	Expansion: Qualitative data revealed positive, negative, and ambivalent experiences, extending the group-level quantitative pattern by showing individual variation. Links to embodiment are indirect, while use and access limitations fall outside CAMIL.
Differentiation of technology- and entertainment-related meanings	The scales include items concerning enjoyment, interest, fun, and willingness to use VR, but individual items were not analysed separately.	M: Meanings focused solely on technology and games became less prominent, whereas learning with enjoyment became more visible. WA: The relative share of technology associations decreased, while entertainment and games remained largely stable.	Partial convergence and expansion: Qualitative findings elaborated the meanings underlying enjoyment and interest. However, they do not show that specific enjoyment items increased or explain the quantitative score differences.
External regulation and patterns beyond the scales/CAMIL	Reverse-scored external regulation scores were higher at posttest, indicating lower endorsement of externally regulated reasons. Other qualitative dimensions were not measured quantitatively.	No prominent qualitative pattern of external reward, pressure, or obligation emerged. Imagination and creativity, social interaction, time, cost, ease of use, and limitations were also identified.	Partial convergence and expansion: The absence of a prominent qualitative pattern of external reward, pressure, or obligation is broadly consistent with the lower endorsement of externally regulated reasons indicated by the reverse-scored quantitative results. Qualitative findings also extended the results by revealing creative, social, and practical dimensions not directly captured by the scales or CAMIL.

Note. M = metaphor; WA = word association. Links to CAMIL represent secondary theoretical interpretations made after the inductive analyses rather than direct measurement of CAMIL constructs.

Discussion

This study examined gifted fifth-grade students' attitudes and motivation towards VR, together with their metaphorical meanings and associative patterns related to IVR, before and after six lesson hours of IVR-supported science teaching. Attitude, total motivation, intrinsic motivation, integrated regulation, and reverse-scored external regulation scores were higher at posttest, with the latter indicating lower endorsement of externally regulated reasons. However, individual patterns were not uniform. Qualitatively, meanings related to learning, educational value, access to information, science, and experimentation became more prominent, whereas the relative weight of technology-focused meanings declined. The reality–virtuality dimension remained central. These patterns were interpreted as descriptive differences between the two measurement points rather than as evidence of academic learning or causal effects of IVR-supported science teaching. Gifted students' characteristics, such as curiosity, exploration, engagement with complex cognitive tasks, and intrinsic motivation (Kuznetsova et al., 2024; Mohseni & Abedi, 2025; Renzulli, 2021), may influence how they engage with and interpret IVR's affordances for interaction, exploration, and multiple representations. Therefore, the greater prominence of meanings related to learning, science, experimentation, and exploration should not be considered solely in relation to IVR's affordances. These patterns should also be considered alongside the depth, complexity, active interaction, and exploration-oriented learning opportunities recommended for gifted students (Kutlu Abu & Dal, 2025; Sternberg et al., 2022; World Council for Gifted and Talented Children, 2021).

Evaluation of Attitude and Motivation Findings

The higher posttest scores for attitudes and total motivation towards VR are generally consistent with previous research. Studies across educational levels have reported positive patterns in attitudes, interest, and motivation following VR use (Avcu & Yaman, 2025; Irwanto et al., 2026; Li et al., 2025; Liu et al., 2022; Makransky & Lilleholt, 2018). The present study extends this general pattern by focusing specifically on attitudes and motivation towards VR itself. In their review of VR and learning motivation, Jiang and Fryer (2024) found that most of the 14 included studies reported higher motivation following VR applications. However, they also noted that the scarcity of long-term designs prevented novelty effects from being ruled out. This caution is equally relevant here. The teaching lasted only six lesson hours, and students' prior IVR experience, the possible contribution of novelty, and the persistence of the observed differences were not examined. Accordingly, the higher posttest scores should not be interpreted as evidence of a lasting or causal effect of IVR on motivation. Similar cautions have been raised in other systematic reviews (Acevedo et al., 2024; Di Natale et al., 2020). The single-centre sample of 73 students should also be considered when interpreting the findings.

Makransky, Borre-Gude, et al. (2019) reported higher intrinsic motivation in IVR than in text-based teaching, while Huang et al. (2021) found that motivation did not decline as students became accustomed to the system across multiple sessions. In contrast, Parong and Mayer (2018) reported higher motivation and engagement in the IVR group but higher learning performance in the slideshow group. This divergence reinforces that positive affective evaluations are not equivalent to academic learning. Although the present study incorporated theoretical preparation and post-IVR discussion, its attitude and motivation findings should not be interpreted as evidence of improved academic learning.

For the motivation subscales, higher posttest scores were observed for intrinsic motivation and integrated regulation. These quantitative patterns showed partial convergence with the greater prominence of qualitative meanings related to learning, educational value, access to information, learning with enjoyment, science, and experimentation. However, the metaphor and word association categories did not directly measure the psychometric motivation subscales, and individual scale items were not analysed separately. Their co-occurrence therefore cannot be interpreted as explaining the quantitative differences or indicating a causal relationship. Li et al. (2025) similarly reported higher intrinsic motivation in an IVR condition than in tablet-based VR and a traditional classroom, broadly aligning with the present pattern. External regulation requires a different interpretation because its items were reverse-scored. The higher posttest score therefore indicates lower endorsement of externally regulated reasons rather than greater external regulation. The absence of a prominent qualitative pattern involving external rewards, pressure, or obligation is broadly consistent with this quantitative pattern, although the qualitative categories do not directly measure external regulation. Thus, this finding is better characterised as partial convergence than as divergence or limited correspondence. Distinguishing the attitude and motivation findings from academic learning is particularly important. Academic achievement, conceptual learning, transfer, and retention were not measured

in this study. Therefore, higher attitude and motivation scores, or students' stronger associations between IVR and learning, should not be treated as evidence of academic learning.

Integration of Metaphorical and Associative Patterns

The reality–virtuality dimension remained central in the metaphor data at both measurement points. However, learning and educational meanings became more prominent following IVR-supported science teaching, whereas meanings focused solely on technology or games became relatively less common. The fact that 65% of students with valid metaphors at both points remained in the same broad category indicates substantial category stability, while some category shifts reflected the incorporation of educational dimensions into students' existing meanings. This pattern is methodologically consistent with Andić et al. (2024), who reported that technology metaphors may vary with experience. Given contextual differences, however, the findings should not be interpreted as lasting conceptual transformation, but as greater prominence of educational functions in some students' metaphors following IVR-supported science teaching. The free word association findings supported and extended the metaphor results. Following IVR-supported science teaching, the relative shares of associations related to science, experimentation, learning, education, and knowledge increased, whereas those related to technology and digital tools decreased; entertainment and games remained largely stable. The continued use of terms such as “technology” and “VR headset” indicates that technological associations did not disappear but became less prominent relative to other associations. Together with the greater visibility of learning with enjoyment in the metaphor data, this pattern suggests that some students associated enjoyment with learning. However, generating more associations is not evidence of greater learning, more developed cognitive structures, or better science understanding. The findings are limited to descriptive group-level associative distributions.

When considered in relation to CAMIL, meanings related to realism, being in another environment, exploration, movement, and embodied experiences in the metaphor and free word association findings can be conceptually related to constructs such as presence, agency, and embodiment. However, because these constructs were not directly measured, the qualitative findings should not be interpreted as evidence of CAMIL components. Rather, these patterns suggest that CAMIL provides a useful secondary framework for interpreting some dimensions of how students experienced and made sense of IVR. At the same time, several qualitative patterns, including creativity, social interaction, cost, ease of use, and other use-related limitations, are not directly represented within CAMIL. This indicates that CAMIL helps to interpret only certain dimensions of the present findings and does not fully capture the range of students' IVR experiences. CAMIL was therefore used not as a comprehensive explanatory model, but as a secondary and partial theoretical framework for interpreting the inductively derived findings. The findings should also not be attributed solely to IVR technology. The teaching included orientation, theoretical preparation, teacher-guided observation and exploration, post-IVR discussion and conceptualisation, and three different science topics. Thus, the observed differences should not be interpreted as consequences of the head-mounted display or level of immersion alone. Meyer et al. (2019) reported higher knowledge, transfer, and self-efficacy following pre-training before IVR. Delgado and Mayer (2025) similarly reported higher knowledge scores, fewer laboratory errors, and lower cognitive load with pre-training. Boel et al. (2025) reported higher knowledge acquisition and intrinsic motivation when teacher guidance and discussion preceded IVR. These studies underscore the importance of considering pedagogical components alongside the IVR experience. Because these components were not tested separately in the present study, differences in attitudes, motivation, metaphors, or associations cannot be attributed to any specific component. CAMIL likewise supports interpreting the findings within the broader IVR-supported science teaching process by considering technological features together with instructional design (Makransky & Petersen, 2021).

Despite higher group-level scores, some students showed lower or unchanged scores, and the qualitative data included references to dizziness, movement difficulties, cost, and use-related limitations, indicating that IVR experiences were not uniform. Jiang et al. (2025), reviewing K–12 STEM studies, also reported distraction, usability problems, and discomfort in VR/AR applications. Although these findings cannot be directly generalised to gifted students, they suggest that IVR experiences may vary across learners. The few references to dizziness and movement difficulties should not be interpreted as simulator sickness. Hsin et al. (2023) emphasised the need for systematic measurement of such symptoms. Because no validated measure was used in the present study, no conclusions can be drawn about their frequency, severity, or causes. Future IVR studies with children should assess physical discomfort directly.

The contribution of this study lies in examining students' experiences following IVR-supported science teaching not only through scale scores but also through metaphorical meanings and spontaneously generated associations. Integration revealed partial convergence between quantitative findings and learning- and science-related qualitative meanings, while the qualitative data expanded the findings by revealing embodied, creative, social, and practical dimensions. For reverse-scored external regulation, the higher posttest scores indicated lower endorsement of externally regulated reasons; the absence of a prominent qualitative pattern involving reward, pressure, or obligation therefore suggests partial convergence rather than divergence. Overall, the quantitative and qualitative findings functioned as complementary sources for capturing different layers of gifted students' IVR experiences.

Conclusions and Implications

In this sample, following six lesson hours of IVR-supported science teaching, higher posttest scores were observed for attitudes towards VR and total motivation, intrinsic motivation, integrated regulation, and reverse-scored external regulation. The qualitative findings further indicated that, while the reality–virtuality dimension remained prominent, meanings related to learning and educational functions became more salient, whereas technology-focused associations became relatively less pronounced. Taken together, the quantitative and qualitative findings revealed patterns of partial convergence and expansion across the different data sources. These patterns should not be interpreted as evidence of causal effects or academic learning, but rather as co-occurring differences observed within the same group over the course of the study. The main contribution of this study lies in integrating psychometric, metaphorical, and associative data to provide a multidimensional account of gifted students' IVR-related experiences. By examining affective scores, metaphorical meanings, and spontaneous associations together without treating them as measures of the same construct, the study offers a cautious mixed-methods approach for investigating how gifted students experience and make sense of IVR in science education. Its significance lies in extending IVR research beyond scale-based outcomes by incorporating students' own meaning-making, while also distinguishing these experiential patterns from evidence of causal effects or academic learning.

Limitations and Future Research

The first and most important limitation of this study is the absence of a comparison group. Therefore, the differences observed between the pre- and post-test should not be interpreted as causal effects of IVR-supported teaching. The IVR experience, science content, teacher guidance, group interactions, post-activity discussions, repeated administration of the data collection instruments, and the novelty of the technology were all embedded within the same teaching process. Information on students' prior VR/IVR experience was not collected. Therefore, the possible contribution of novelty to the observed patterns could not be assessed. Future research could examine IVR-supported teaching against active comparison conditions using the same content and pedagogical activities. The study group consisted of 73 gifted fifth-grade students attending a single BİLSEM in Türkiye who voluntarily participated in the study. The participants were selected through convenience sampling; therefore, the sample cannot be considered representative of the broader population of gifted students. Accordingly, the findings should not be generalised to other groups of gifted students, educational institutions, or national contexts. The relatively modest sample size may also have limited the statistical sensitivity of the study, particularly for detecting smaller effects. Because the organisation of gifted education, programme structures, and cultural and educational contexts may vary across countries, this study cannot determine whether similar patterns would emerge in different educational systems. Future multi-site studies involving different institutions, regions, and countries could examine the extent to which these findings are observed across diverse contexts. The post-test measures were administered immediately after the teaching process. It is therefore unknown whether the patterns observed in attitudes, motivation, metaphors, and associations persist over time. Delayed and repeated measurements could examine whether these patterns are associated with short-term experience and novelty or with more enduring evaluations. Academic achievement, conceptual learning, transfer, retention, presence, agency, embodiment, cognitive load, and simulator sickness were not directly measured in this study. Accordingly, the qualitative patterns should not be interpreted as direct measurement results for these constructs. Future research could complement measures of attitudes and motivation with topic-specific learning tests, delayed measurements, and validated measures of presence, cognitive load, and simulator sickness. Finally, the metaphor and free word-association data may have been influenced by students' linguistic expression, interpretation of the task, and repeated administration. Because the number of associations differed across administrations and students generated more than one association, the

associations were not treated as independent observations and were interpreted descriptively. Future research could track individual transitions through interviews and concept maps.

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Declaration of Interest

The authors have no conflicts of interest to declare.

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