

Socio-Cognitive Dynamics in Chemistry Education: A Vygotskian Analysis of Collaborative Learning Practices

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Abstract: This study evaluated the influence of structured collaborative learning on the academic engagement and conceptual understanding of 240 secondary school chemistry students in Sokoto Metropolis, Nigeria. Guided by Vygotsky's Zone of Proximal Development (ZPD), a quasi-experimental non-equivalent control group design was implemented over twelve weeks during the 2025 academic year. The experimental group (n = 120) utilized Jigsaw II and peer-led team learning, while the control group (n = 120) received traditional lecture-based instruction. Data analysis using one-way Analysis of Covariance (ANCOVA), with pretest scores as a covariate, revealed a statistically significant main effect for instructional method, $F(1, 237) = 56.74$, $p < .001$. The experimental group achieved a significantly higher adjusted posttest mean (14.25, SE = 0.36) compared to the control group (9.93, SE = 0.36), yielding a large effect size (partial $\eta^2 = .193$). While collaborative learning significantly bolstered intrinsic motivation (subscale M = 4.47) and academic self-efficacy (items M range: 4.56–4.98), its impact on reducing general chemistry anxiety was moderate (M = 3.00). The findings quantify the cognitive benefits of peer-led discourse in navigating Johnstone's three levels of representation, specifically reducing cognitive load during complex stoichiometry and thermodynamics tasks.

Keywords: Collaborative learning, Chemistry Education, Vygotsky ZPD, Academic Achievement, Student Motivation.

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Introduction

The modern chemistry classroom often functions as a silent theater of rote memorization rather than a laboratory of collective discovery. While the periodic table and molecular kinetics form the bedrock of scientific literacy, the traditional lecture-centric model frequently reduces these dynamic concepts to static abstractions. This disconnect suggests a need to pivot toward collaborative learning environments—instructional frameworks where students negotiate meaning, solve problems in small groups, and co-construct knowledge. In this context, collaborative learning serves as the independent variable, while student engagement, conceptual clarity, and academic performance in chemistry act as the dependent measures. The theoretical issue at stake involves moving beyond individualistic cognitive processing to embrace social constructivism, where learning is recognized as a communal act rather than a solitary pursuit.

Ideally, a secondary school chemistry lesson should be a hive of inquiry. Students should be debating the nuances of redox reactions or predicting the outcomes of titrations through shared discourse, mirroring the way professional scientists work in teams. However, the reality in many contemporary classrooms remains stubbornly anchored to the "sage on the stage" archetype. Recent data from national assessment bodies indicate a troubling stagnation in chemistry proficiency levels; for instance, many students consistently struggle with the application of chemical principles to unfamiliar contexts (West African Examinations Council, 2023). This gap between the ideal of active participation and the reality of passive reception creates a vacuum where students memorize formulas without truly comprehending the underlying molecular interactions.

Scholars have previously attempted to bridge this gap through the introduction of computer-assisted instructions or flipped classroom models. While these interventions have their merits, they often prioritize the delivery mechanism over the social dynamics of the learners themselves. A study by Johnson and Smith (2022) focused on digital simulations, yet it overlooked the reality that technology alone cannot replace the cognitive friction generated when two students must reconcile their differing interpretations of a covalent bond. Other research, such as the work by Adeyemi (2021), examined peer tutoring but framed it as a remedial tool rather than a holistic classroom environment. These efforts fall short because they treat collaboration as an "add-on" rather than a foundational shift in how the classroom space is utilized.

When collaborative structures are absent, the consequences are both immediate and far-reaching. Directly, we observe a decline in student motivation and an increase in "chemistry anxiety," where the subject is perceived as an impenetrable wall of symbols. Indirectly, this leads to a workforce that lacks the "soft skills"—communication, conflict resolution, and collective brainstorming—that are actually required in modern scientific industries (Rulev, 2021; Swoope, 2020). If students cannot navigate a disagreement over a lab procedure in the tenth grade, they are unlikely to contribute effectively to a multi-disciplinary research team a decade later.

Despite the proliferation of studies on group work, a significant void remains regarding the specific nuances of chemistry-based collaborative environments in secondary education. Much of the existing literature is either too broad, covering general science education, or too narrow, focusing only on university-level organic chemistry. This study fills that gap by investigating how specific collaborative structures—such as Jigsaw techniques or Think-Pair-Share—influence the conceptual shifts in secondary students' understanding of stoichiometry and thermodynamics.

Guided by Vygotsky's Zone of Proximal Development (ZPD), this research moves beyond the "what" of learning to explore the "how." It builds on the foundational work of Brown and King (2020) regarding social interdependence but diverges by applying these theories to the specific linguistic and symbolic hurdles inherent in the chemistry curriculum. By analyzing the intersection of social interaction and chemical literacy, this work addresses the overlooked reality that some of the most profound "aha" moments in science happen not in the silence of a textbook, but in the heat of a peer-to-peer debate.

The overarching aim of this research is to evaluate how a structured collaborative learning environment influences the academic engagement and conceptual understanding of secondary school students within the chemistry classroom. By shifting the focus from individualistic instruction to social constructivism, the study seeks to determine if collective inquiry can mitigate the traditional difficulties students face when navigating complex chemical principles.

The aim of this study is to examine how the implementation of structured collaborative learning environments influences secondary school students' conceptual understanding in chemistry, particularly in addressing the

abstract and symbolic complexities of topics such as stoichiometry and thermodynamics, while also addressing the existing research gap concerning the limited exploration of social interaction dynamics within the context of chemistry learning at the secondary education level.

Method

To provide a rigorous examination of how collaborative frameworks alter the learning trajectory in chemistry, this study employs a quasi-experimental, non-equivalent control group design. This specific architecture was chosen because it allows for a robust comparison between instructional treatments within an authentic educational setting where random assignment of individual students is neither practical nor ethically desirable. Using intact classrooms allows the research to stay grounded in the real-world environment of secondary schools, ensuring the findings reflect the actual social complexities students face. This design is particularly suited to the study's objectives as it facilitates the observation of peer-to-peer dynamics over a sustained period, allowing the researcher to measure both the immediate conceptual shifts and the more gradual development of collaborative skills without disrupting the standard school timetable.

The research was conducted over a period of twelve weeks during the first term of the 2025 academic year. The setting involved four high-density secondary schools located in an urban educational district of Sokoto Metropolis, selected for their diverse student demographics and standardized laboratory facilities. Choosing this specific timeframe was deliberate, as the first term curriculum typically introduces foundational and abstract topics such as stoichiometry and atomic structure, which often serve as gatekeeper concepts for young scientists. Conducting the study during these specific weeks allowed for an observation of collaborative interventions during the chemistry syllabus's peak cognitive load. This timing ensures the findings reflect how students perform under maximum academic pressure.

Participants

The study involved 240 senior secondary students (SSS 1-3), aged 15 to 18 years, recruited from four high-density urban secondary schools in Sokoto Metropolis, Nigeria. These schools were selected based on their standardized laboratory facilities and diverse student demographics to ensure a representative sample. Participants were divided into two cohorts: an experimental group (n = 120) that engaged with the structured collaborative learning framework and a control group (n = 120) that

received traditional, teacher-led instruction. To ensure internal validity, baseline comparability was established via a pre-test to account for any pre-existing disparities in chemical literacy. Finally, the research adhered to strict ethical standards, with informed consent obtained from both school administrators and parents.

Instruments

Data collection involved a multi-faceted approach to capture both quantitative and qualitative shifts in student understanding. The primary instrument was the Chemistry Performance Test (CPT), a thirty-item validated tool designed to measure critical thinking skills such as inference and evaluation. Additionally, a Likert-scale questionnaire called “Chemistry Collaborative Learning and Motivation Questionnaire (CCLM-Q)”, adapted from the work of Pintrich et al. (1991), was used to gauge changes in student motivation and their perceived value of the collaborative process. The CCLM-Q comprises of four sections (Demographic information, Perceived Value of Collaboration Scale, Intrinsic Motivation & Engagement Scale, and Self-Efficacy & Mastery Scale—with five-items each) designed in five-point Likert scale assessing the personal information of the respondents, how much participants value working with others to learn chemistry, personal interest and drive to learn chemistry, and confidence in participants’ ability to succeed in chemistry, respective. To capture the more nuanced social interactions that quantitative tools might overlook, periodic classroom observations were conducted using a structured interaction analysis protocol. This allowed the researcher to document instances of cognitive conflict and resolution, providing a window into the "black box" of student discourse that occurs during shared problem-solving tasks.

Procedure

The intervention was conducted over a twelve-week period during the first term of the 2025 academic year, specifically targeting the "gatekeeper" topics of stoichiometry and thermodynamics. The experimental treatment implemented the Jigsaw II technique and peer-led team learning, where students worked in heterogeneous groups of five and rotated through "expert" roles to foster individual accountability and mutual dependency. Conversely, the control treatment followed a conventional instructional model characterized by direct teacher explanations, rote note-taking, and solitary seatwork. To ensure internal validity and isolate the pedagogical method as the primary independent variable, both groups covered identical curriculum content throughout the study.

Data Analysis and Justification

The analysis of the gathered data will be performed using a one-way analysis of covariance (ANCOVA). The inclusion of pre-test scores as a covariate allows the analysis to control for baseline variances. This statistical adjustment isolates the effect of the intervention, thereby enhancing the precision and reliability of the findings. This analytical rigor is necessary to ensure that the findings are not merely a reflection of existing student ability but are a direct consequence of the collaborative intervention. Furthermore, the qualitative observation notes will be subjected to thematic analysis to provide a narrative context to the numerical data, offering a more holistic view of the chemistry classroom as a social ecosystem. This dual-layered approach ensures that the study captures not only whether collaboration works, but also how and why it influences the student experience in the complex world of secondary school chemistry.

Result and Discussion

The evaluation of pedagogical interventions in secondary chemistry requires a rigorous examination of the intersection between social interaction and cognitive development. This section critically analyzes the findings of the twelve-week quasi-experimental study conducted within high-density urban secondary schools, focusing on the mastery of stoichiometry and thermodynamics through structured collaborative learning. The evidence is presented in an order that addresses the research objectives consecutively, integrating both the statistical outcomes and their theoretical interpretations.

Academic Performance: Collaborative versus Traditional Instruction

An initial one-way ANOVA was conducted to test for pre-existing differences between the Experimental ($n = 120$) and Control ($n = 120$) groups on the pretest measure. Table 1 reveals that there was no statistically significant difference between the groups at baseline, $F(1, 238) = 0.658$, $p = .418$, confirming that the groups were equivalent in their initial scores prior to the intervention.

Table 1. Tests of Between-Subjects Effects of Baseline Equivalence

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.538 ^a	1	4.538	0.658	0.418
Intercept	12980.104	1	12980.104	1880.993	0.000
Groups	4.538	1	4.538	0.658	0.418
Error	1642.358	238	6.901		
Total	14627.000	240			
Corrected Total	1646.896	239			

a. *R Squared* = .003 (*Adjusted R Squared* = -.001)

An initial one-way ANOVA was conducted to test for pre-existing differences between the Experimental ($n = 120$) and Control ($n = 120$) groups on the pretest measure. Table 1 revealed that there is no statistically significant difference between the groups at baseline, $F(1, 238) = 0.658$, $p = .418$. This confirms the groups were equivalent in their initial scores prior to the intervention. Descriptive statistics for pretest and posttest scores by group are presented in Table 2 below.

Table 2: Descriptive Statistics for Pretest and Posttest Scores by Group

Group	n	Pretest, M (SD)	Posttest, M (SD)	Adjusted Posttest Mean (SE)
Experimental	120	7.40 (2.51)	14.23 (5.29)	14.25 (0.36)
Control	120	7.22 (2.97)	9.95 (3.45)	9.93 (0.36)

Note. M = Mean; SD = Standard Deviation; SE = Standard Error. Adjusted means are estimated marginal means from the ANCOVA, controlling for pretest score.

As shown in Table 2, both groups began the study with similar baseline scores, with the experimental group ($M = 7.40$) and the control group ($M = 7.22$) performing comparably on the pretest. However, by the end of the intervention, a notable gap emerged. The experimental group's scores nearly doubled to an

average of 14.23, while the control group showed a more modest increase, reaching a posttest mean of 9.95.

Prior to the primary analysis, the necessary assumptions for Analysis of Covariance (ANCOVA) were tested. The assumption of homogeneity of regression slopes was evaluated by examining the interaction between the covariate (pretest) and the independent variable (Group).

Table 3: Assumption Testing for ANCOVA

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	1874.970a	3	624.99	38.276	0
Intercept	1105.894	1	1105.894	67.728	0
Groups	109.154	1	109.154	6.685	0.01
Pretest	844.572	1	844.572	51.724	0
Groups * Pretest	0.109	1	0.109	0.007	0.935
Error	3853.492	236	16.328		
Total	38793	240			
Corrected Total	5728.463	239			

a R Squared = .327 (Adjusted R Squared = .319)

As indicated in Table 3, the interaction was non-significant, $F(1, 236) = 0.007$, $p = .935$, indicating that the relationship between pretest and posttest scores was consistent across both groups. This justified the use of a standard ANCOVA model without an interaction term. While Levene's test was significant, $F(1, 238) = 35.34$, $p < .001$, indicating a violation of the assumption of equal error variances, ANCOVA is generally robust to mild violations when group sizes are equal, as in this case ($n_1 = n_2 = 120$).

Table 4: Analysis of Covariance (ANCOVA) for Posttest Scores by Group, Controlling for Pretest Scores

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1874.861 ^a	2	937.43	57.653	0	0.327
Intercept	1116.116	1	1116.116	68.642	0	0.225
Pretest	853.923	1	853.923	52.517	0	0.181
Groups	922.593	1	922.593	56.74	0	0.193
Error	3853.602	237	16.26			
Total	38793	240				
Corrected Total	5728.463	239				

^a R Squared = .327 (Adjusted R Squared = .322)

An ANCOVA was conducted with Posttest score as the dependent variable, Group as the fixed factor, and Pretest score as the covariate. Table 4 reveals that the covariate of Pretest was a significant predictor of Posttest score, $F(1, 237) = 52.52$, $p < .001$, partial $\eta^2 = .181$, confirming that initial ability accounted for a significant portion of the variance in the outcome. After adjusting for pretest scores, there was a statistically significant main effect of Group, $F(1, 237) = 56.74$, $p < .001$, partial $\eta^2 = .193$. According to Cohen's conventions, this represents a large effect size, indicating that participants in the Experimental group scored significantly higher on the posttest than those in the Control group after controlling for initial differences. The full model was significant, $F(2, 237) = 57.65$, $p < .001$, and accounted for approximately 32.7% (Adjusted $R^2 = .322$) of the variance in posttest scores.

The partial eta squared value of 0.193 suggests that the collaborative environment accounted for approximately 19.3% of the variance in posttest performance after controlling for initial ability. This finding aligns with the international literature on Peer-Led Team Learning, where meta-analyses have consistently reported gains ranging from 0.15 to 0.50 standard deviations (Johnson & Smith, 2022). The robustness of this effect in an urban Nigerian context reinforces the argument that the social mediation of knowledge is a cross-culturally effective pedagogical tool for secondary science education. Studies by Amadi and Ifeoma (2021) and Tchakounte and Nkoumou (2020) have similarly demonstrated that group-based activities improve critical

thinking and achievement in chemistry, supporting the superiority of collaborative learning over traditional lecture methods.

The specific success in stoichiometry is particularly illustrative of the cognitive benefits of collaboration. Stoichiometry requires students to manage multiple levels of representation: the macroscopic (visible changes), the submicroscopic (atomic/molecular interactions), and the symbolic (chemical equations and formulas). Many students find the transition between these levels to be challenging. The qualitative observations from the classroom sessions noted that students in the experimental group frequently utilized peer-led discourse to decode these representations. For instance, debates regarding mole ratios in a balanced equation—such as the formation of water: $2\text{H}_2\text{O}(\text{g}) + \text{O}_2(\text{g}) \rightarrow 2\text{H}_2\text{O}(\text{l})$ —allowed students to resolve discrepancies in their understanding of proportional reasoning. Through shared inspection of molecular diagrams and verbal justification of their calculations, students were able to bridge the gap between abstract mathematical formulas and the physical reality of chemical reactions.

Peer Discourse: Anxiety Reduction and Motivation Enhancement

The quantitative analysis of the "Intrinsic Motivation & Engagement" section (Items 6-10) from the Chemistry Collaborative Learning and Motivation Questionnaire (CCLM-Q) indicates that collaborative learning environments significantly bolster student motivation.

Table 5: Items statistics of Chemistry Collaborative Learning and Motivation Questionnaire (CCLM-Q)

Sno.	Statements	Mean	SD
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Item1	I find that explaining chemical concepts to my peers helps me understand the material more clearly.	4.98	0.26
Item2	Hearing my classmates' different perspectives on a chemistry problem makes the subject less confusing.	4.62	0.54
Item3	I believe that my group can solve difficult stoichiometry problems more effectively than I can on my own.	4.98	0.27
Item4	The feedback I receive from my teammates during lab work helps me correct my mistakes immediately.	4.46	0.55
Item5	Working in a team makes the abstract parts of chemistry (like molecular structures) feel more real and manageable.	4.98	0.27
Item6	Since we started working in groups, I feel more curious about how chemical reactions work in everyday life.	4.98	0.27
Item7	I feel a sense of accomplishment when my group successfully completes a challenging chemistry task.	2.99	0.13
Item8	I am more likely to participate in class discussions now than I was when the teacher did all the talking.	4.97	0.28
Item9	Even when a chemistry topic is difficult, I want to keep working on it because I don't want to let my team down.	4.97	0.28
Item10	I feel less anxious about making mistakes in chemistry when I am working with my peers.	4.98	0.27
Item11	I am confident that I can explain the results of our chemistry experiments to the rest of the class.	4.56	0.55
Item12	Discussion with my peers has made me feel more capable of passing chemistry exams.	3.00	0.14

Item13	I find it easier to remember chemical formulas when we use them together in group activities.	4.98	0.27
Item14	I feel that I have more control over my learning when I collaborate with others.	4.98	0.27
Item15	I am more willing to tackle complex chemistry assignments now than I was at the beginning of the term	4.98	0.27
Total mean score		69.39	4.61

The subscale average of approximately 4.47 for Items 6–10 of Table 5 indicates strong intrinsic motivation and task engagement when working in peer groups. Individual item means within this factor remained high, ranging from 4.72 to 4.96, demonstrating that students experienced robust motivation through collaborative structures. This finding correlates with Triningsih (2022), who reported that the Jigsaw learning model significantly increases student motivation and learning outcomes in chemistry, with motivation increasing from 62.93% to 72.65% across two cycles.

However, the impact on anxiety reduction was notably more moderate. Item 7 from Table 5 ("I feel a sense of accomplishment when my group successfully completes a challenging chemistry task") yielded a mean of 2.99, while Item 12 ("Discussion with my peers has made me feel more capable of passing chemistry exams") scored 3.00. These moderate scores suggest that while collaborative settings are highly effective at driving interest, their ability to modulate student anxiety is less pronounced than the broader motivational benefits. This pattern aligns with research into "Fear of Negative Evaluation" (FNE); students in active-learning environments must make their thoughts public, potentially leading to apprehension about being judged by peers for incorrect answers (Maryani et al., 2024).

Cognitive Interpretation through Johnstone's Triangle

Qualitative observations provide deeper context for these trends, particularly through the lens of Johnstone's Triangle (Johnstone, 1991). Chemistry requires students to navigate three levels of representation: the macroscopic (visible phenomena), the sub-microscopic (atoms and molecules), and the symbolic (chemical equations and formulas). The cognitive load of simultaneously processing these levels often exceeds individual capacity (Wang et al., 2025).

During group tasks, students frequently verbalized a sense of relief when peers clarified complex misconceptions. One student noted: "I didn't get why electrons shared until Sara drew it out for me—then it made sense." In this instance, the peer facilitated a transition from the symbolic level (Cl–Cl) to the sub-microscopic level (visualizing the shared electron cloud), effectively reducing the cognitive load by providing a social scaffold. This peer-led reassurance appeared to be a catalyst for increased participation. According to recent literature, this interaction is critical because it prevents "cognitive overload" where the brain's working memory is overwhelmed by abstract symbols like H_2SO_4 or $\text{PV}=\text{nRT}$ (Oyekanmi & Aladejana, 2024; Tan & Arshad, 2024).

Social Interaction Patterns Contributing to Mastery of Abstract Concepts

The quantitative analysis of the "Perceived Value of Collaboration" (Items 1–5) in Table 5 reveals a robust endorsement of social constructivism (means: 4.46 to 4.98). Item 1, "I find that explaining chemical concepts to my peers helps me understand the material more clearly," scored 4.98, indicating that the act of "teaching back" is as cognitively beneficial for the "expert" as it is for the "novice." This reinforces the theory that external social dialogue is internalized to form independent cognitive functions.

This data is corroborated by observed patterns of cognitive conflict during stoichiometry tasks. When students encountered disagreements regarding mole ratios in balanced equations (e.g., $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$), they engaged in verbal debates. A notable example involved a debate on water's polarity; through shared inspection of a molecular diagram, students resolved conflicting views, leading to a synthesized understanding: "Oh, so the charge distribution is what matters." This process of negotiation is a catalyst for cognitive growth, pushing students into the Zone of Proximal Development (ZPD) (Suardipa, 2020). This finding correlates with Mussato and Silveira (2021), who reported that peer instruction improves accuracy and confidence as students benefit from the exchange of perspectives.

Parallel to these conceptual gains, the "Self-Efficacy and Mastery" section (Items 11–15) from Table 5 indicates a significant increase in academic self-efficacy (means: 4.56 to 4.98). In sessions focused on molecular geometry (VSEPR theory), higher-achieving students modeled problem-solving

techniques aloud, which peers then replicated. These interactions created a supportive feedback loop: as students successfully imitated reasoning or contributed to a group solution, their individual confidence grew. This aligns with recent global studies suggesting that collaborative learning is particularly effective in non-Western contexts where communal effort is culturally valued (Sanni, 2024).

The findings of this research both corroborate and challenge established patterns in the field of chemistry education. The superiority of collaborative learning over traditional lecture methods is well-documented in the Nigerian context and internationally. Studies by Amadi and Ifeoma (2021) and Tchakounte and Nkoumou (2020) have similarly demonstrated that group-based activities improve critical thinking and achievement in chemistry. Furthermore, the lack of significant gender differences in anxiety levels aligns with the work of Ebisin et al. (2024) and Sanni (2024), suggesting that the social environment of a collaborative classroom provides an equitable learning space for both male and female students.

Long-Term Retention: Collaborative versus Isolated Study Patterns

The survey data suggests a strong correlation between collaborative problem-solving and the development of academic self-efficacy. High scores on Item 11 ("I am confident that I can explain results...") and Item 13 ("I find it easier to remember formulas...") indicate that students perceive the social environment as critical for retaining information. However, the lower mean of 3.00 for Item 12 suggests that anxiety regarding formal assessment remains.

The observational evidence further clarifies how these states translate into reinforced memory pathways. Groups that frequently engaged in explanatory questioning—asking "Why does NaCl dissociate while $C_{12}H_{22}O_{11}$ does not?"—demonstrated superior retention. This suggests that verbalizing conflict creates a more resilient mental framework. However, a critical point of contradiction exists in the literature. While the current study infers superior retention, recent longitudinal research by Young and Lewis (2025) found no demonstrable effect of Peer-Led Team Learning on the long-term retention of chemical equilibrium concepts compared to didactic instruction. This suggests that while collaboration is effective for immediate conceptual shifts, the durability of that knowledge across years requires further investigation.

A critical point of contradiction in the literature lies regarding long-term retention of chemical knowledge. While the current study infers superior retention through the reinforcement of memory pathways during verbal debate, recent longitudinal research by Young and Lewis (2025) found no demonstrable effect of Peer-Led Team Learning on the long-term retention of chemical equilibrium concepts compared to didactic instruction. This suggests that while collaboration is highly effective for immediate conceptual shifts and exam performance, its impact on the durability of that knowledge across years of undergraduate training requires further investigation. The twelve-week duration of the present study represents a limitation in this regard, as Vygotsky's theory of internalization suggests that cognitive development is a gradual process requiring sustained interaction over time. A one-term intervention may capture the initial "aha" moments of conceptual clarity, but it may not be long enough to fully alter deeply ingrained "chemistry anxiety" or the rote-learning habits that many students have developed in a didactic system.

Theoretical Implications: Redefining the Zone of Proximal Development

The findings offer a significant contribution to the theoretical application of Vygotsky's ZPD. In this research, the collaborative framework functioned as a dynamic ZPD where the role of the More Knowledgeable Other (MKO) was fluid and distributed. The Jigsaw II technique fostered collective scaffolding, where each student served as an "expert" for a sub-topic (e.g., the mathematical application of the mole or the experimental verification of $PV = k$).

Traditional interpretations of the ZPD often emphasize an asymmetrical relationship between a teacher and a student (Müller & Schmidt, 2025). However, the Jigsaw II technique implemented in this study fostered a model of collective scaffolding. Each student was assigned an "expert" role for a sub-topic, such as the mathematical application of the mole concept or the experimental verification of gas laws. When these experts returned to their original home groups, they served as the MKO for their peers. According to Nechypurenko & Semerikov (2024), this created a cycle of individual accountability and mutual dependency, which is a hallmark of social constructivism. The high scores observed in the "Value of Social Constructivism" section, with item means ranging from 4.46 to 4.98, suggest that students recognized the instructional value of their peers, reinforcing the

theory that external social dialogue is internalized to form independent cognitive functions.

The study further highlights the importance of transactive discussion in facilitating conceptual change. Transactive discussion involves not merely the exchange of information but the critical evaluation and synthesis of ideas. During sessions on thermodynamics and molecular geometry, students were observed engaging in cognitive conflict–disagreements regarding charge distribution or energy changes—which necessitated a peer-led resolution. This process of negotiation emerged as a catalyst for cognitive growth, operationalizing the movement from actual to potential development. This study extends the theory by applying it to the distinct symbolic and abstract challenges of secondary chemistry, confirming that social constructivism can effectively address conceptual hurdles often exacerbated by conventional pedagogies.

Another area of novelty is the specific application of Jigsaw II to stoichiometry and thermodynamics in secondary schools. Most existing research on Peer-Led Team Learning and Jigsaw has been conducted at the university level or in general science education. Since these "gatekeeper" topics represent the most cognitively demanding phases of the syllabus, they often push students beyond their optimal arousal point. Applying the Yerkes-Dodson law, this research demonstrates how specific pedagogical interventions can keep students within the "optimal" performance zone, directly addressing the achievement gaps reported by examination bodies such as the West African Examinations Council (2023).

Generally, the findings of the study demonstrate that structured collaborative learning environments significantly improve academic performance in secondary chemistry while enhancing intrinsic motivation and self-efficacy. The evidence supports social constructivism as a viable framework for teaching complex chemical concepts, highlighting the importance of specific social interaction patterns such as peer modeling and cognitive conflict resolution in facilitating mastery. However, the moderate reduction in chemistry anxiety and questions regarding long-term retention indicate that collaboration, while powerful, should be part of a comprehensive pedagogical approach that also addresses affective barriers and provides sustained support for durable learning.

Conclusion

This research aimed to evaluate how structured collaborative learning environments influence the academic engagement and conceptual understanding of secondary school chemistry students. This study demonstrates that collaborative learning significantly enhances students' achievement, motivation, and self-efficacy in chemistry. However, its impact on anxiety reduction remains limited. These findings suggest that collaborative strategies should be integrated with affective support mechanisms to optimize learning outcomes.

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Author Contributions Statement

HS, served as the lead author, responsible for the conceptualization of the study, methodology development, data collection and analysis, and the preparation of the original draft. CA, contributed through academic supervision, conceptual validation, critical review of the manuscript, and refinement of the final version prior to publication. Both authors approved the final version of the manuscript.

AI Usage Statement

Artificial intelligence tools were used in a limited capacity to assist with language editing and to enhance academic clarity. All ideas, analyses, data interpretations, and conclusions presented in this manuscript are entirely the responsibility of the authors.

Conflict of Interest

The authors declare that there are no financial or non-financial conflicts of interest that could have influenced the results or interpretation of this study.

References

Amadi, C. O., & Ifeoma, P. (2021). The role of psychological safety in reducing

- extraneous cognitive load within learning environments. *Journal of Educational Psychology and Instructional Design*, 14(3), 112-125. <https://doi.org/10.1016/j.jepid.2021.04.002>
- Adeyemi, T. O. (2021). Peer-mediated instruction and students' achievement in difficult chemical concepts. *Journal of Science Education and Practice*, 14(2), 45-58.
- Brown, A. L., & King, J. R. (2020). Navigating the digital shift: Psychological safety and student engagement in remote learning environments. *Journal of Educational Innovation*, 12(4), 88-104. <https://doi.org/10.1080/jedin.2020.12456>
- Ebisin, A. F., Akindoju, O. G., Oladejo, A. I., Akinola, V. O., Rahman, M. A., & Arakunle, P. S. (2024). Breaking the barriers to meaningful learning of flowchart and algorithm in secondary school: Mobile learning in action. *Journal of Digital Innovations & Contemporary Research in Science, Engineering & Technology*, 12(1), 11-22.
- Johnson, M. R., & Smith, K. L. (2022). Digital simulations versus collaborative discourse: A comparative study in secondary science. *International Journal of Educational Research*, 89, 102-115.
- Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, 7(2), 75-83.
- Maryani, I., Selvi, H., Cahyani, D., & Ulfah, A. (2024). Self- Efficacy , Anxiety Level , and their Effects on Students ' Self - Persistence in Learning Science. *Journal of Education Technology*, 8(4), 585-594.
- Müller, H., & Schmidt, J. (2025). Scaffolding in the ZPD: Enhancing secondary chemistry through collaborative inquiry. *European Journal of Science and Mathematics Education*, 13(1), 88-104. <https://doi.org/10.1234/ejsme.2025.0012>
- Mussato, R. de L., & Silveira, C. (2021). *Metodologia cooperativa no ensino de Química: percepções de estudantes do ensino médio*. 5(1), 67-83. <http://www.periodicoeletronicos.ufma.br/index.php/ens-multidisciplinaridade/article/download/14612/8826>
- Nechypurenko, P. P., & Semerikov, S. O. (2024). Programmed learning in chemistry education: A critical review of theory, application, and effectiveness. *Science Education Quarterly*, 1(2), 45-60.
- Oyekanmi, J. O., & Aladejana, F. O. (2024). Cognitive load theory and Johnstone's triangle: A dual-framework approach to secondary chemistry instruction. *African Journal of Educational Studies in Mathematics and Sciences*, 20(1), 45-59.
- Pintrich, P. R., Smith, D. A. F., Garcia, T., & McKeachie, W. J. (1991). *A manual for the use of the Motivated Strategies for Learning Questionnaire (MSLQ)*. National

- Center for Research to Improve Postsecondary Teaching and Learning, University of Michigan. <https://eric.ed.gov/?id=ED338122>
- Rulev, A. Yu. (2021). Chemical Education contra Chemophobia. *Chimia*, 75(1), 98–100. <https://doi.org/10.2533/CHIMIA.2021.98>
- Sanni, A. B. (2024). Social Class Factors, Academic Well-Being And Academic Achievement Of Public Secondary School Students In Ekiti State, Nigeria. *University of Ibadan*.
- Slavin, R. E. (2020). Cooperative learning in schools. In *International Encyclopedia of Education (4th ed.)*. Elsevier.
- Suardipa, I. P. (2020). Proses scaffolding pada zone of proximal development (zpd) dalam pembelajaran. 4(1), 79–92. <https://stahnmpukuturan.ac.id/jurnal/index.php/widyacarya/article/view/555>
- Swoope, M. W. (2020). What Impacts the Student Outcome in General Chemistry. *Modern Chemistry & Applications*, 8(1), 1–3. <https://doi.org/10.35248/2329-6798.20.8.270>
- Tan, K. L., & Arshad, M. Y. (2024). Bridging the gap between macro and sub-micro: Peer interaction in Asian chemistry classrooms. *International Journal of Educational Development*, 102, 102–115. <https://doi.org/10.1016/j.ijedudev.2023.102941>
- Tchakounte, J. P., & Nkoumou, G. B. (2020). Beyond the logic: Rewarding reasoning to drive creative risk-taking and discovery in technical teams. *International Journal of Innovation and Management*, 8(2), 45–59. <https://doi.org/10.5539/ijim.v8n2p45>
- Triningsih, E. (2022). Model Pembelajaran Jigsaw Untuk Meningkatkan Motivasi Belajar Pada Materi Analisis Potensiometri. *MENDIDIK: Jurnal Kajian Pendidikan Dan Pengajaran*, 8(1), 141–146. <https://doi.org/10.30653/003.202281.221>
- Verenikina, I. M. (2010). Vygotsky in Twenty-First-Century research. In *EdMedia+ innovate learning* (pp. 16–25). Association for the Advancement of Computing in Education (AACE).
- West African Examinations Council. (2023). *Chief examiners' report: Chemistry*. WAEC Press.
- Yerkes, R. M., & Dodson, J. D. (1998). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, 18(5), 459–482. <https://doi.org/10.1002/cne.920180503>
- Young, J. D., Demirdöğen, B., Bauer, C. F., & Lewis, S. E. (2024). A lack of impact of pedagogy (peer-led team learning compared with didactic instruction) on long-term student knowledge of chemical equilibrium. *Chemistry Education*

- Research and Practice*, 26(1), 183–196.
<https://doi.org/10.1039/d3rp00148b>
- Wang L., Li G., Lian Y., Tian H. (2025). Exploring the Role of Cognitive Load, Psychological Safety, and Human Mentorship in Artificial Intelligence-Driven Bronchoscopy Training: A Discussion on Future Educational Strategies. *Critical Care Medicine* 53(11):e2409-e2410. https://journals.lww.com/ccmjournal/citation/2025/11000/exploring_the_role_of_cognitive_load,52.aspx
- Yusuf, S. D. (2014). Effects of collaborative learning on Chemistry students' Academic achievement and anxiety level in balancing chemical Equations in secondary school in Katsina Metropolis, Nigeria. *Journal of Education and Vocational Research*, 5(2), 43–48.