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ARTICLE

Multidimensional Interest and Achievement Outcomes Following Immersive Virtual Reality Integration in Undergraduate Chemistry: A Quasi-Experimental Study in a Caribbean Context

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The use of Immersive Virtual Reality (IVR) as a pedagogical tool for chemistry has gained momentum over the past decade. However, less is known about the specific dimensions of student interest that may or may not shift following IVR integration under authentic instructional constraints. This quasi-experimental pre-test post-test study examined the effects of smartphone-based IVR implementation on undergraduate chemistry interest and academic performance in a Caribbean university context. Two equivalent groups (Test, $n = 58$; Control, $n = 58$) completed the Chemistry Study Interest Questionnaire (C-SIQ) before and after the intervention, and a 60-item achievement test across six introductory topics. The Test group demonstrated significant gains in overall interest ($p = 1.52 \times 10^{-2}$) and in the dimension of intrinsic orientation ($p = 4.47 \times 10^{-4}$), while feelings-related and value-related valences did not change significantly ($p > 0.05$). Achievement outcomes favoured the Test group overall ($p = 1.27 \times 10^{-21}$). These findings are consistent with theoretical perspectives suggesting that IVR affordances may align more strongly with intrinsic motivational processes than affective or value-based components. The study contributes evidence from a resource-constrained Small Island Developing State (SIDS) context and highlights the importance of theoretical alignment and topic sensitivity in evaluating IVR integration in chemistry education.

Introduction

In chemistry, meaningful learning depends on students' ability to coordinate multiple levels of representation, including the macroscopic, sub microscopic, and symbolic (Gilbert, 2008; Kozma and Russell, 1997). Many foundational topics in undergraduate chemistry, such as molecular orbital theory, atomic structure, electrostatics, and intermolecular interactions, require learners to visualise entities and processes that are not directly observable (Johnstone, 1991; Gilbert and Treagust, 2009; Wu et al., 2001). The cognitive demands associated with constructing and translating among these representations are well documented, and difficulties in developing accurate mental models often lead to fragmented understanding and reliance on procedural knowledge rather than conceptual reasoning (Taber, 2001). As a result, there has been sustained interest in pedagogical approaches that can support students' visualisation, interpretation, and integration of abstract chemical concepts (Wu and Shah, 2004; Treagust et al., 2003).

Immersive virtual reality (IVR) has emerged as a promising instructional tool in this regard (Makransky and Lilleholt, 2018;

Jensen and Konradsen, 2018; Radianti et al., 2020). By situating learners within interactive three-dimensional environments, IVR allows users to inspect, manipulate, and navigate representations of chemical structures and processes in ways that are not possible with traditional two-dimensional media. Research in STEM education suggests that immersive environments can support learning when appropriately integrated into instruction (Merchant et al., 2014; Radianti et al., 2020; Makransky and Petersen, 2021). These affordances are particularly relevant for chemistry, where spatial reasoning and the ability to conceptualise structure, property relationships are central to disciplinary understanding (Wu and Shah, 2004; Kozma and Russell, 2005; Stieff, 2013). However, despite increasing interest in IVR, questions remain regarding the extent to which it contributes to meaningful learning beyond novelty effects, and whether its impact is consistent across different learning outcomes (Makransky et al., 2019; Shin, 2024; Thiele, M. et al., 2025).

From a constructivist perspective, learning is understood as an active process in which students construct knowledge through interaction with materials, tasks, and peers (Piaget, 1970; Vygotsky, 1978; Bodner, 1986). Within this framework, the value of IVR lies not simply in its technological novelty, but in its capacity to provide interactive environments in which learners can explore representations, test ideas, and refine their understanding (Dalgarno and Lee, 2010; Merchant et al., 2014; Makransky and Petersen, 2021). The ability to manipulate three-dimensional structures and observe immediate feedback

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may support learners in restructuring prior conceptions and developing more coherent scientific understanding (Dede et al., 2017; Matovu et al., 2023). In addition, immersive environments can support embodied forms of learning, where physical interaction and spatial engagement contribute to cognitive processing (Johnson-Glenberg, 2018). Such affordances are particularly relevant in chemistry, where understanding depends on appreciating orientation, proximity, and dynamic relationships among molecular entities (Wu and Shah, 2004; Kozma and Russell, 2005; Stieff and Uttal, 2015).

Empirical work in chemistry education supports these theoretical claims. Collaborative IVR experiences have been shown to improve students' conceptual understanding of hydrogen bonding and molecular structures by enabling interaction with representations and peer discussion (Matovu et al., 2023). Similarly, IVR-based learning has been found to support students' understanding of complex biochemical processes, such as enzyme–substrate interactions, by facilitating the integration of structural, electronic, and spatial concepts (Matovu et al., 2025). At the same time, these studies highlight that the benefits of IVR are not automatic and depend critically on instructional design, task structure, and the nature of assessment.

Despite these advances, the literature remains limited in two important respects. First, research examining students' interest in chemistry following IVR exposure has frequently treated interest as a unidimensional construct, limiting insight into how different components of interest respond to immersive learning environments. Second, relatively little work has examined IVR implementation under authentic instructional conditions in resource-constrained contexts, such as Small Island Developing States (SIDS), where technological access, cost, and curricular alignment present unique challenges. These gaps limit both the theoretical precision and the contextual relevance of existing findings.

The present study addresses these limitations by examining how IVR integration influences multidimensional chemistry interest and academic performance in an undergraduate Caribbean context. Rather than asking whether IVR “works” in general terms, this study investigates which dimensions of interest change, and whether those changes are associated with measurable differences in achievement across specific chemistry topics.

Theoretical Framework

This study is grounded in a multidimensional conceptualisation of interest as a distinct construct in educational psychology. Interest is not treated as synonymous with motivation. Instead, it is understood as a specific psychological state and disposition that reflects engagement, value, and affective orientation toward a domain (Schiefele, 1991; Hidi and Renninger, 2006; Krapp, 2002). Within chemistry education, this distinction is operationalised through the Chemistry Study Interest Questionnaire (C-SIQ), which

differentiates among intrinsic orientation, feelings-related valences, and value-related valences (Schiefele et al., 1992). This framework allows for a more precise analysis of how different aspects of students' engagement with chemistry may be differentially influenced by instructional interventions (Hidi and Renninger, 2006; Krapp and Prenzel, 2011; Lin et al., 2013; Renninger and Hidi, 2016; Akkerman et al., 2020).

Intrinsic orientation refers to internally driven engagement and curiosity toward chemistry content, whereas feelings-related valences capture affective responses, and value-related valences reflect perceived importance or relevance of the subject. Theoretical models of interest development suggest that these components do not necessarily change in parallel, and that instructional environments may selectively influence particular dimensions depending on their design and affordances (Hidi and Renninger, 2006; Krapp, 2002).

While interest is conceptually distinct from motivation, Self-Determination Theory (SDT) provides a useful complementary perspective for understanding how instructional environments may support changes in interest-related processes. SDT posits that learning environments that support autonomy and competence can foster more internally driven forms of engagement (Deci and Ryan, 2000). IVR environments, through their interactive and exploratory affordances, may provide opportunities for learners to engage with chemistry content in ways that support these psychological needs. For example, the ability to manipulate molecular structures, explore representations from multiple perspectives, and control the pace of interaction may support learners' sense of agency and conceptual understanding (Wu and Shah, 2004; Kozma and Russell, 2005; Merchant et al., 2014; Parong and Mayer, 2018; Makransky and Petersen, 2021).

The theoretical model guiding this study suggests that IVR may be more likely to influence intrinsic orientation than other components of interest, given its emphasis on interactive and exploratory engagement. Changes in feelings-related or value-related dimensions may require additional contextualisation, such as explicit connections to real-world applications or career pathways, which extend beyond immersive visualisation alone (Krapp, 2002; Hidi and Renninger, 2006; Eccles and Wigfield, 2002; Deci and Ryan, 2000; Renninger and Hidi, 2016; Makransky and Petersen, 2021). This perspective frames IVR not as a universally transformative tool, but as one whose effects may be selective and dependent on both instructional design and context.

Research Questions

Guided by this theoretical framework, the present study addresses the following research questions:

1. Does IVR integration produce changes in overall chemistry interest and its subcomponents?
2. Does IVR integration improve chemistry achievement relative to traditional instruction?
3. Are IVR effects topic-dependent across introductory chemistry content?



Research Objectives

To answer the research questions, the following objectives were defined:

1. To investigate the effect of 3D IVR technology aided immersion on chemistry interest in introductory undergraduate chemistry students with the use of the Chemistry Study Interest Questionnaire (C-SIQ).
2. To compare the effect of 3D IVR technology aided immersion on the subcomponents of interest as defined in the C-SIQ.
3. To investigate the effect of 3D IVR technology aided immersion on chemistry performance in undergraduate chemistry students with a customized chemistry performance quiz based on molecular orbital theory, the periodic table, atomic properties, isomerism, the gas laws and electrostatics.
4. To compare the effect of 3D IVR across topics quizzed for chemistry performance analysis.

Study Hypotheses

The researchers formulated hypotheses to be tested:

$$H_0: I_{TG1} = I_{TG2} (H_01) \quad H_0: I_{CG1} = I_{CG2} (H_02)$$

where I= Chemistry Interest, TG1=Test Group Pre-Test, TG2=Test Group Post-Test, CG1=Control Group Pre-Test, CG2=Control Group Post-Test

$$H_0: F_{TG1} = F_{TG2} (H_03) \quad H_0: F_{CG1} = F_{CG2} (H_04)$$

Where F=Feeling-related Valences

$$H_0: V_{TG1} = V_{TG2} (H_05) \quad H_0: V_{CG1} = V_{CG2} (H_06)$$

Where V=Value-related Valences

$$H_0: IO_{TG1} = IO_{TG2} (H_07) \quad H_0: IO_{CG1} = IO_{CG2} (H_08)$$

Where IO=Intrinsic Orientation

$$H_0: P_{TG} = P_{CG} (H_09)$$

where P= Chemistry Performance, TG=Test Group, CG=Control Group

Methodology

This section outlines the research design, participants, intervention, instruments, and analytical procedures employed in the study.

Participants and Design

A quasi-experimental design was employed involving undergraduate students enrolled in Introductory Chemistry I (CHEM 1066) at The University of the West Indies, St. Augustine. Participants were divided into two groups. One was a TG (n = 58), which received IVR-supported instruction as well as traditional instruction (scheduled lectures and tutorials). The second was a CG (n = 58), which received traditional instruction alone. Group assignment followed an odd/even allocation approach consistent with institutional scheduling constraints. This design reflects authentic classroom conditions while allowing for comparison between instructional approaches.

Baseline equivalence between groups was assessed prior to the intervention. Independent samples tests indicated no

statistically significant differences between the TG and CG on overall Chemistry Study Interest Questionnaire (C-SIQ) scores or any of its subscales ($p > 0.05$). Additionally, demographic characteristics and prior academic qualifications, including Caribbean Secondary Education Certificate (CSEC) and Caribbean Advanced Proficiency Examination (CAPE) results, were comparable across groups, supporting the validity of subsequent comparisons.

Intervention

The intervention was implemented over the course of the instructional period, over 9 weeks. During this time students were allowed flexible access to the IVR resources and could engage with the content at their own pace. Additionally, the TG received the traditional instruction scheduled for the semester. This approach was intended to reflect realistic implementation conditions within a resource-constrained educational setting. The CG received equivalent instructional content through standard scheduled lectures and tutorials without the use of IVR.

Hardware and Software

Students allocated to the TG were equipped with an immersive virtual reality headset system, consisting of a VR Head Mounted Display (HMD) paired with a smartphone (Fig. 1). Each TG participant in the study was given a set of instructions for using the hardware and accessing the software for the study (Fig. 2). These instructions were provided after the phones in the headsets were connected by Bluetooth. Once the set up was completed, the TG participants were then free to navigate the MEL VR Application.



Figure 1 HMD and smartphone used for this study

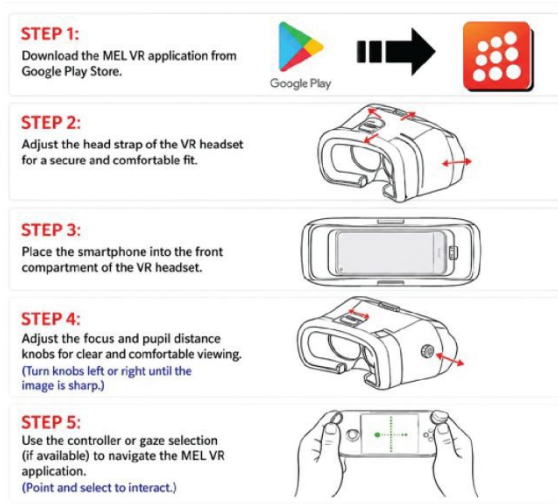


Figure 2 Instructions for use of the VR headset and MEL VR software to TG

The IVR Learning Experience

The IVR intervention utilised the MEL Chemistry VR platform delivered through smartphone-based head-mounted displays. Following an orientation session, students in the TG were given access to the IVR resources for nine weeks and were free to engage with the learning experiences outside scheduled class time. The intervention was primarily exploratory in nature rather than instructor guided. Students independently navigated the virtual environments and interacted with three-dimensional representations of chemistry concepts aligned with topics being covered in Introductory Chemistry 1 (CHEM 1066).

The chemistry lessons began in a virtual lab (Fig. 3) and once selected, the user was taken to the lesson selected. The lessons were between 3 minutes and 7 minutes long and the user was able to zoom in to the molecular level. For example, in the lesson on atomic properties, users were able to “shrink” up to a billion times to observe atoms and the crystal structure of Sulphur (See Fig. 4). The lessons on isomerism included structural isomerism, cis-trans isomerism and optical isomerism. There were also VR labs including those where users were able to build isomers and another where users had to determine if a molecule was an isomer or not (Fig. 5).



Figure 3 Screenshot of the start of the MEL VR Chemistry Lessons

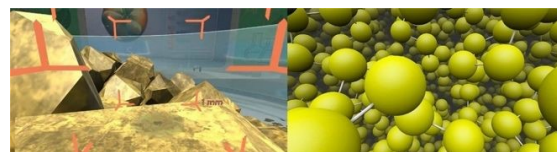


Figure 4 The start (left) and end (right) of zooming in on the crystal structure of Sulphur

These experiences allowed learners to observe chemical entities and processes from multiple perspectives and to interact with representations that are typically inaccessible in traditional classroom settings. The IVR activities were intended to complement rather than replace lectures and tutorials, with all students continuing to receive the standard curriculum.

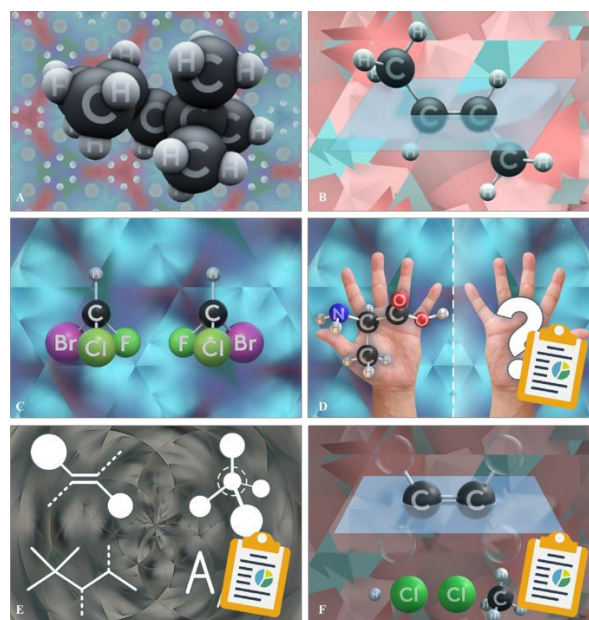


Figure 5 Screenshots of the lessons and labs on isomerism in the MEL VR application. A- Structural Isomers, B- Cis-trans Isomers, C- Optical Isomers, D- Isomers or Not (Lab), E- Optical Isomers (Lab), F- Build Isomers (Lab)

Student participation was facilitated through flexible access to the hardware and software. Although usage was not formally monitored through learning analytics, students were encouraged to engage with the resources throughout the intervention period at their own pace. This implementation approach was designed to reflect authentic educational conditions within a resource-constrained university setting.

Instruments

Student interest in chemistry was measured using the Chemistry Study Interest Questionnaire (C-SIQ), administered both before and after the intervention. The instrument assesses interest across three dimensions: intrinsic orientation, feelings-related valences, and value-related valences. Internal



consistency reliability for the present sample, as measured by Cronbach's alpha, ranged from acceptable to strong across subscales. Confirmatory factor analysis confirmed construct validity of the instrument within this context.

Academic performance was assessed using a 60-item multiple-choice test (Supplemental Information) developed by course instructors and aligned with the learning objectives of the course. The assessment covered six key topics: molecular orbital theory, periodic table, atomic properties, isomerism, gas laws, and electrostatics. As the knowledge assessment was designed as a curriculum-aligned measure of student performance rather than a standalone psychometric instrument, evidence for its coherence is presented through test design, topic balance, and alignment with learning outcomes. Internal consistency reliability of the assessment, evaluated using the Kuder–Richardson Formula 20 (KR-20), was 0.65. Given that the assessment was developed as a curriculum-aligned measure spanning six distinct introductory chemistry topics, this value was considered acceptable for the exploratory purposes of the present study. Further details are provided in the Supporting Information (Appendix S1).

Statistical analysis

Statistical analyses were conducted using Microsoft Excel and IBM SPSS Statistics. Differences in chemistry interest between TG and CG across pre- and post-intervention measurements were examined using analysis of variance (ANOVA), with additional analyses conducted to evaluate changes across the three dimensions of the Chemistry Study Interest Questionnaire (C-SIQ): intrinsic orientation, feelings-related valences, and value-related valences. Hypotheses were tested at a 95% confidence level ($p < 0.05$). A summary of statistical outputs is provided in the Supporting Information (Appendix S2) accompanying this paper.

The psychometric properties of the C-SIQ were examined to support its use in the present study context. Evidence for structural validity was assessed using confirmatory factor analysis (CFA), with model fit evaluated using multiple indices, including the chi-square statistic (χ^2), Goodness of Fit Index (GFI), Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR), using commonly accepted interpretive thresholds (Hair et al., 2019; Kline, 2016). Internal consistency reliability of the instrument was evaluated using Cronbach's alpha (Cronbach, 1951).

Post-intervention academic performance differences between the TG and CG were examined using ANOVA, with additional topic-specific analyses conducted across the six chemistry topics assessed: molecular orbital theory, periodic table, atomic properties, gas laws, electrostatics, and isomerism. To complement significance testing and provide an indication of practical educational impact, effect sizes were calculated using Cohen's d (Cohen, 1988). All inferential analyses were conducted at a 95% confidence level.

Reliability and supporting validity evidence for the 60-item chemistry knowledge assessment were also examined. Content validity was supported through test blueprinting and alignment of items with course learning objectives. Internal consistency reliability of the dichotomously scored assessment was evaluated using the Kuder–Richardson Formula 20 (KR-20), appropriate for binary-scored instruments (Kuder and Richardson, 1937). Item-level analyses, including item difficulty and point-biserial discrimination indices, were used to evaluate item quality and the assessment's capacity to differentiate levels of student understanding. A summary of these analyses is provided in the Supporting Information (Appendix S1).

Ethical Considerations

Ethical approval for this study was obtained from the Campus Research Ethics Committee of The University of the West Indies, St. Augustine, prior to data collection. All procedures involving human participants were conducted in accordance with institutional ethical standards. Participants were recruited from the Introductory Chemistry I course and were provided with detailed information about the purpose and procedures of the study via the course learning management system. Informed consent was obtained electronically from all participants prior to participation. Participation was entirely voluntary, and students were informed of their right to withdraw from the study at any time without penalty. To ensure confidentiality, no personally identifiable information was collected, and all data were anonymised prior to analysis. Data were securely stored and accessible only to the research team. The study adhered to established ethical guidelines for research involving human subjects, including respect for participant autonomy, confidentiality, and data protection.

Findings

Analysis of overall chemistry interest using the C-SIQ indicated a statistically significant increase for the TG following IVR exposure ($p = 1.52 \times 10^{-2}$), while no significant change was observed for the CG ($p = 0.569$). Further analysis of the C-SIQ subscales revealed that this increase was not uniform across all dimensions of interest (Table 1). A statistically significant improvement was observed for intrinsic orientation in the TG ($p = 4.47 \times 10^{-4}$), whereas no significant differences were found for feelings-related valences ($p = 0.159$) or value-related valences ($p = 0.179$). For the CG, no statistically significant changes were observed across any of the three subscales ($p > 0.05$), indicating stability in interest levels in the absence of IVR exposure.

Table 1 Statistical comparison of overall interest and subscale scores before and after IVR exposure.



Interest Scale	p-Value	Interpretation
TG Overall Interest	0.015244	Reject Null Hypothesis
CG Overall Interest	0.568897	Fail to Reject Null Hypothesis
Feelings-Related Valences		
TG	0.159467	Fail to Reject Null Hypothesis
CG	0.514960	Fail to Reject Null Hypothesis
Value-Related Valences		
TG	0.178804	Fail to Reject Null Hypothesis
CG	0.665446	Fail to Reject Null Hypothesis
Intrinsic Orientation		
TG	0.000447	Reject Null Hypothesis
CG	0.640717	Fail to Reject Null Hypothesis

The psychometric properties of the C-SIQ were assessed to confirm suitability for the study context (Table 2). Confirmatory factor analysis indicated acceptable model fit, with Goodness of Fit Index (GFI = 0.92), Comparative Fit Index (CFI = 0.94), Root Mean Square Error of Approximation (RMSEA = 0.05), and Standardized Root Mean Square Residual (SRMR = 0.04). The chi-square statistic ($\chi^2 = 120.35$, $df = 135$) was non-significant, further supporting model adequacy. Internal consistency reliability was high, with Cronbach's alpha values exceeding acceptable thresholds, indicating strong reliability of the instrument within this sample.

Table 2 Model fit indices for C-SIQ in this study

Fit Index	Value	Threshold	Interpretation
χ^2	120.35	---	---
df	135	---	---
χ^2/df	0.89	<3.00	Excellent fit
p-value	>0.05	<0.05	Non-significant
GFI	0.92	≥ 0.90	Acceptable fit
CFI	0.94	≥ 0.90	Acceptable fit
RMSEA	0.05	<0.06	Good fit
SRMR	0.04	<0.08	Good fit
Cronbach's α	0.88	>0.70	Acceptable internal consistency

Post-intervention comparisons of academic performance revealed a statistically significant difference between the TG and CG ($p = 1.27 \times 10^{-21}$), with the former achieving higher mean scores across all assessed topics (Table 3). Topic-specific analysis indicated that the magnitude of differences varied across content areas (Fig. 6). The TG achieved higher mean scores in molecular orbital theory (82.6% vs 70.5%), periodic table (87.6% vs 68.8%), atomic properties (82.8% vs 69.1%), gas laws (82.4% vs 72.2%), and electrostatics (92.2% vs 75.9%). In contrast, the difference observed for isomerism was comparatively smaller (75.0% vs 71.6%). Cohen's d values varied substantially across topics, ranging from a small-to-moderate effect for isomerism ($d = 0.38$) to very large effects for periodic table ($d = 1.46$) and atomic properties ($d = 1.47$), with large effects observed for molecular orbital theory ($d = 0.81$), gas laws ($d = 1.02$), and electrostatics ($d = 1.23$) (Table 4). Table 3 TG and CG comparison - overall chemistry performance

SUMMARY - Anova: Single Factor, Chemistry Quiz Scores for Test Group and Control Group - Post TG 3D-IVR Exposure

Groups	Count	Sum	Average	Variance
TG Mean Quiz Score	58	48.58333	0.837644	0.000931
CG Mean Quiz Score	58	41.38333	0.713506	0.005424

ANOVA

Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.446897	1	0.446897	140.6453	1.27E-21	3.92433
Within Groups	0.362232	114	0.003177			
Total	0.809128	115				

Critical Value, $\alpha=0.05$
For Control Group, P-value = 1.27E-21, so we reject the null hypothesis H_0

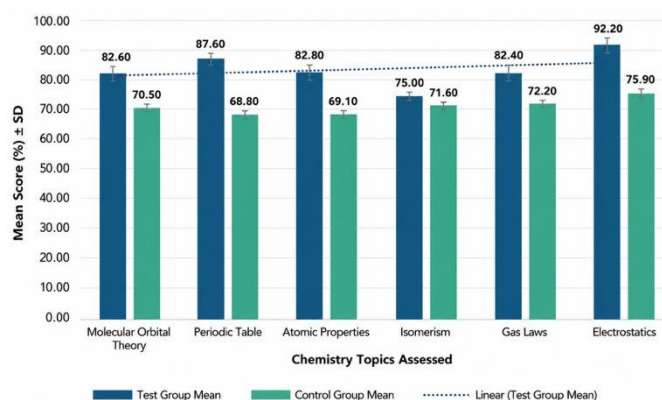


Figure 6 Topic Specific comparison for chemistry performance

Table 4 Cohen's D comparison for 6 chemistry topics

Topic	Cohen's D	Interpretation
Molecular Orbital Theory	0.81	Large effect
Periodic Table	1.46	Very Large effect
Atomic Properties	1.47	Very Large effect
Isomerism	0.38	Small - moderate effect
Gas Laws	1.02	Large effect
Electrostatics	1.23	Large effect

Internal consistency reliability of the assessment, evaluated using the Kuder–Richardson Formula 20 (KR-20), was 0.65. Given that the assessment was developed as a curriculum-aligned measure spanning six distinct introductory chemistry topics, this value was considered acceptable for the exploratory purposes of the present study.

Discussion

The present study examined the effects of immersive virtual reality (IVR) integration on undergraduate chemistry interest and academic performance within a Caribbean higher education context, with particular emphasis on the multidimensional nature of interest. The findings indicate that there was a significant increase in overall chemistry interest, driven specifically by gains in intrinsic orientation, while feelings-related and value-related valences remained unchanged. In parallel, there was a significantly higher academic performance across all assessed topics, with effect sizes ranging from small-to-moderate to very large depending on the content area. Taken together, these findings suggest that



IVR does not exert a uniform influence on student outcomes but rather operates in a selective and context-dependent manner across both affective and cognitive domains. It is important to note the present study did not directly examine the relationship between changes in intrinsic orientation and achievement outcomes. Consequently, no causal or correlational interpretation should be inferred regarding the parallel improvements observed in these two domains.

Selective effects of IVR on multidimensional interest

A central contribution of this study lies in demonstrating that IVR does not influence chemistry interest as a unitary construct. The observed increase in overall interest was attributable specifically to gains in intrinsic orientation, with no corresponding changes in feelings-related or value-related valences. This finding provides empirical support for the multidimensional conceptualisation of interest (Hidi and Renninger, 2006; Krapp, 2002) and underscores the importance of disaggregating interest into its constituent components when evaluating instructional interventions.

Theoretically, this pattern aligns with the proposition that instructional environments characterised by interactivity, learner control, and immediate feedback preferentially support internally driven engagement. Within the framework of Self-Determination Theory, intrinsic orientation reflects learners' experiences of autonomy and competence (Deci and Ryan, 2000). The IVR environment in this study afforded students the ability to manipulate three-dimensional representations, explore chemical structures from multiple perspectives, and regulate their pace of interaction. These affordances are consistent with conditions known to support intrinsic forms of engagement and may explain the observed increase in intrinsic orientation (Deci and Ryan, 2000; Hidi and Renninger, 2006; Parong and Mayer, 2018; Makransky and Petersen, 2021; Renninger and Hidi, 2016).

In contrast, the absence of change in feelings-related and value-related valences suggests that immersive visualisation alone is insufficient to influence affective attachment or perceived relevance of chemistry. These dimensions are more strongly shaped by contextual and experiential factors, including real-world applications, career pathways, and personal meaning. This finding is consistent with theoretical models of interest development, which posit that different components of interest evolve through distinct mechanisms and may require sustained or contextually rich experiences to shift meaningfully (Hidi and Renninger, 2006; Krapp, 2002).

Importantly, this study advances current IVR research by moving beyond general claims of increased engagement to a more precise account of which dimensions of interest are affected and why. This level of specificity remains underdeveloped in the literature, where interest is frequently treated as a single construct.

Topic-dependent effects on academic performance

The results further indicate that IVR exposure was associated with improved academic performance across all

assessed topics; however, the magnitude of these effects varied substantially. Very large effects were observed for periodic table and atomic properties, large effects for molecular orbital theory, gas laws, and electrostatics, and a comparatively smaller effect for isomerism. This variation provides strong empirical support for the proposition that the effectiveness of IVR is dependent on the alignment between its affordances and the representational demands of specific chemistry topics (Makransky and Petersen, 2021).

Topics such as molecular orbital theory, atomic properties, and electrostatics involve abstract, spatially complex representations that are difficult to visualise using traditional instructional approaches. The ability to interact with three-dimensional models and observe dynamic relationships in IVR environments directly supports the cognitive processes required for understanding these concepts. In contrast, isomerism, while involving spatial reasoning, also requires the ability to translate between multiple representational forms, including symbolic notation and structural diagrams. Without explicit scaffolding to support this representational translation, the benefits of immersive visualisation may be attenuated (Kozma and Russell, 1997; Treagust *et al.*, 2003; Wu and Shah, 2004; Gilbert and Treagust, 2009; Stieff, 2011; Sevan and Talanquer, 2014). The comparatively smaller effect observed for isomerism may reflect the fact that successful learning in this topic requires not only spatial visualisation but also translation between symbolic conventions, structural formulas, and nomenclature systems. These representational demands may not be fully addressed through immersive visualisation alone.

This finding is significant because it challenges the implicit assumption that IVR is uniformly beneficial across chemistry content. Instead, it highlights the need for careful alignment between technological affordances and the cognitive and representational demands of the subject matter. Such alignment is essential if IVR is to support meaningful learning rather than surface-level engagement.

Implications for theory and practice

Taken together, these findings contribute to a more theoretically grounded understanding of how IVR functions as a pedagogical tool in chemistry education. First, the selective effect on intrinsic orientation supports the argument that IVR primarily operates through mechanisms associated with autonomy and competence, rather than broadly enhancing all dimensions of student interest. Second, the topic-dependent variation in performance outcomes demonstrates that the effectiveness of IVR is contingent on its alignment with disciplinary representations.

From a practical perspective, these results suggest that IVR should not be implemented as a stand-alone solution, but rather as part of an integrated instructional design. To influence broader dimensions of interest, such as value and affect, IVR experiences may need to be combined with contextualised learning activities that emphasise real-world relevance and

career connections. Similarly, for topics requiring representational translation, IVR should be supplemented with structured guidance and opportunities for reflection.

A further contribution of this study lies in its context. The implementation of smartphone-based IVR in a Small Island Developing State (SIDS) demonstrates that immersive technologies can be integrated within resource-constrained educational environments. This extends the current literature, which is predominantly based in well-resourced contexts, and provides evidence for the feasibility of scalable, cost-effective approaches to immersive learning.

Limitations and future research

Several limitations should be acknowledged. The quasi-experimental design limits causal inference, and variation in students' engagement with IVR was not directly controlled. Additionally, the potential influence of novelty effects cannot be excluded, as initial exposure to immersive technologies may enhance engagement independently of instructional value.

A further limitation is that the study did not directly examine the relationship between changes in chemistry interest and academic performance. Although increases in intrinsic orientation and achievement were observed concurrently within the TG, the extent to which these outcomes were related was not investigated. Future studies should employ correlational or structural modelling approaches to explore potential associations between affective and cognitive outcomes in IVR-supported chemistry learning.

The achievement component of the study employed a post-test-only comparison and did not include a pre-intervention measure of chemistry achievement for the assessed topics. Although the groups were comparable with respect to demographic characteristics, academic qualifications, and baseline chemistry interest, differences in prior topic-specific knowledge cannot be completely excluded. Consequently, the achievement findings should be interpreted with appropriate caution. The achievement findings should also be interpreted considering the characteristics of the assessment instrument. The 60-item chemistry knowledge assessment demonstrated a KR-20 coefficient of 0.65, indicating acceptable internal consistency for a curriculum-based instrument spanning multiple introductory chemistry topics. Given the broad content coverage of the assessment, the reliability coefficient was considered sufficient for the group-level comparisons undertaken in this study.

Future research should examine the longitudinal stability of the observed gains in intrinsic orientation and investigate how structured and guided IVR interventions influence both interest and learning outcomes. Further work is also needed to develop topic-specific design principles for IVR in chemistry education, particularly for areas requiring complex representational reasoning. Integrating IVR with explicit scaffolding for representational translation represents a promising direction for enhancing its effectiveness across a broader range of chemistry topics.

Conclusion

This study examined the effects of immersive virtual reality (IVR) on undergraduate chemistry interest and academic performance within a Caribbean higher education context, with particular emphasis on the multidimensional nature of interest. The findings demonstrate that IVR integration does not produce uniform effects across student outcomes but instead operates selectively across both affective and cognitive domains.

In relation to interest, the results provide clear evidence that IVR preferentially supports intrinsic orientation, while exerting limited influence on feelings-related and value-related valences. This finding reinforces the importance of conceptualising interest as a multidimensional construct and highlights the need to move beyond aggregate measures when evaluating instructional interventions. In relation to academic performance, the study shows that IVR can support substantial learning gains; however, these gains are strongly dependent on the alignment between IVR affordances and the representational demands of specific chemistry topics. The observed variation in effect sizes across topics underscores the importance of content sensitivity in the design and evaluation of immersive learning environments.

Taken together, these findings contribute to a more nuanced understanding of IVR as a pedagogical tool. Rather than functioning as a universally effective innovation, IVR appears to be most impactful when its interactive and visual affordances are deliberately aligned with both the cognitive and motivational dimensions of learning. This has important implications for theory, suggesting that the effects of immersive technologies are mediated by their relationship to specific psychological processes, and for practice, indicating that effective implementation requires careful integration with instructional design and curriculum objectives.

Importantly, this study extends the existing literature by providing evidence from a Small Island Developing State (SIDS) context, demonstrating that smartphone-based IVR can be meaningfully implemented within resource-constrained environments. This highlights the potential for scalable and accessible approaches to immersive learning in chemistry education, while also emphasising the need for complementary instructional strategies to support broader dimensions of student engagement.

Overall, the findings underscore the importance of theoretically informed and contextually grounded approaches to the integration of immersive technologies in chemistry education. They point to the need for continued research that examines not only whether such technologies are effective, but how, for whom, and under what conditions they support meaningful learning.

Author contributions

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Donna Hitlal: Conceptualization; Methodology; Investigation; Formal analysis; Data curation; Writing – original draft; Writing – review & editing; Visualization.

Denise Beckles: Supervision; Methodology; Writing – review & editing; Project administration.

Dianne Thurab-Nkhosi: Validation; Formal analysis; Writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The datasets generated and analysed during the current study are not publicly available due to ethical and privacy considerations but are available from the corresponding author on reasonable request.

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Supporting Information

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Appendix S1. Reliability and Internal Consistency of the Chemistry Knowledge Assessment

S1.1 Overview of the Assessment Instrument

Academic performance was assessed using a 60-item multiple-choice chemistry knowledge test developed for *Introductory Chemistry I* and aligned with course learning objectives. The assessment sampled six core content areas relevant to the intervention: molecular orbital theory, periodic table, atomic properties, isomerism, gas laws, and electrostatics, with ten items allocated to each topic to ensure balanced representation across the curriculum. All items were dichotomously scored (1 = correct; 0 = incorrect). Content validity was supported through test blueprinting and alignment of items with instructional outcomes, with items designed to span a range of conceptual and reasoning demands appropriate for introductory chemistry.

S1.2 Internal Consistency Reliability

Internal consistency reliability of the assessment was evaluated using the Kuder–Richardson Formula 20 (KR-20), which is appropriate for dichotomously scored instruments (Kuder and Richardson, 1937):

$$KR-20 = \frac{k}{k-1} \left(1 - \frac{\sum pq}{\sigma^2} \right)$$

where k is the number of items, p is the proportion of students answering an item correctly, $q = 1 - p$, and σ^2 is the variance of total test scores.

Table S1.1. KR-20 Reliability Calculation Summary

COMPONENT	VALUE
Number of items (k)	60
Number of Students	116
Mean test score	46.66
SD	5.12
Variance of total scores (σ^2)	26.21
$\sum pq$	9.50
KR-20	0.65



S1.3 TOPIC SUMMARY STATISTICS

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Table S1.3.1 Molecular Orbital Theory

Item	Difficulty (p)	Discrimination (rpb)
Q1	0.853	-0.054
Q2	0.759	-0.011
Q3	0.853	-0.039
Q4	0.621	0.251
Q5	0.862	0.009
Q6	0.543	0.257
Q7	0.828	0.098
Q8	0.638	0.540
Q9	0.871	0.127
Q10	0.828	0.149

Table S1.3.2 Periodic Table

Item	Difficulty (p)	Discrimination (rpb)
Q11	0.716	0.672
Q12	0.776	-0.036
Q13	0.879	-0.073
Q14	0.819	0.070
Q15	0.836	-0.047
Q16	0.836	-0.101
Q17	0.974	-0.021
Q18	0.690	0.671
Q19	0.672	0.551
Q20	0.621	0.488

Table S1.3.3 Atomic Properties

Item	Difficulty (p)	Discrimination (rpb)
Q21	0.871	0.074
Q22	0.767	0.250
Q23	0.879	-0.094
Q24	0.724	0.337
Q25	0.724	0.345
Q26	0.698	0.457
Q27	0.759	0.255
Q28	0.664	0.432
Q29	0.672	0.336
Q30	0.698	0.311



Table S1.3.4 Gas Laws

Item	Difficulty (p)	Discrimination (rpb)
Q31	0.776	0.053
Q32	0.733	0.170
Q33	0.716	0.296
Q34	0.724	0.301
Q35	0.793	0.124
Q36	0.836	0.065
Q37	0.698	0.373
Q38	0.733	0.221
Q39	0.638	0.500
Q40	0.741	0.238

Table S1.3.5 Electrostatics

Item	Difficulty (p)	Discrimination (rpb)
Q41	0.767	0.133
Q42	0.759	0.192
Q43	0.767	0.168
Q44	0.733	0.279
Q45	0.741	0.142
Q46	0.724	0.337
Q47	0.759	0.185
Q48	0.707	0.321
Q49	0.724	0.333
Q50	0.733	0.239

Table S1.3.6 Isomerism

Item	Difficulty (p)	Discrimination (rpb)
Q51	0.802	0.247
Q52	0.776	0.348
Q53	0.931	-0.173
Q54	0.595	0.568
Q55	0.862	0.143
Q56	0.940	0.030
Q57	0.940	-0.042
Q58	0.940	-0.077
Q59	0.793	0.135
Q60	0.914	-0.153

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Table S1.3.7 Difficulty and Discrimination – Topic Summary

TOPIC	MEAN DIFFICULTY	MEAN DISCRIMINATION
Molecular Orbital Theory	0.766	0.133
Periodic Table	0.782	0.217
Atomic Properties	0.761	0.076
Gas Laws	0.733	0.044
Electrostatics	0.776	0.105
Isomerism	0.849	0.102

OVERALL

Statistic	Value
KR-20	0.65
Mean item difficulty	0.78
Mean discrimination	0.11

S1.4 CHEMISTRY PERFORMANCE QUIZ**CHEMISTRY PERFORMANCE QUIZ - MOLECULAR ORBITAL THEORY****1. Which of the following statements about molecular orbitals (MOs) is true?**

- Bonding MOs have higher energy than their corresponding atomic orbitals.
- Antibonding MOs are formed by the constructive interference of atomic orbitals.
- A σ^* (sigma-star) orbital has a node between the nuclei.
- π -bonding orbitals result from the end-to-end overlap of atomic orbitals.
- Only s orbitals contribute to molecular orbital formation.

Answer: c) A σ^* (sigma-star) orbital has a node between the nuclei.

2. In a homonuclear diatomic molecule, how does the energy ordering of π and σ molecular orbitals change as the atomic number increases ($Z > 8$)?

- π orbitals are always lower in energy than σ orbitals.
- The σ_{2p} orbital becomes lower in energy than the π_{2p} orbitals for $Z > 8$.
- The σ_{2p} orbital remains higher in energy than the π_{2p} orbitals for all diatomic molecules.
- The energy order of π and σ orbitals remains unchanged with increasing atomic number.
- The π_{2p} and σ_{2p} orbitals merge in energy for heavier diatomic molecules.

Answer: b) The σ_{2p} orbital becomes lower in energy than the π_{2p} orbitals for $Z > 8$.

3. According to Molecular Orbital Theory, what is the bond order of the O_2^+ (oxygen cation) species?

- 1.5
- 2.0
- 2.5
- 3.0
- 3.5

Answer: c) 2.5

4. Which of the following diatomic species is diamagnetic?

- a) B₂
- b) O₂
- c) C₂
- d) N₂⁺
- e) O₂⁺

Answer: c) C₂

5. Which of the following best describes the bonding in carbon monoxide (CO) using Molecular Orbital Theory?

- a) CO has a bond order of 2.
- b) The highest occupied molecular orbital (HOMO) is primarily localized on oxygen.
- c) The lowest unoccupied molecular orbital (LUMO) is primarily localized on carbon.
- d) The molecule has significant π back-donation from oxygen to carbon.
- e) The bonding MOs have contributions from only carbon because of electronegativity differences.

Answer: c) The lowest unoccupied molecular orbital (LUMO) is primarily localized on carbon.

6. In Molecular Orbital Theory, which of the following statements about bond order is correct?

- a) Bond order is always an integer.
- b) A bond order of zero indicates a stable molecule.
- c) Higher bond order generally corresponds to greater bond strength.
- d) Bond order is defined as the sum of bonding and antibonding electrons divided by two.
- e) Bond order is independent of electron configuration.

Answer: c) Higher bond order generally corresponds to greater bond strength.

7. What happens to the bond order of O₂ when it is ionized to O₂⁻?

- a) Increases
- b) Decreases
- c) Remains the same
- d) Cannot be determined
- e) Becomes zero

Answer: b) Decreases

8. Which molecular orbital of CO₂ is the highest in energy and typically unoccupied?

- a) π^* (antibonding)
- b) σ^* (antibonding)
- c) π (bonding)
- d) σ (bonding)
- e) Nonbonding orbital

Answer: a) π^* (antibonding)

9. Which statement about heteronuclear diatomic molecules (e.g., NO, HF) is correct?

- a) Molecular orbitals are equally shared between both atoms.
- b) More electronegative atoms contribute more to bonding orbitals.
- c) Antibonding orbitals are always localized on the less electronegative atom.



- d) The bond order must always be an integer.
e) The bond order is always the same as in the homonuclear case.

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Answer: b) More electronegative atoms contribute more to bonding orbitals.

10. In the MO diagram of benzene, what is the total number of π molecular orbitals?

- a) 3
b) 4
c) 5
d) 6
e) 12

Answer: d) 6

CHEMISTRY PERFORMANCE QUIZ – THE PERIODIC TABLE

11. Which of the following statements about the periodic table is correct?

- a) Elements in the same period exhibit similar chemical properties.
b) The atomic radius increases across a period due to increased nuclear charge.
c) Ionization energy generally increases across a period from left to right.
d) Alkali metals are found in Group 2 of the periodic table.
e) Noble gases have the highest electronegativity values in their respective periods.

Answer: c) Ionization energy generally increases across a period from left to right.

12. Which of the following trends is NOT correctly described?

- a) Atomic radius decreases across a period due to increased effective nuclear charge.
b) Ionization energy decreases down a group due to increased shielding.
c) Electronegativity generally increases across a period.
d) Electron affinity is always negative for all elements.
e) Transition metals often exhibit variable oxidation states due to d-orbital involvement.

Answer: d) Electron affinity is always negative for all elements.

(Some elements, such as noble gases and alkaline earth metals, have positive or near-zero electron affinities.)

13. The most electronegative element in the periodic table is:

- a) Oxygen
b) Nitrogen
c) Fluorine
d) Chlorine
e) Sulfur

Answer: c) Fluorine

14. Which of the following correctly describes the lanthanide contraction?

- a) It results from increasing shielding effect in the 4f orbitals.
b) It is responsible for the similar sizes of the 4d and 5d transition metals.
c) It causes a dramatic increase in atomic radii among the lanthanides.

- d) It leads to the expansion of d-orbitals in transition metals.
e) It has no significant effect on periodic trends.

Answer: b) It is responsible for the similar sizes of the 4d and 5d transition metals.

15. Which of the following groups contains only metalloids?

- a) B, Al, Si, Ge
b) B, Si, Ge, As, Sb, Te
c) Al, Si, P, S
d) C, Si, Sn, Pb
e) Be, Mg, Ca, Sr

Answer: b) B, Si, Ge, As, Sb, Te

16. Which of the following statements about noble gases is FALSE?

- a) They have full valence shells.
b) Their ionization energies are among the highest in the periodic table.
c) They are chemically inert under standard conditions.
d) They readily form ionic compounds with alkali metals.
e) Xenon can form compounds with fluorine and oxygen under specific conditions.

Answer: d) They readily form ionic compounds with alkali metals.

17. Which of the following best explains why transition metals exhibit multiple oxidation states?

- a) Their s-orbital electrons are held very weakly.
b) The presence of partially filled d-orbitals allows different numbers of electrons to be lost.
c) Their nuclear charge is significantly higher than that of main-group elements.
d) They have the highest electron affinities of any element.
e) They always form a +2 oxidation state.

Answer: b) The presence of partially filled d-orbitals allows different numbers of electrons to be lost.

18. The first-row transition metal with the highest number of unpaired d-electrons in its ground state is:

- a) Scandium (Sc)
b) Vanadium (V)
c) Chromium (Cr)
d) Iron (Fe)
e) Zinc (Zn)

Answer: c) Chromium (Cr) (It has six unpaired d-electrons in the $3d^5 4s^1$ configuration.)

19. Which of the following elements has the highest second ionization energy?

- a) Sodium (Na)
b) Magnesium (Mg)
c) Aluminum (Al)
d) Potassium (K)
e) Calcium (Ca)

Answer: d) Potassium (K)



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20. The diagonal relationship in the periodic table explains similarities between which pairs of elements?

- a) Lithium and Sodium
- b) Carbon and Silicon
- c) Boron and Aluminum
- d) Lithium and Magnesium
- e) Calcium and Strontium

Answer: d) Lithium and Magnesium (*Elements in the same diagonal position in the periodic table often exhibit similar properties due to comparable charge densities.*)

CHEMISTRY PERFORMANCE QUIZ – ATOMIC PROPERTIES

21. Which of the following best explains why atomic radii decrease across a period in the periodic table?

- a) The number of protons increases, pulling electrons closer to the nucleus.
- b) Electron-electron repulsion significantly increases, causing the atom to contract.
- c) The number of core electrons increases, leading to stronger shielding.
- d) The number of valence electrons remains constant, leading to a size decrease.
- e) Ionization energy decreases across a period, causing atomic size to shrink.

Answer: a) The number of protons increases, pulling electrons closer to the nucleus.

22. Which of the following factors primarily determines atomic radius?

- a) The number of valence electrons
- b) The number of core electrons only
- c) The balance between nuclear charge and electron shielding
- d) The total number of protons only
- e) The ionization energy of the atom

Answer: c) The balance between nuclear charge and electron shielding

23. Which of the following atoms has the largest atomic radius?

- a) Na
- b) Mg
- c) Al
- d) Si
- e) Cl

Answer: a) Na

(*Atomic radius decreases across a period due to increasing Z_{eff} .*)

24. Why does ionization energy generally increase across a period?

- a) Electron shielding increases.
- b) The number of valence electrons decreases.
- c) Atomic size increases.
- d) Effective nuclear charge increases.
- e) The number of protons remains constant.

Answer: d) Effective nuclear charge increases.



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25. Which of the following elements has the highest first ionization energy?

- a) Na
- b) Mg
- c) Al
- d) P
- e) Ar

Answer: e) Ar

(Noble gases have the highest ionization energies in their periods due to their full valence shells.)

26. Which element has the most negative electron affinity, meaning it releases the most energy upon gaining an electron?

- a) Li
- b) O
- c) N
- d) Cl
- e) Ne

Answer: d) Cl

27. Which of the following correctly explains why noble gases have positive or near-zero electron affinities?

- a) They have high ionization energies.
- b) Their electron clouds repel additional electrons due to a full valence shell.
- c) They have a very small atomic radius.
- d) Their d-orbitals are involved in bonding.
- e) They readily form negative ions.

Answer: b) Their electron clouds repel additional electrons due to a full valence shell.

28. What is the correct trend for electronegativity across the periodic table?

- a) It increases down a group and increases across a period.
- b) It decreases across a period and increases down a group.
- c) It increases across a period and decreases down a group.
- d) It remains constant across a period but decreases down a group.
- e) It depends only on atomic mass.

Answer: c) It increases across a period and decreases down a group.

29. Which of the following statements correctly describes the trend in ionic radius compared to atomic radius?

- a) Cations are larger than their parent atoms because they gain protons.
- b) Cations are smaller than their parent atoms because they lose valence electrons.
- c) Anions are smaller than their parent atoms due to increased Z_{eff} .
- d) Anions and cations are always the same size as their parent atoms.
- e) Ionic radius is independent of electron configuration.

Answer: b) Cations are smaller than their parent atoms because they lose valence electrons.

30. Which of the following elements would have the smallest second ionization energy?

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3 a) Na
4 b) Mg
5 c) Al
6 d) Si
7 e) Cl
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10 **Answer: b) Mg**
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13 CHEMISTRY PERFORMANCE QUIZ – ISOMERISM 14

15 **31. Which of the following statements correctly describes structural (constitutional) isomers?**

- 16 a) They have the same molecular formula but different connectivity of atoms.
17 b) They have identical physical and chemical properties.
18 c) They always exist in equilibrium with each other.
19 d) They differ in the arrangement of atoms in space but have the same connectivity.
20 e) They have different molecular formulas but belong to the same homologous series.

21 **Answer: a) They have the same molecular formula but different connectivity of atoms.**
22

23 **32. Which of the following is NOT an example of structural isomerism?**

- 24 a) Chain isomerism
25 b) Position isomerism
26 c) Functional group isomerism
27 d) Geometric (cis-trans) isomerism
28 e) Tautomerism

29 **Answer: d) Geometric (cis-trans) isomerism** (*This is an example of stereoisomerism, not structural isomerism.*)
30

31 **33. Which type of isomerism arises due to restricted rotation around a double bond or a cyclic system?**

- 32 a) Optical isomerism
33 b) Chain isomerism
34 c) Geometrical (cis-trans) isomerism
35 d) Functional group isomerism
36 e) Metamerism

37 **Answer: c) Geometrical (cis-trans) isomerism**
38

39 **34. Which of the following compounds can exhibit cis-trans isomerism?**

- 40 a) 1-chloropropane
41 b) 2-butene
42 c) Methanol
43 d) Benzene
44 e) Ethane

45 **Answer: b) 2-butene** (*It has a C=C bond with different groups attached to each carbon.*)
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47 **35. Which of the following statements about enantiomers is TRUE?**
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3 a) Enantiomers have different molecular formulas.
4 b) Enantiomers rotate plane-polarized light in opposite directions.
5 c) Enantiomers can be interconverted by simple rotation around a single bond.
6 d) Enantiomers have different boiling points.
7 e) Enantiomers cannot be separated by physical methods.
8

9
10 **Answer: b) Enantiomers rotate plane-polarized light in opposite directions.**

11 **36. What is the minimum number of chiral centers required for a molecule to exhibit optical**
12 **isomerism?**

- 13
14 a) 0
15 b) 1
16 c) 2
17 d) 3
18 e) 4

19 **Answer: b) 1** (*A molecule with one chiral center is usually chiral and can exhibit optical isomerism.*)

20 **37. Which type of isomerism is exhibited by C₃H₆O where one isomer is propanal and another is**
21 **acetone?**

- 22 a) Chain isomerism
23 b) Functional group isomerism
24 c) Geometrical isomerism
25 d) Optical isomerism
26 e) Tautomerism

27 **Answer: b) Functional group isomerism** (*Propanal is an aldehyde, while acetone is a ketone.*)

28 **38. Which of the following molecules exhibits meso isomerism?**

- 29 a) 2-butanol
30 b) 2-chloropropane
31 c) 2,3-dichlorobutane
32 d) 3-methylpentane
33 e) Benzene

34 **Answer: c) 2,3-dichlorobutane** (*It has a plane of symmetry, making it a meso compound.*)

35 **39. Which of the following is NOT a characteristic of diastereomers?**

- 36 a) They have different physical properties.
37 b) They are non-superimposable mirror images.
38 c) They have different boiling and melting points.
39 d) They may exhibit cis-trans isomerism.
40 e) They do not rotate plane-polarized light in equal and opposite directions.

41 **Answer: b) They are non-superimposable mirror images**

42 **40. Which type of isomerism is observed in ethers where the alkyl groups attached to the**
43 **oxygen differ in size?**

- 44 a) Chain isomerism
45 b) Functional group isomerism
46 c) Geometrical isomerism

- d) Metamerism
e) Optical isomerism

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Answer: d) Metamerism (*Metamerism occurs in compounds like ethers, ketones, and amines when different alkyl groups are attached to the same functional group.*)

CHEMISTRY PERFORMANCE QUIZ – GAS LAWS

41. Which of the following statements correctly describes Boyle's Law?

- a) The volume of a gas is directly proportional to its pressure at constant temperature.
b) The volume of a gas is inversely proportional to its pressure at constant temperature.
c) The pressure of a gas is directly proportional to its temperature at constant volume.
d) The volume of a gas is directly proportional to its temperature at constant pressure.
e) The number of moles of gas does not affect the volume at constant temperature and pressure.

Answer: b) The volume of a gas is inversely proportional to its pressure at constant temperature.

42. The ideal gas equation $PV=nRT$ implies which of the following relationships?

- a) If pressure increases while the number of moles and temperature remain constant, volume increases.
b) If the number of moles of gas increases while pressure and temperature remain constant, volume decreases.
c) If temperature increases at constant volume, pressure increases.
d) If volume is held constant, decreasing the number of gas molecules increases pressure.
e) If pressure decreases and temperature remains constant, volume decreases.

Answer: c) If temperature increases at constant volume, pressure increases.

43. The partial pressure of a gas in a mixture is determined using:

- a) Boyle's Law
b) Charles' Law
c) Dalton's Law
d) Avogadro's Law
e) Graham's Law

Answer: c) Dalton's Law

44. According to Avogadro's Law, which of the following is true?

- a) Equal volumes of gases at the same temperature and pressure contain equal numbers of molecules.
b) The total pressure of a gas mixture is the sum of the individual gas pressures.
c) The rate of diffusion of a gas is inversely proportional to its molar mass.
d) The volume of a gas is directly proportional to its pressure at constant temperature.
e) The energy of gas molecules is proportional to the inverse of their velocity.

Answer: a) Equal volumes of gases at the same temperature and pressure contain equal numbers of molecules.

45. Which of the following statements correctly describes Graham's Law of Effusion?

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- The rate of effusion of a gas is directly proportional to its molar mass.
 - The rate of effusion of a gas is inversely proportional to the square root of its molar mass.
 - The rate of diffusion of a gas is independent of molar mass.
 - The rate of effusion is dependent only on the temperature of the gas.
 - All gases diffuse at the same rate under identical conditions.

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Answer: b) The rate of effusion of a gas is inversely proportional to the square root of its molar mass.

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46. A sample of oxygen gas occupies 10.0 L at 25°C and 1.00 atm. What will be the volume if the pressure is doubled while temperature remains constant?

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- 5.0 L
 - 10.0 L
 - 20.0 L
 - 40.0 L
 - 0.5 L

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Answer: a) 5.0 L

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(According to Boyle's Law: $P_1V_1=P_2V_2$, so doubling the pressure halves the volume.)

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47. The van der Waals equation accounts for deviations of real gases from ideal behavior by including terms that correct for:

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- Molecular size and intermolecular forces.
 - Molecular polarity and atmospheric pressure.
 - Gas compressibility and temperature.
 - Isothermal expansion and heat capacity.
 - The kinetic energy of gas molecules.

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Answer: a) Molecular size and intermolecular forces.

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48. Which of the following correctly explains why real gases deviate from ideal behavior at high pressures?

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- The kinetic energy of gas molecules increases significantly.
 - The volume of gas molecules becomes significant compared to the total volume.
 - The temperature of the gas decreases due to compression.
 - The gas molecules completely stop moving.
 - The molar mass of the gas increases at high pressures.

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Answer: b) The volume of gas molecules becomes significant compared to the total volume.

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(At high pressures, the assumption that gas molecules occupy negligible volume breaks down, causing deviation from ideal gas behavior.)

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49. According to the kinetic molecular theory of gases, which of the following is NOT an assumption?

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- Gas particles are in constant, random motion.
 - The volume of gas particles is negligible compared to the total volume.
 - There are strong intermolecular forces between gas particles.
 - The average kinetic energy of gas particles is proportional to temperature in kelvin.
 - Gas particles undergo perfectly elastic collisions.

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Answer: c) There are strong intermolecular forces between gas particles.

(Ideal gases are assumed to have negligible intermolecular forces.)

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50. If a gas expands against a vacuum, which of the following correctly describes the process?

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- a) The gas does work on the surroundings.
- b) The surroundings do work on the gas.
- c) The process is isothermal and reversible.
- d) The expansion is spontaneous and does no work.
- e) The expansion results in an increase in temperature.

Answer:

d) The expansion is spontaneous and does no work.

(Expansion against a vacuum is called free expansion, where no work is done as there is no external pressure.)

CHEMISTRY PERFORMANCE QUIZ – ELECTROSTATICS

51. Which of the following statements about Coulomb's law is correct?

- a) The force between two point charges is directly proportional to the square of the distance between them.
- b) The force between two point charges is inversely proportional to the product of the charges.
- c) The force between two point charges is inversely proportional to the square of the distance between them.
- d) The force between two point charges depends only on the magnitude of the charges, not their separation.
- e) Coulomb's law applies only to charges in a vacuum.

Answer: c) The force between two point charges is inversely proportional to the square of the distance between them.

52. What happens to the electric field inside a conductor in electrostatic equilibrium?

- a) It is zero.
- b) It is uniform and nonzero.
- c) It points outward from the surface.
- d) It depends on the type of material of the conductor.
- e) It varies with the charge distribution inside the conductor.

Answer: a) It is zero.

53. Which of the following correctly describes the behavior of electric field lines?

- a) They originate from negative charges and terminate at positive charges.
- b) They always form closed loops.
- c) They are always perpendicular to the surface of a conductor in electrostatic equilibrium.
- d) They represent paths along which a charge must move.
- e) They never intersect unless in a non-uniform field.

Answer: c) They are always perpendicular to the surface of a conductor in electrostatic equilibrium.

54. The electric potential at a point is defined as:

- a) The force per unit charge at that point.
- b) The work done per unit charge in bringing a charge from infinity to that point.

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- c) The energy stored in an electric field.
 - d) The rate at which charge flows past a point.
 - e) The amount of charge stored per unit voltage.

Answer: b) The work done per unit charge in bringing a charge from infinity to that point.

55. According to the principle of charge conservation, which of the following statements is true?

- a) Charge can be created but not destroyed.
- b) The total charge in an isolated system remains constant.
- c) Electrons and protons can be created in different amounts during a reaction.
- d) Charge can be transferred from one object to another, but its total amount in the universe is constantly increasing.
- e) A neutral object cannot gain or lose charge.

Answer: b) The total charge in an isolated system remains constant.

56. Which of the following best describes an equipotential surface?

- a) It is a surface on which the electric potential is the same at all points.
- b) It is a surface on which the electric field strength is uniform.
- c) It is a surface where the charge density is maximum.
- d) It is a surface along which the electric field is parallel.
- e) It is a surface that always intersects electric field lines.

Answer: a) It is a surface on which the electric potential is the same at all points.

57. A parallel plate capacitor is charged and then disconnected from the battery. If the plate separation is doubled, what happens to the voltage between the plates?

- a) It is halved.
- b) It remains the same.
- c) It doubles.
- d) It becomes zero.
- e) It increases exponentially.

Answer: c) It doubles

58. Why is capacitance important in electrochemical cells such as batteries and supercapacitors?

- a) It determines the voltage at which a battery operates.
- b) It helps store charge, which can be quickly released to provide power.
- c) It is responsible for the movement of ions in the electrolyte.
- d) It prevents the loss of charge due to electron leakage.
- e) It ensures that only oxidation reactions occur at the anode.

Answer: b) It helps store charge, which can be quickly released to provide power.

59. A charge of $+3\mu\text{C}$ is placed at the origin. What is the direction of the electric field at the point (0, 5) cm?

- a) Towards the charge
- b) Away from the charge
- c) Parallel to the y-axis, pointing downward



- 1
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3 d) Perpendicular to the y-axis
4 e) Zero
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6 **Answer: b) Away from the charge**
7

8 **60. A conducting sphere of radius R carries a charge Q. Where is the electric field maximum?**
9

- 10 a) Inside the sphere
11 b) On the surface of the sphere
12 c) Just outside the sphere
13 d) At infinity
14 e) It is uniform everywhere.
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16 **Answer: c) Just outside the sphere**
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Supplemental Information**Appendix S2 - C-SIQ Raw Data****Table S2.1. OVERALL TG1 vs TG2**

SUMMARY - Anova: Single Factor, Comparing Test Group 1 with Test Group 2						
Groups	Count	Sum	Average	Variance		
TG1	58	142.3889	2.454981	0.27577		
TG2	58	128.9216	2.222785	0.23940		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	1.563526	1	1.5635260	6.069945	0.015244	3.92433
Within Groups	29.36468	114	0.257585			
Total	30.92821	115				
Critical Value, $\alpha=0.05$						
For Test Group, P-value =0.015244, so we reject the null hypothesis H_0 1						

Table S2.2. OVERALL CG1 vs CG2

SUMMARY - Anova: Single Factor, Comparing Control Group 1 with Control Group 2						
Groups	Count	Sum	Average	Variance		
CG1	58	134.7222	2.322797	0.119647		
CG2	58	138.1667	2.382184	0.120670		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.102278	1	0.102278	0.326424	0.568897	3.92433
Within Groups	35.71935	114	0.313328			
Total	35.82163	115				
Critical Value, $\alpha=0.05$						
For Control Group, P-value =0.568897, so we fail to reject the null hypothesis H_0 2						

Table S2.3. FEELINGS-RELATED VALENCES – TG1 VS TG2

SUMMARY - Anova: Single Factor, Comparing Feelings Related Valences for TG1 with Feeling Related Valences for TG2						
Groups	Count	Sum	Average	Variance		
Feeling Valences TG1	58	141.4286	2.438424	0.254824		
Feeling Valences TG2	58	134.1429	2.312808	0.201545		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.457600	1	0.457600	2.005397	0.159467	3.92433
Within Groups	26.01302	114	0.228184			
Total	26.47062	115				
Critical Value, $\alpha=0.05$						
For Control Group, P-value =0.159467, so we fail to reject the null hypothesis H_0 3						



Table S2.4 FEELINGS-RELATED VALENCES – CG1 VS CG2View Article Online
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SUMMARY - Anova: Single Factor, Comparing Feelings Related Valences for CG1 with Feeling Related Valences for CG2						
Groups	Count	Sum	Average	Variance		
Feeling Valences CG1	58	135.7143	2.339901	0.283443		
Feeling Valences CG2	58	139.5714	2.406404	0.317796		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.128255	1	0.128255	0.426635	0.51496	3.92433
Within Groups	34.27058	114	0.300619			
Total	34.39884	115				
Critical Value, $\alpha=0.05$						
For Control Group, P-value =0.51496, so we fail to reject the null hypothesis H_04						

Table S2.5. VALUE-RELATED VALENCES – TG1 VS TG2

SUMMARY - Anova: Single Factor, Comparing Value Related Valences for TG1 with Value Related Valences for TG2						
Groups	Count	Sum	Average	Variance		
Value Valences TG1	58	142.2857	2.453202	0.396089		
Value Valences TG2	58	134.0000	2.310345	0.250725		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.591837	1	0.591837	1.830006	0.178804	3.92433
Within Groups	36.86840	114	0.323407			
Total	37.46024	115				
Critical Value, $\alpha=0.05$						
For Control Group, P-value =0.178804, so we fail to reject the null hypothesis H_05						

Table S2.6. VALUE-RELATED VALENCES – CG1 VS CG2

SUMMARY - Anova: Single Factor, Comparing Value Related Valences for CG1 with Value Related Valences for CG2						
Groups	Count	Sum	Average	Variance		
Value Valences CG1	58	135.1429	2.330049	0.330975		
Value Valences CG2	58	138.0000	2.379310	0.417867		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.070373	1	0.070373	0.187951	0.665446	3.92433
Within Groups	42.68403	114	0.374421			
Total	42.75440	115				
Critical Value, $\alpha=0.05$						
For Control Group, P-value =0.665446, so we fail to reject the null hypothesis H_06						



Table S2.7. INTRINSIC ORIENTATION – TG1 VS TG2

SUMMARY - Anova: Single Factor, Comparing Intrinsic Orientation for TG1 with Intrinsic Orientation for TG2

Groups	Count	Sum	Average	Variance
Intrinsic Orientation TG1	58	144.25	2.487069	0.435137
Intrinsic Orientation TG2	58	121.50	2.094828	0.247429

ANOVA

Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	4.461746	1	4.461746	13.07345	0.000447	3.92433
Within Groups	38.90625	114	0.341283			
Total	43.36800	115				

Critical Value, $\alpha=0.05$
For Control Group, P-value = 0.000447, so we reject the null hypothesis H_0

Table S2.8. INTRINSIC ORIENTATION – CG1 VS CG2

SUMMARY - Anova: Single Factor, Comparing Intrinsic Orientation for CG1 with Intrinsic Orientation for CG2

Groups	Count	Sum	Average	Variance
Intrinsic Orientation CG1	58	132.25	2.280172	0.493591
Intrinsic Orientation CG2	58	136.00	2.344828	0.613657

ANOVA

Source of Variation	SS	df	MS	F	P-value	Fcrit
Between Groups	0.121228	1	0.121228	0.218972	0.640717	3.92433
Within Groups	63.11315	114	0.553624			
Total	63.23438	115				

Critical Value, $\alpha=0.05$
For Control Group, P-value = 0.640717, so we fail to reject the null hypothesis H_0

Supporting Documents

THE UNIVERSITY OF THE WEST INDIES

ST. AUGUSTINE, TRINIDAD AND TOBAGO, WEST INDIES

CAMPUS RESEARCH ETHICS COMMITTEE

TELEPHONE: (1-868) 662-2002 ext. 82755 E-mail: campusetics@sta.uwi.edu

November, 8 2021

Donna Hitlal
Department of Chemistry
Faculty of Science and Technology
Email: donna.hitlal@my.uwi.edu

Dear Donna Hitlal,

Ref: CREC-SA.1179/09/2021

Title: Teaching and learning chemistry for Generation Z – deep learning by technology aided immersion in chemistry.

I am pleased to advise that your application for research on the above captioned topic has been approved on behalf of Campus Research Ethics Committee, St. Augustine.

Approval is valid for one (1) year.

Sincerely,

Professor Jerome De Lisle
Chair
Campus Research Ethics Committee

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CITI ETHICS CERTIFICATE



Completion Date **25-Nov-2019**
Expiration Date **24-Nov-2023**
Record ID **34357269**

This is to certify that:

Donna Hitlal

Has completed the following CITI Program course:

- RCR Basic Course** (Curriculum Group)
- Group 3: ST. AUGUSTINE** (Course Learner Group)
- 1 - Basic Course** (Stage)

Under requirements set by:

University of the West Indies



Verify at www.citiprogram.org/verify/?wa2017480-43e4-404a-ae52-a53053d06f8b-34357269

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Chemistry Education Research and Practice Accepted Manuscript



CONSENT FORM

a. What is the purpose of this research?

This study will investigate the effect of Immersive Virtual Reality Technology on Introductory Undergraduate Chemistry students' motivation and performance in Chemistry at The UWI, STA.

b. How long it will take to complete this project?

The completion time for this project is 1 year

c. Why are you selected for this research?

You were selected for this study because you are a registered student at The UWI, STA and you are enrolled in CHEM 1066 in the academic year 2023/24.

d. Why is this document for obtaining informed consent important?

To ensure that you and other volunteers in the study are aware that Campus Ethics guideline have been followed so that this study will have extremely little or no impact on you. Consenting to participate will mean that you are prepared to be a part of the study.

e. What do we expect you to do in this study?

You will be asked to answer 2 questionnaires and a quiz online.

1. A Chemistry Motivation Survey
2. A Demographics Survey
4. A Chemistry Quiz

f. Which procedures are investigational, which are routine? What is the expected duration, how frequently you have to participate and where will the activities take place?

The surveys will all be done online and any meetings with students will be done virtually. Each survey should take approx. 10 minutes to complete and will be collected when students find it convenient during semester 1 academic year 2023/2024

g. How many participants are involved in the study approximately?

Approx. 120 students will be involved in the study

h. What are the risks or discomforts that may result from your participation in the study?

There are no risks associated with this study.

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i. What help and treatments are available if any adverse reactions occur? How can you access them? Is there any compensation available if serious adverse effects occur?

There are no risks associated with this study.

j. Are there any potentially beneficial treatments or procedures that are withheld for the purpose of the study?

No. There are no treatments to be withheld.

k. Are there any anticipated circumstances under which the study/participation may be terminated by the researchers without regard your consent?

There are no anticipated circumstances under which you may be terminated by the researcher without regard your consent.

l. What are the benefits to you (and the wider society) by this study? (State clearly if there is no direct benefit to the participant, but only societal benefit)

This project will be the first of its kind in our Caribbean region and if found to increase students' motivation and interest in chemistry and to increase students' performance, then the VR technology could possibly change the way that we teach chemistry. With chemistry having an impact on all areas of life from food technology, medicines, pharmaceuticals, cosmetics and so much more, chemists are always in demand. If this new strategy of teaching chemistry with virtual reality is found to increase student motivation, interest and performance, then this study will indeed be beneficial to chemistry as a profession.

m. Does this study involve more than minimal risk? Are there any appropriate alternative procedures or courses of treatment that might be advantageous to you?

There are no risks associated with this study.

n. Do you have the right to pursue the alternatives?

Yes. The you can pursue any alternative.

o. How will confidentiality be maintained regarding your data? Who will have access to the data, how the data will be reported and /or published?

The data will be stored on the personal computer owned by the researcher, Donna Hitlal. This computer is outfitted with a password that is only known to the researcher. This information will be stored for a maximum of 3 months from collection. There will be no names or student numbers collected in any of the surveys. The surveys will be 100% confidential and all data will only be exposed to the researcher and the supervisor. The data will not be duplicated, nor will it be made available to any other person or

organization under any circumstances. The data will be published as part of the researcher's PhD thesis.

p. Are there any costs involved and are there any compensations provided?

There are no costs or compensation to the volunteers of the study.

q. Do I have the freedom to withdraw from the study anytime?

Yes. You can withdraw from this study at any time.

r. Will withdrawing from the study have any impact on my treatment?

There will be no impacts on you for withdrawing from the study.

s. Do you have to right to ask questions anytime during the study? Whom should you contact? (Including a member of the UWI Ethics Committee).

Questions can be asked at any time during the study.

The Primary researcher contact is as follows:

Donna Hitlal

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Email: donna.hitlal@my.uwi.edu

Researcher's Supervisor:

Dr. Denese Beckles

The Department of Chemistry

Faculty of Science and Technology

Email: denese.beckles@uwi.edu

Campus Ethics can also be contacted at campusethics@sta.uwi.edu for any queries.

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3 April 15th, 2026
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6 The Associate Editor
7 Chemical Education Research and Practice
8

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10 Re: CERP Submission - Multidimensional Interest and Achievement Outcomes Following
11 Immersive Virtual Reality Integration in Undergraduate Chemistry: A Quasi-Experimental
12 Study in a Caribbean Context
13

14 15 **Data Availability Statement**

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17 The data supporting this study are not publicly available due to ethical and privacy
18 considerations. The dataset contains information collected from undergraduate students
19 at The University of the West Indies, and includes responses that could potentially
20 compromise participant anonymity if shared in full.
21

22
23 Ethical approval for this study was obtained from the Campus Research Ethics Committee
24 of The University of the West Indies (Ref: CREC-SA.1179/09/2021). All participants provided
25 informed consent under conditions that their data would be used solely for research purposes
26 and reported in aggregate form.
27

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29 De-identified data may be made available from the corresponding author upon reasonable
30 request, subject to approval by the relevant ethics committee and in accordance with
31 institutional data protection guidelines.
32

33
34 Yours sincerely,
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36
37 **Donna Hitlal, PhD**

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