

HoloChemAR: An Augmented Reality Application for Chemistry Education

Georgiana Matcovici

Faculty of Computer Science,
Alexandru Ioan Cuza University
Iasi, Romania

georgiana.matcovici@uaic.ro

Gabriel Constantinescu

Faculty of Computer Science,
Alexandru Ioan Cuza University
Iasi, Romania

georgeconstantinescu@gmail.com

Adrian Iftene

Faculty of Computer Science,
Alexandru Ioan Cuza University
Iasi, Romania

adiftene@info.uaic.ro

ABSTRACT

Teaching chemistry is challenging because many concepts involve invisible molecular structures and laboratory experiments that require specialized equipment, time, and supervision. Mixed reality can address these limitations by combining immersive visualization with interactive learning. This paper presents HoloChemAR, a HoloLens 2 application designed to support chemistry education through virtual laboratory experiments and interactive molecular construction. The application enables students to perform guided chemical reactions, visualize molecules in three dimensions, build compounds using natural hand and eye interactions, receive voice guidance, and consult an AI-based chemistry assistant. HoloChemAR was implemented in Unity using MRTK, Azure Speech Services, and a Groq-based AI backend. The system was evaluated with 25 participants of different educational backgrounds, assessing usability and perceived usefulness. The results indicate high user satisfaction and positive feedback regarding interaction, learning support, and engagement, suggesting that mixed reality can provide an effective complement to traditional chemistry education.

AUTHOR KEYWORDS

Augmented Reality; Chemistry Education; User-System Interaction; HoloLens 2; Natural Interaction; Human-Computer Interaction.

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INTRODUCTION

E-learning has become an essential component of modern education, enabling the delivery of educational content through digital technologies and online platforms [14]. The widespread adoption of digital learning environments has significantly improved access to scientific knowledge while providing greater flexibility for both students and educators. A comprehensive meta-analysis conducted by the U.S. Department of Education reported that students using digital learning resources generally achieved slightly better learning outcomes than those relying exclusively on traditional face-to-face instruction [9]. The benefits are particularly relevant when digital resources complement conventional classroom teaching. Among emerging educational technologies, Mixed Reality (MR) and Augmented Reality (AR) have attracted increasing attention because they seamlessly integrate virtual objects into the physical environment while preserving real-world awareness and physical social interaction [1, 3, 8]. Unlike Virtual Reality (VR), which completely isolates the student from their surroundings, AR maintains full situational awareness—a critical aspect in classroom settings where teacher-student and

peer-to-peer collaboration is essential [13]. Furthermore, AR allows physical laboratory equipment to be augmented with contextual real-time data and molecular structures, bridging abstract theoretical chemistry with physical reality [4–6].

MR is especially relevant to chemistry because many concepts concern structures and processes that cannot be directly observed. Atoms, bonds, molecular geometry, and reactions can be represented as interactive three-dimensional objects, allowing learners to inspect them from different viewpoints and manipulate them directly. Virtual laboratory activities can additionally reproduce selected experimental steps without requiring the same equipment, preparation time, or supervision as a physical laboratory. Recent immersive-learning studies indicate that the value of VR and MR can extend beyond knowledge acquisition to learner engagement and the overall learning experience. This supports the use of MR as a complementary educational medium in which visualization and active interaction reinforce theoretical explanations.

The Microsoft HoloLens 2 [2, 11, 12] serves as an optimal hardware foundation for exploring natural user-system interaction in AR. With low-latency hand tracking and eye tracking, users can interact with 3D holograms using intuitive micro-gestures (e.g., pinching, grabbing) and gaze selection. Motivated by these interaction capabilities, this paper presents HoloChemAR, an interactive AR application designed for chemistry education. The focus of this work lies in mapping design decisions to interaction modalities—specifically direct hand manipulation, eye-gaze targeting, and conversational AI guidance—to lower the cognitive load associated with learning spatial chemistry concepts.

The HoloChemAR application combines guided chemical reactions, interactive molecular construction, challenge-based practice, voice instructions, and an AI-based chemistry assistant. This combination is intended to connect theoretical understanding with practical experimentation and active problem solving in a single environment.

RELATED WORK & INTERACTION DESIGN COMPARISON

Multiple platforms have explored digital tools for STEM and chemistry education, each presenting distinct interaction paradigms:

- **MEL Science / MEL VR** [10]: Utilizes smartphone-based VR (Google Cardboard). While accessible, it lacks spatial awareness and natural input, relying on head-gaze or external clickers. Furthermore, VR molecular construction modules often fail to provide real-time validation or tactile spatial feedback.
- **Futuclass Education** [7]: Offers immersive VR gamified escape rooms. While engaging, full VR isolation

limits classroom integration and real-world instructor interaction. Its chemistry activities illustrate the potential of gamification and level-based learning.

- **Vic's Science Studio** [16]: Provides a virtual lab environment for desktop or VR, focusing primarily on simulating liquid mixing rather than direct spatial manipulation of molecular structures. It nevertheless demonstrates the value of safe virtual experimentation.
- **ARChem** [15]: A handheld AR application for smartphones. It provides quick 3D previews but constrains user interactions to a 2D touch screen, missing 3D spatial direct manipulation. It also includes quizzes covering molecular chemistry concepts.
- **VirtualChemLabs** [17]: A web-based 2D simulation platform lacking spatial depth and immersive affordances. Its browser-based approach provides accessibility but not direct manipulation of virtual chemical entities.

Unlike existing solutions, HoloChemAR leverages hand-tracking and eye-tracking on a head-mounted AR display to allow direct 6-DOF (Degrees of Freedom) manipulation of chemical entities while maintaining full awareness of the physical learning environment. It also combines visual, textual, auditory, and conversational feedback in the same learning workflow.

SYSTEM ARCHITECTURE AND INTERACTION DESIGN

HoloChemAR was developed in Unity using the Mixed Reality Toolkit (MRTK). The application architecture connects local holographic interface elements with cloud-based intelligence services (Figure 1). The local application manages rendering, spatial interaction, laboratory logic, and compound validation, while Azure Speech Services and the Groq-based AI backend provide speech and conversational capabilities.

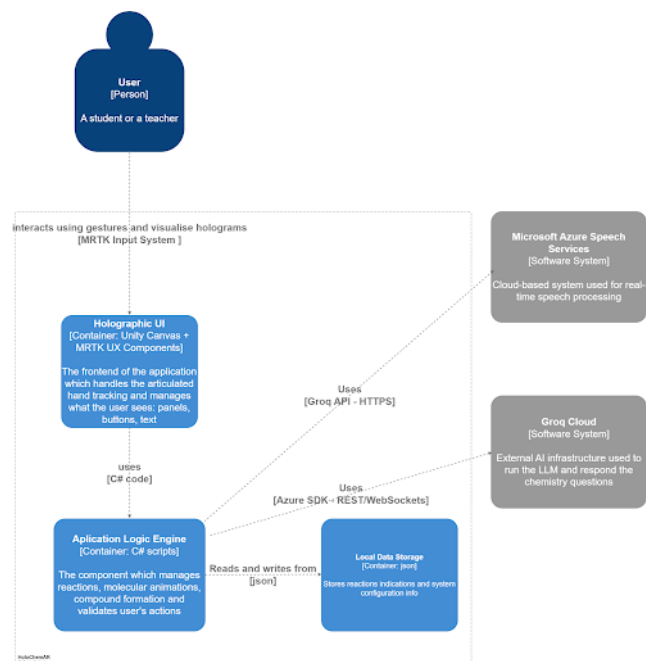


Figure 1: Container Diagram and System Architecture for HoloChemAR, showing interactions between the Holographic UI, Logic Engine, Azure Speech, and Groq AI Agent.

The Holographic UI manages the 3D interface, hand and eye tracking, and spatial anchoring. The Logic Engine contains C# scripts responsible for reaction logic, laboratory instruments, collisions, atom interactions, and compound validation. A local JSON data source stores reaction-specific textual instructions, keeping instructional content separate from the main application logic.

Interaction Specificities: Hand and Eye Interaction

To ensure intuitive user-system interaction, HoloChemAR integrates multi-modal input mechanism:

- **Eye Gaze Targeting:** Eye tracking is utilized for rapid object selection and UI panel activation without requiring physical reach, reducing fatigue during long learning sessions.
- **Direct Hand Manipulation:** Users can perform natural grabbing, pinching, and scaling gestures on virtual chemical apparatus and individual atoms. Proximity-based feedback (visual highlights and audio cues) indicates when an atom is in proximity to form a chemical bond, as in Figure 2.
- **Voice and Conversational AI:** Integrated Azure Speech Services convert spoken queries into text for an LLM assistant (Groq backend). To safeguard against AI hallucinations in educational contexts, the prompt system uses structured domain-specific constraints (system prompt grounded in standard chemistry textbooks) and fallbacks.

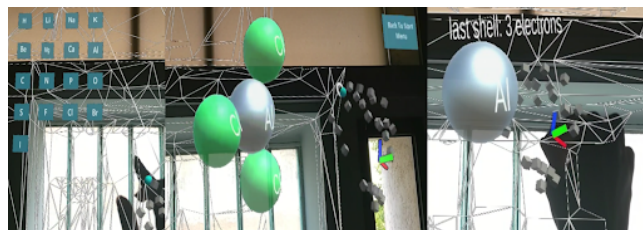


Figure 2: HoloChemAR: Augmented reality visualization of chemical compounds using natural hand interaction.

The backend is organized into components with clear responsibilities. LabController manages the selected reaction, laboratory objects, and reaction-specific instructions. Tool controllers maintain the state of bottles, glassware, pipettes, spatulas, and tubes, including visual properties and particle effects. AtomsController handles atom interaction and the possible compounds that can be formed, while CompoundController manages formed compounds. JSONController reads local instructions, AudioController provides speech synthesis through Azure Cognitive Services, and AIAgentController connects the application to the Python server used by the Groq-based chemistry assistant.

APPLICATION SCENES

The application is structured into three key operational modules:

- (1) **Main Menu:** Offers selection between guided experiments, interactive compound building, and assessment challenges.
- (2) **Laboratory Scene:** Allows students to perform simulated chemical reactions following multimodal voice and visual instructions (Figure 3).

- (3) Practice and Challenge Scene: Users select atoms to construct molecules. Real-time physics and chemical validation engines verify valency and geometry.

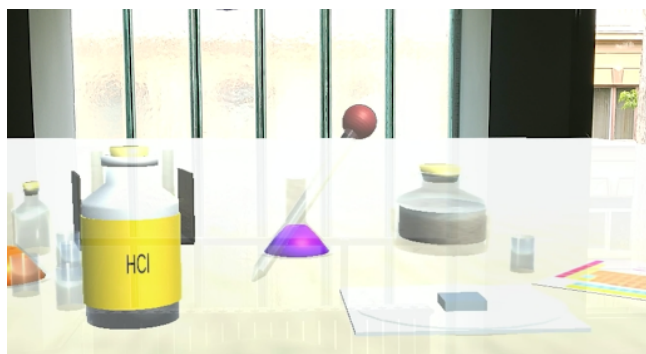


Figure 3: Laboratory Scene in HoloChemAR displaying interactive chemical reaction equipment.

Main Menu

The main menu provides access to the principal learning activities. Users can choose a reaction, enter guided compound formation, start the challenge mode, access the AI assistant, or exit the application. This organization lets learners move between experimentation, guided practice, and assessment within the same spatial interface.

Laboratory Scene

This scene allows users to carry out chemical reactions according to audio instructions and, through the graphical interface, observe their visual effects and molecular structures. Virtual instruments are manipulated through hand tracking, while reaction-specific instructions and visual states are updated by the application logic.

Practice and Challenge Scene

Depending on the selected option, this scene allows users either to practice combining atoms to form chemical compounds, with helpful indications and AI-agent assistance, or to assess acquired knowledge without the same indications. Feedback is provided on whether the resulting compound is chemically valid.

USER EXPERIMENTS AND EVALUATION

A evaluation study was conducted with 25 participants ($N = 25$, including students and chemistry educators) to evaluate usability, interaction fidelity, and system usefulness. Participants differed in age, educational background, experience with AR/VR/MR devices, and knowledge of chemistry.

Participant Demographic and Experience

Participant information was collected using a Google Forms questionnaire. The relevant information included age group, gender, educational background, and experience with mixed reality devices. Most participants were between 20–25 years old and were students, while the group also included one teacher. Over 80% had never used a HoloLens 2 headset. A brief 5-minute training session was provided to familiarize users with spatial gestures, eye-gaze targeting, pressing holographic buttons, and grabbing objects. While 84% had prior experience with 3D gaming environments, over 80% had never

used a HoloLens 2. The gaming experience was relevant because it provided familiarity with three-dimensional spaces, depth, and orientation, although participants still needed to learn the interaction conventions of the headset.

Usability and Perceived Usefulness

Feedback was gathered using standardized post-test questionnaires (evaluated on a 1–10 scale). Ease-of-use scores were overwhelmingly positive (average $> 8.2/10$), with participants noting that natural hand manipulation quickly became intuitive after brief exposure. Perceived usefulness for educational engagement achieved an average score of $9.1/10$.

Participants reported that the lack of previous HoloLens 2 experience made the first interactions less intuitive, but their understanding improved after the training session. The post-test feedback also indicated that the application's modules were sufficiently structured to support learning basic chemistry concepts and that the combination of laboratory and molecular activities was useful. The laboratory component was appreciated because it allowed participants to observe reaction effects while following step-by-step instructions, whereas the compound-formation component supported active exploration of molecular structures. The AI assistant was designed as an additional source of contextual help, allowing users to ask chemistry-related questions while remaining inside the learning environment.

The qualitative responses also provided useful information for the iterative development of the application. Participants suggested making the interaction with laboratory instruments and atoms smoother, increasing the amount of explanatory information available in the interface, improving visual elements, and making reaction effects clearer. These observations were considered together with the numerical usability and usefulness scores, providing a basis for prioritizing interaction and presentation improvements.

Limitations and Design Iterations

Based on initial user testing feedback, several interaction refinements were executed:

- **Collider Optimization:** Physics colliders on glassware and atomic models were enlarged and smoothed to reduce accidental slippage during hand-tracking grabs and to allow smoother, more precise movements.
- **UI Clarity:** Textual instructions within floating AR panels were resized and contrasted for improved readability against varying real-world backgrounds, and more detailed instructions were added.
- **Visual Feedback:** Visual components and reaction effects were adjusted in response to participant suggestions.

Evaluation Limitations: The current study evaluated usability and subjective interaction experience. Measuring specific long-term learning outcomes requires a formal randomized controlled trial comparing AR users against a traditional control group, which is planned for future work. The relatively small sample and the predominance of participants from a similar age group also mean that the findings should primarily be interpreted as evidence of usability and perceived usefulness.

CONCLUSION

HoloChemAR demonstrates how head-mounted Augmented Reality and natural multimodal interaction (hand-tracking, eye-gaze, and conversational AI) can transform chemistry education. By shifting the focus from abstract technical implementation to human-centered interaction design, the application provides an intuitive, safe, and engaging environment for exploring invisible molecular structures.

The application combines guided laboratory experimentation, molecular and ionic compound construction, challenge-based practice, voice instructions, and an AI chemistry assistant. The evaluation with 25 participants produced positive results for usability and perceived usefulness, while also identifying practical improvements to interaction and interface design. Overall, the results support the use of HoloChemAR as a complementary learning environment that integrates laboratory and molecular aspects of chemistry. The natural gestures and eye tracking provided by HoloLens 2 offer suitable hardware support for this type of interaction, while voice guidance and the AI assistant extend the learning experience beyond purely visual manipulation. Future work should extend the evaluation toward objective learning outcomes and compare the proposed approach with traditional chemistry-learning methods.

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