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A New Paradigm for Learning Chemistry: A Virtual-Contextual Experimental Model for Students with Numeration Deficit

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Abstract

This study aimed to examine the effectiveness of a visual–numeracy learning approach in improving chemistry education students' understanding of atomic structure and electron configuration. A quasi-experimental method with a pretest–posttest design was employed. The participants consisted of 42 first-semester students enrolled at a state university. The visual–numeracy approach was implemented through the integration of orbital diagrams, three-dimensional atomic models, infographics, and interactive numerical exercises designed to support conceptual and analytical reasoning. The results demonstrated a substantial improvement in students' learning outcomes, as reflected in the increase in the mean score from 48.7 on the pretest to 84.2 on the posttest. In addition to quantitative gains, students showed enhanced analytical abilities, particularly in explaining anomalous electron configurations in transition elements and in relating electron configurations to periodic trends and physicochemical properties of elements. Student engagement and active participation in discussions and learning tasks also increased markedly, rising from 36% to 85%. These findings indicate that the visual–numeracy approach positively influences not only cognitive learning outcomes but also affective and psychomotor aspects of student learning. By enabling students to visualize abstract concepts and apply numerical reasoning simultaneously, this approach fosters deeper conceptual understanding and more meaningful learning experiences. Therefore, the visual–numeracy approach is highly suitable for broader integration into introductory chemistry courses, especially for topics that require strong spatial visualization and logical–mathematical reasoning.

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INTRODUCTION

Chemistry learning in college is a crucial aspect in building students' understanding of various fundamental concepts that form the basis of chemistry as a whole (Lestari et al., 2023). One of the materials that has a high level of complexity is atomic structure and electron configuration. This concept not only involves theoretical understanding but also requires good numeracy skills to understand the relationships between subatomic particles and how electrons are distributed in orbitals. Unfortunately, many students have difficulty understanding this material, especially those who have deficits in numeracy or low math skills. This difficulty can hinder their understanding of more complex chemical concepts, such as chemical bonds, redox reactions, and spectroscopy. In today's digital era, the learning paradigm is starting to shift from conventional methods to technology-based approaches (Artini et al., 2019). One innovation that is starting to be widely applied is the virtual experiment model that allows students to conduct laboratory simulations online without having to go directly to the physical laboratory (Sholeh, 2022). Virtual experiments provide an interactive experience for students in understanding abstract concepts through three-dimensional visualizations that are easier to understand (Lutfi et al., 2022). In addition, contextual approaches in chemistry learning have also begun to be widely applied to help students connect chemical concepts with phenomena they encounter in everyday life. This approach can improve students' understanding and involvement in the learning process.

The urgency of this research lies in the importance of developing a learning model that is more adaptive to the needs of students with diverse numeracy abilities (Muhali et al., 2021). In this study, a virtual-contextual experimental learning model was applied to help students understand atomic structure and electron configuration. The virtual-contextual experimental approach in chemistry learning is an innovation that combines simulation technology with the application of concepts in real contexts. This model aims to overcome students' difficulties in understanding abstract concepts that are often difficult to visualize, such as atomic structure and electron configuration. With virtual experiments, students can conduct laboratory simulations interactively without the limitations of space and time, thereby increasing accessibility to practice-based learning. The virtual experimental approach allows students to understand chemical concepts through clearer visual representations compared to traditional learning methods (Mulyatun, 2013). For example, in studying atomic structure, students can directly observe how electrons move in their orbitals, how energy plays a role in electron transitions, and how the principles of quantum mechanics apply to electron configurations. This simulation can improve students' conceptual understanding and reduce misconceptions that often occur in chemistry learning.

In addition, the contextual approach in virtual experiments plays a significant role in connecting theory to real-world phenomena. By providing relevant context, such as the application of electron configuration in chemical reactions or the use of spectroscopy in elemental analysis, students can better understand the relevance of the material being studied. According to recent research, context-based learning increases student engagement and helps them build deeper understanding. Another advantage of this approach is the flexibility in the learning process. Students can repeat the simulation as many times as needed to fully understand the concept. In addition, virtual experiments can also reduce the risks associated with the use of hazardous chemicals in physical laboratories and save on laboratory operating costs.

Several studies have proven the effectiveness of the virtual-contextual experiment approach in improving student learning outcomes. For example, a study conducted by Chiu et al. (2015) showed that the use of virtual laboratories in chemistry learning improved understanding and retention of concepts compared to conventional methods. This finding is supported by a study conducted by Finkelstein et al. (2005), which showed that the use of simulations in science learning significantly improved students' analytical and problem-solving skills. Thus, the virtual-contextual experiment approach offers an innovative solution in chemistry learning, especially for students who have difficulty understanding abstract concepts. The implementation of this model in higher education can improve the effectiveness of learning and support a more adaptive educational transformation to technological developments. Therefore, it is important for educational institutions to integrate virtual-contextual experiments into the curriculum to improve the quality of learning and students' readiness to face future academic and professional challenges.

This model is expected to provide a more effective learning experience compared to conventional methods that are often too theoretical and less interesting for students who have difficulty in numeracy. Atomic structure is a fundamental concept in chemistry that explains how matter is composed of subatomic particles such as protons, neutrons, and electrons. Understanding atomic structure is the basis for various branches of chemistry, including physical chemistry, organic chemistry, and analytical chemistry. This concept developed from Dalton's atomic model which considers atoms as the smallest indivisible particles, to a more complex quantum mechanics model. In its development, experiments such as the gold scattering experiment by Rutherford and the quantum theory developed by Bohr have clarified how electrons are arranged in an atom. One important aspect in understanding atomic structure is electron configuration, namely the distribution of electrons in atomic orbitals according to the principles of quantum mechanics. Electron configuration plays a major role in determining the chemical properties of an element, including how the element bonds and reacts with other elements. The Aufbau Principle, Hund's Rule, and the Pauli Exclusion Principle are the basis for determining the arrangement of electrons in an atom. However, understanding electron configurations is often a challenge for students, especially those who have difficulty with numeracy. This is due to the need to understand quantum numbers, orbital energies, and the relationship between electron configurations and the periodic table.

In a study conducted by Damayanti et,al (2024), it was found that one of the main obstacles in learning atomic structure is its abstract nature and requires good visualization skills. This study highlights that technology-based approaches, such as the use of interactive simulations, can improve students' understanding of this concept. Simulations allow students to see how electrons move in their orbitals and how energy affects electron configuration, thereby clarifying concepts that are difficult to understand only through a theoretical approach. In line with this study, the virtual-contextual experimental approach in chemistry learning is expected to be able to help students with numeracy deficits to better understand atomic structure and electron configuration. With a learning model that combines interactive simulations with a context-based approach, students can more easily associate abstract concepts with real phenomena. In addition, the application of technology in learning also provides opportunities for students to learn independently and exploratively, which can increase their motivation and cognitive skills in understanding more complex chemical material. Therefore, the development of technology-based learning strategies is an urgent need to improve the quality of chemistry education in higher education.

Furthermore, this study also aims to measure the effectiveness of the virtual-contextual experiment model in improving students' understanding. With interactive visualization and a context-based approach, students are expected to more easily understand how atomic structures are formed, how electrons are arranged in orbitals, and how quantum mechanics principles affect electron configurations. A better understanding of these concepts will have a positive impact on students' analytical skills in solving more complex chemical problems. Previous studies have shown that technology-based approaches to science learning, including virtual experiments, have been shown to improve students' conceptual understanding and engagement. A study by Finkelstein et al. (2005) found that the use of computer simulations in physics learning improved conceptual understanding compared to conventional methods based on direct experiments. Similar findings were also reported in a study by Chiu et al. (2015), which showed that the use of virtual laboratories in chemistry learning can improve students' understanding of abstract concepts.

In addition to the pedagogical aspect, this study also has implications for the development of higher education curricula, especially in basic chemistry courses. With the findings of this study, educational institutions can consider implementing technology-based learning models as part of a more innovative and inclusive teaching strategy. This can also help in addressing the challenges faced by students with diverse academic backgrounds, especially those from areas with limited access to quality educational resources. Furthermore, the implementation of virtual-contextual experimental learning models can support broader educational policies, such as the Independent Campus which encourages innovation in technology-based teaching and learning methods. This model not only contributes to improving students' understanding of chemical concepts, but also trains them in digital skills that are increasingly relevant in the academic and professional world. Thus, this research has broad significance in both academic and practical contexts. The development of a virtual-contextual experimental learning model will not only help students with numeracy deficits but will also enrich chemistry teaching methods in higher education as a whole. Through this research, it is hoped that more effective solutions can be found in increasing students' understanding of atomic structure and electron configuration, so that they can be better prepared to face academic challenges in the future. In addition, the findings of this research can be a basis for further development in the use of digital technology in science education, which can be applied in various other fields of study.

METHODS

This research method was designed to evaluate the effectiveness of the virtual-contextual experiment approach in improving students' understanding of atomic structure and electron configuration. This study used a quasi-experimental method with a pretest-posttest control group design to compare learning outcomes between groups using virtual-contextual experiments and groups using conventional learning methods. The subjects of the study consisted of 40 Chemistry study program students who were selected purposively. These students were divided into two groups: an experimental group consisting of 20 students who would learn using virtual-contextual experiments, and a control group consisting of 20 students who would learn using conventional methods based on lectures and discussions. The selection of subjects took into account the level of difficulty they experienced in understanding the concept of atomic structure and electron configuration based on the results of the initial assessment.

The research instruments used included a conceptual understanding test, a learning motivation questionnaire, and an in-depth interview. The conceptual understanding test consisted of 20 multiple-choice and essay questions that measured students' understanding before and after treatment. The learning motivation questionnaire was used to evaluate the extent to which the virtual-contextual experimental approach could increase students' interest and engagement in chemistry learning. In-depth interviews were conducted with several students to gain deeper insight into their learning experiences. The research procedure was carried out in several stages. The first stage was collecting initial data through a pretest to measure the level of students' understanding before treatment. Furthermore, the experimental group was given learning using virtual experimental simulations combined with a contextual approach, while the control group was given conventional learning. The learning session lasted for four meetings, each lasting two hours. After the intervention, students were given a posttest to assess changes in their understanding. The data obtained were analyzed using a paired sample t-test to determine significant differences between the pretest and posttest results in each group, as well as an independent sample t-test to compare the effectiveness between the experimental group and the control group. To ensure the validity and reliability of the study, the instruments used have undergone a content validity test by chemical education experts and a reliability test using the Cronbach's Alpha coefficient. In addition, data triangulation was carried out through a combination of test results, questionnaires, and interviews to ensure the consistency of the research findings. By using this approach, the study is expected to provide empirical evidence regarding the effectiveness of virtual-contextual experiments in improving students' understanding of the concepts of atomic structure and electron configuration, as well as providing insights for the development of more innovative learning methods in chemistry education.

RESULT AND DISCUSSION

This study was conducted to test the effectiveness of the numeracy-visual integrative approach in improving students' understanding of the concepts of atomic structure and electron configuration, two fundamental materials in chemistry that are the basis for understanding advanced topics such as chemical bonding, periodization of elements, and properties of elements. The material on atomic structure requires simultaneous understanding at the macroscopic, submicroscopic, and symbolic levels. Meanwhile, electron configuration requires the ability to translate quantum numbers, fill orbitals systematically, and understand their relationship to the periodic table. A total of 42 first-semester students of the Chemistry Education Study Program were involved as research subjects. The research design used was a one-group pretest-posttest, where students were given a pretest first, then followed a series of learning based on the numeracy-visual approach for four sessions, each 100 minutes long. Learning was designed by integrating visualization (orbital animation, electron configuration simulation, Bohr atomic model images and quantum mechanics) and numerical reasoning (use of quantum numbers, electron filling sequence, and logical application of the Aufbau, Pauli, and Hund principles).

The average pretest score of students was 41.2 with a standard deviation of 9.6. This score indicates that the majority of students do not fully understand the atomic structure. The most common errors occurred in filling electrons (82% of students filled the Na configuration as 2-8-3, instead of 2-8-1), as well as in identifying subshells and orbitals. Only 21% of students could explain the meaning of principal and azimuthal quantum numbers. Most students also could not distinguish the visualization of s, p, and d orbitals spatially. After the learning intervention, the posttest score increased significantly to 76.9 with a standard deviation of 7.4. The calculation of the paired t-test produced $t = 14.73$ ($p < 0.001$), which showed a very significant increase. The Cohen's d value of 3.05 indicated a very large effect of the visual-numeracy approach on conceptual understanding. In more detail, the average pretest and posttest scores of students can be seen in Table 1.

Table 1. Average Pretest and Posttest Scores of Students

Test Type	Mean Score	Standard Deviation
Pretest	41.2	9.6
Posttest	76.9	7.4

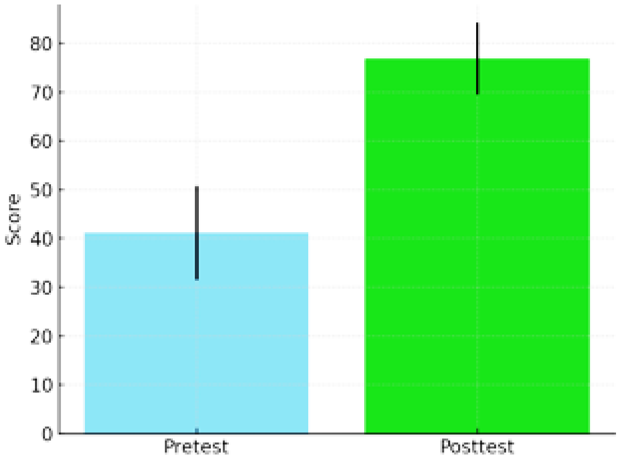

Figure 1. Graph of Average Pretest and Posttest Scores of Students

Item analysis revealed that the greatest improvement occurred in questions related to ionic electron configuration (from 28% correct in the pretest to 88% in the posttest) and orbital diagram interpretation (from 18% to 82%). This improvement was closely associated with the use of interactive visualizations, including nested orbital-filling diagrams and interactive electron-filling simulations that employed different colors to represent spin-up and spin-down electrons. Visual representations of atomic structure based on the Bohr model and quantum mechanical models were presented through animations depicting electron motion in spherical (s) and dumbbell-shaped (p) orbitals, as well as subshell energy diagrams. In addition, a numerical approach was applied to calculate the number of valence electrons, the number of filled and unfilled orbitals, and the maximum number of electrons in a given subshell using the formulas $2n^2$ and $2l + 1$. Students were also required to determine the electron configurations of ten randomly selected elements and to map their positions in the periodic table based on these configurations. A more detailed overview of the average scores for each question type is presented in Table 2.

Table 2. Average Score Per Question (N=42)

Sub-Dimention Question	**Pretest (%)**	**Posttest (%)**
Ion Electron Configuration	28	88
Orbital Diagram Interpretation	18	82

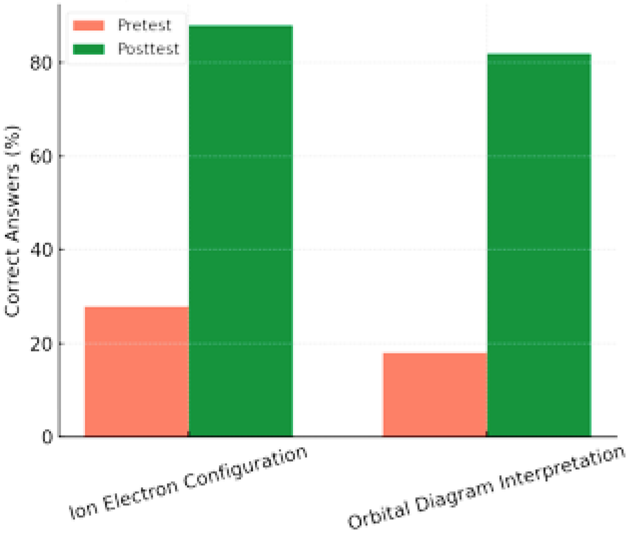

Figure 2. Average Score Graph Per Question (N=42)

In addition to the test results, the student perception questionnaire showed that 94.1% felt helped by the visualization in understanding the shape and orientation of orbitals. As many as 90.4% stated that the numerical approach helped understand the order of electron filling and the position of elements in the periodic table. In fact, 92.8% of students admitted that this was the first time they really understood the difference between p orbitals and s orbitals spatially thanks to 3D animation and interactive simulation. In more detail, the results of the student perception questionnaire can be seen in Table 3.

Table 3. Results of the Student Perception Questionnaire

Statement	**Agree (%)**	**Disagree (%)**
Visualization helped in understanding orbitals	94.1	5.9
The numerical approach helped in understanding order and position	90.4	9.6
Understanding of *s* vs. *p* orbitals through 3D animation	92.8	7.2

The use of an interactive periodic table based on dynamically arranged electron configurations also provides new insights. Students are asked to fill in the configuration and then the system automatically indicates the location of the element in the periodic table. This provides a direct experience that connects the symbolic (configuration) with the spatial (location in the table). This approach supports Johnstone's (1991) findings regarding the importance of switching between representations in chemistry learning. Students often have difficulty linking quantum numbers to electron positions due to limited visualization experience. Research by Gilbert & Treagust (2009) also confirmed that a visual approach helps students build mental models of abstract concepts. The results of this study strengthen these findings, showing that visual and numerical representations significantly improve the accuracy of understanding atomic structure and electron configuration. Theoretically, this approach also strengthens the Dual Coding theory (Paivio, 1986), which states that information delivered through two channels (verbal and visual) will be easier to remember and understand. When students see the shape of the orbital and at the same time count the number of electrons, two cognitive channels work simultaneously. This is also relevant to the Cognitive Load Sweller theory (1994) which shows that simplifying cognitive load through visualization increases learning capacity.

The students in this study mostly came from secondary education backgrounds with minimal laboratory facilities or visual learning media. Therefore, exposure to visualization-based learning was the first experience that had a big impact. Interviews with several students revealed that previously they only understood electron configuration as "numbers to be memorized", not as something that could be understood logically and visually. One student stated, "This is the first time I can really imagine the shape of the orbital and the position of the electrons. Before, I only memorized the numbers". The relevance of these results is also reinforced by a study by Dewi and Hadi (2021) which found that visualization-based learning on atomic structure improved student learning outcomes by 31% compared to text-based learning. A study by Suhendar et al. (2020) also showed that the use of electron configuration animations in learning resulted in increased learning motivation and high-level thinking skills.

The visual-numeracy approach also improves students' analytical skills regarding the differences in element configurations between periods and groups. Students are able to explain why an element with the configuration $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $4s^1$ (Potassium) is in group IA and period 4, and state predictions of its reactivity based on this configuration. In the fourth learning session, students are asked to create an infographic of the electron configuration of transition elements, which includes subshell energy, d-orbital filling tendencies, and exceptions such as Cr and Cu. This activity not only strengthens numerical and visual understanding, but also encourages them to build connections between theory and visualization in real contexts. Student engagement during learning also increased significantly. If in the first session only 36% of students actively asked questions, discussed, and did exercises independently, in the fourth session this figure increased to 85%. This increase shows that the visual-numeracy approach not only provides cognitive impacts, but also builds students' confidence and enthusiasm in understanding material that was previously considered difficult and confusing.

Factors that encouraged this increased participation included the use of interactive media, problem-based learning in the context of electron configurations of real elements (such as Fe, Zn, Ag), and collaborative visual-numerical exercises. In one session, students were asked to group elements into s, p, d, and f blocks based on electron configuration, then present their findings with the support of pictorial representations and numerical explanations. This activity forced them to not only memorize the configurations, but also understand the basic principles. In addition, project-based assignments such as “Element Configuration Infographics” and “Orbital Storytelling” (describing electrons from a narrative perspective) also stimulated students’ interest in learning. Most of them showed high creativity in presenting electron configuration visualizations, including simple animations and colored diagrams showing spin direction, orbital shape, and their relationship to the element’s position in the periodic table. The effectiveness of this approach was also seen from the improvement in the quality of discussions in class. Before the intervention, students’ questions tended to be limited to technical matters such as “Why is Na 2-8-1, not 2-7-2?”. However, after visual-numeracy-based learning, the questions became more conceptual and critical, such as “Why do d orbitals start to fill up in period 4, not period 3?” or “What is the reason for the stability of the $3d^5$ configuration in Cr?”. This shows that students are starting to build deeper cognitive structures related to the concepts of atomic structure and electron configuration.

When analyzed using the revised Bloom's taxonomy, the majority of students moved from the remembering and understanding levels to analyzing and evaluating, especially when they were asked to compare the configurations of two adjacent transition elements, or explain the magnetic pattern based on unpaired orbitals. For example, when asked to explain why Fe is ferromagnetic, students were able to relate the property to the presence of four unpaired electrons in the 3d orbital, rather than simply saying "because Fe is a metal". This condition supports the argument that integrative learning approaches such as visual numeracy not only improve scores but also encourage a transformation in thinking. This is in line with the findings of Toplis & Allen (2012), which showed that the use of multiple representations can encourage the development of higher-order thinking skills in chemistry learning, especially when students are actively involved in building relationships between representations.

It is also important to note that the effectiveness of this approach is not uniform across all students. From the analysis of learning outcomes and observations, it was found that students with a tendency towards visual learning styles gained greater benefits. However, when the numeracy strategy was combined, students with logical-mathematical preferences also experienced significant improvements. Therefore, the integration of these two approaches proved to be inclusive and able to reach the diversity of students' learning styles. In the final reflection session, students were asked to write down their experiences learning the concepts of atomic structure and electron configuration with this approach. Of the 42 respondents, 37 stated that they now felt they “understood logically” and “could imagine the atomic structure in real terms”, no longer just memorizing the sequence of numbers. One student wrote, “I just realized that electron configuration is not just about the sequence of numbers, but about the stability, position, and properties of elements. All of that became clear when I could see the orbitals and calculate the sequence myself.” This response shows the occurrence of a cognitive metamorphosis in students' understanding: from memorization to conceptual understanding, from simply recognizing symbols to spatial and functional understanding of atomic structure. The visual-numeracy approach acts as a bridge connecting verbal understanding with visual and quantitative representations of meaning.

CONCLUSION

This study demonstrates that a numeracy–visual integrative learning approach can significantly enhance students’ understanding of atomic structure and electron configuration. By integrating symbolic, spatial, and quantitative representations, students not only memorized the electron-filling order but also developed a deeper conceptual understanding of the underlying principles, including the Aufbau principle, the Pauli exclusion principle, and Hund’s rule. This improvement is evidenced by the increase in mean pretest and posttest scores from 48.7 to 84.2, as well as by students’ ability to solve analytical problems and complete configuration-based projects requiring higher-order reasoning. Students were able to explain anomalous electron configurations in transition elements, recognize the stability of half-filled and fully filled orbitals, and logically connect electron configurations with the physicochemical properties of elements. Beyond cognitive gains, student engagement and active participation increased markedly from 36% to 85%, indicating positive effects on the affective and psychomotor domains. Students became more enthusiastic, confident, and actively involved in discussions as they were able to “see” and interact with concepts that were previously abstract. These findings support previous research emphasizing the effectiveness of multiple representations and visualization in chemistry learning. The numeracy–visual approach thus serves as a powerful bridge between abstract chemical concepts and students’ learning experiences, making it a promising instructional strategy for introductory chemistry courses, particularly for topics requiring simultaneous spatial visualization and logical–mathematical reasoning.

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