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ChemPOV: Evaluating a digital game-based learning tool for organic chemistry through student-researcher collaboration

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Abstract

In this study, we aim to investigate the application of game-based learning in organic chemistry education through the development and implementation of ChemPOV, a digital multiplayer board game. Uniquely, our team involved high school students collaborating with university researchers, providing insights into both the efficacy of the game and the value of engaging young students in chemical education research. Our team conducted trials with 176 junior high school students, divided into control and experimental groups. Data was collected through pre- and post-game surveys and quizzes. Results indicated correlations between student interest, engagement, and enjoyment in organic chemistry, with a minute improvement in academic performance for the experimental group. We also examined the benefits of applied learning experiences for the student researchers, who developed skills in research methodology, game design, and scientific communication. They participated in literature reviews, data analysis, and presented findings at international conferences. This research trial demonstrates the potential of involving young students in substantive research efforts and is a potential model for more inclusive approaches in STEM education.

Introduction

Applied learning is commonly accepted to be the incorporation of academic knowledge and skills into real-world settings, such as corporations, service projects, internships, and undergraduate research (Ash & Clayton, 2009). The motivation behind educators including applied learning techniques in their teaching methodologies is a belief that the contextualisation of the subject matter, drawing relevance between the content being taught and students' future career or further education, will empower and motivate students, whilst also eliciting active participation (Harrison, 2006). In the context of chemical research, applied learning is all the more relevant.

Yet, the introduction of real-world elements to the education of chemistry requires a deeper layer of complexity. Chemistry education has traditionally been plagued with students' inability to comprehend its relevance in the real world despite its reputation as the 'Central Science' (Stuckey et al., 2013). Modern developments in the field, including systems thinking, problem-based learning, as well as game-based learning (GBL), all aim to better engage students and relate their education in the classroom context to real world applications (Orgill et al., 2019; Costa et al., 2023; Putri et al., 2022). These have come a long way in the advancement of chemistry education as a whole. Alongside the development of digital and virtual reality tools, the chemistry education field has evolved greatly (Wohlfart et al., 2023; Laricheva & Ilikchyan, 2023).

Importantly, chemical education research is a highly applied field that has transitioned from individual teacher ideas about how student learning can be improved to a sophisticated enterprise employing the scientific method to formulate and test falsifiable hypotheses through student-focused trials (Bunce & Robinson, 1997; Cooper & Stowe, 2018). For this research to be both fruitful and impactful for chemistry students, it is crucial that chemical education researchers possess both a robust theoretical foundation and the necessary practical skills (Bunce & Robinson, 1997). A strong theoretical base enables researchers to craft effective investigative questions, while practical skills are vital for executing the research process. Although a solid conceptual understanding is linked to research proficiency to some extent, the active and applied use of research skills is necessary. The concept of applied retrieval systems to bolster learning outcomes has been previously documented in the context of undergraduate student learning (Agarwal et al., 2012; Cogliano et al., 2021). Accordingly, just as in the context of student learning, this mechanism is instrumental in fostering continuous improvement in a researcher's ability to conduct studies effectively.

Unfortunately, this very need for experience applying the use of research skills in investigative chemical education trials is often discouraging for young chemistry students, making the chemical education research space seem inaccessible. Examining recent publications in reputable chemical education journals confirms this observation—a very small fraction of these publications constitute high-school or early college students as first or second authors. Changes to undergraduate curricula by inclusion of Course-Based Undergraduate Research Experience (CURE) has been shown to be effective at making scientific research more inclusive and accessible for all students (Bangera & Brownell, 2014). Early research experience can play an important role in the development of students' epistemological (knowledge-based), intrapersonal (self-identity) and interpersonal dimensions (relationships) (Yuhao, 2014). Yuhao's qualitative study on undergraduate research programs in China revealed that such experiences encourage students to develop independent thinking, self-confidence, and collaborative skills. The development of these skills appears tightly associated with good mentorship, including the allowance of student self-authorship. However, such programmes do not exist at every college and are essentially non-existential at the high school level, rendering the research space in general somewhat inaccessible to younger students.

The three lead authors of this article, however, are an exception. Starting as 11th-grade high school students, they established a research partnership with Senpai Learn—a chemistry education research group at the National University of Singapore (NUS). Together, the students worked with Senpai Learn to carry out two separate investigative trials of ChemPOV (Fung et al., 2021), a digital multiplayer organic chemistry game designed in collaboration with the NUS Information Technology department. The results from these trials were analysed and presented by the three lead authors at three separate leading international chemistry conferences. Coaching students in higher education has been previously demonstrated to yield positive development to student metacognition and self-regulated learning skills (Divo et al., 2024). In the case of the student researchers in this group, the mentorship they received whilst under the Senpai Learn team proved valuable to the development of necessary skills in chemistry education research. The team at Senpai Learn adopted the following mentorship strategies that made it conducive for us to develop such skills in chemistry education research: (1) Providing a psychologically safe environment for students, (2) Offering challenging opportunity for growth, and (3) Evaluating and providing timely feedback for students.

For (1), it is essential to foster a space where their opinions are heard without fear of negative judgement. This encourages open communication and allows students to express themselves freely. The Senpai Learn team also helps to provide a safe space for students to make mistakes as making mistakes is essential for learning. Additionally, it is important to cultivate an atmosphere where students feel comfortable seeking help and asking questions without hesitation. By promoting these values, students are more likely to feel respected, develop curiosity, and build resilience, all of which are crucial for their personal and academic growth. For (2), Senpai Learn believes that providing students with challenging opportunities encourages them to step out of their comfort zones and push their boundaries. This can be achieved by empowering students to take the lead on projects, where mentors offer valuable guidance and support. Additionally, students can be given the chance to present their research and projects at scientific conferences, both locally and internationally. They can also be encouraged to write and submit scientific papers to reputable peer-reviewed journals, allowing them to share their findings with the broader scientific community. And finally, for (3), the Senpai Learn team provides regular evaluations and timely feedback to facilitate student improvement. This feedback is carefully crafted to promote critical thinking and encourage students to consider problems from multiple perspectives.

Herein, we present the motivations behind the assembly of our unique research team, the careful process in which lead authors surveyed the necessary chemistry education literature to design effective game trials, our initial findings, and key takeaways. We hope this insight will prove useful to other young chemistry students looking to enter the field as well as chemistry educators looking to collaborate with younger students on chemistry education research projects.

Methodology

Assembly of the ChemPOV research team

The aforementioned three student researchers were high school students in the National University of Singapore's specialised high school in STEM and were part of the SCIENTIA programme which encouraged students to pursue a junior research project. As classmates bonded by a shared love for teaching, gaming, and organic chemistry, the student researchers came together as a group under the PARTY approach: Passion, Aspiration, Relationship, Teamwork, Youth (Choo et al., 2024).

They reached out to the corresponding author to take up positions as research trainees in his chemistry education and pedagogy lab, Senpai Learn, with the portfolio of developing and trialling the team's new digital, multiplayer board game, ChemPOV, on young students.

ChemPOV was chosen as it was a game requiring reasoning skill in organic chemistry. From personal observations, the student researchers noticed that learning organic chemistry was an especially challenging task for most of their classmates, having a disproportionately high number of students learning its contents by means of rote learning. This appeared to be correlated with frequent negative attitudes towards the subject. Being passionate about organic chemistry fundamentals, the three student researchers felt strongly about investigating the efficacy of an organic chemistry pedagogical intervention over ones potentially targeting other branches of chemistry.

Once the chemistry education intervention was decided, the student researchers embarked on their maiden voyage in the field of academic research and gained exposure to the workings of a research team. They undertook various tasks and roles as a research trio while working on the project (Table 1).

Table 1: List of roles undertaken in the ChemPOV research project by the student researchers under the supervision of the research mentor.

Role	Description
Administrative	- Coordinate team communication and research planning sessions - Support with administrative processes to ensure compliance with ethical protocols
Content	- Craft organic chemistry reaction schemes - Create organic chemistry Multiple Choice Questions (MCQs) - Vet content material for game
Writing	- Wrote the first draft for conference abstracts for submissions - Wrote the first draft manuscript for publication - Conduct literature review and screen for relevance
Data Analysis	- Develop survey questions and extraction of data - Analyse data and create data visualisations of findings using computer softwares
Communication	- Design and create poster layout to communicate insights - Oral presentation of research findings at international conferences
General	- Feedback and suggestion of improvements to game design and features - Meeting summaries and minutes

The ChemPOV research experience

The student researchers had their initial exposure to research, and their involvement as high schoolers held great significance to the research process. For starters, the environment and method of study between high school and university are vastly different, with the university generally providing greater agency to the learner and teaching courses with content experts. High school has more pedagogically trained teachers where students are more guided across their wide array of subjects. This research experience provided various new perspectives and insights into university for the student researchers and these experiences had the potential to influence their career decisions and university courses.

In particular, designing the first drafts of appropriate MCQs and organic chemistry reaction schemes targeted at university students proved to be significantly daunting for the student researchers during the initial phase of the project. Design of organic chemistry synthesis scheme cards required knowledge of organic reactions typically only covered at the undergraduate level. The student researchers, however, were dedicated and passionate about organic chemistry. Through an aggregation of self-study, engagement with textbooks, online educational resources and in-school Chemistry Olympiad training programmes, the student researchers developed a strong understanding of more advanced undergraduate organic chemistry principles. The synthesis schemes, designed by carefully intertwining a combination of undergraduate organic chemistry topics, proved to be very challenging, especially since no hints were provided. A thorough review of the synthesis schemes designed by the Senpai Learn research team revealed negligible conceptual errors in the schemes, showcasing the firm grasp the student researchers had acquired of the necessary organic chemistry principles utilised in the reaction schemes. Apart from conceptual fundamentals, the student researchers familiarised themselves with tools like ChemDraw to produce the final set of reaction schemes—a valuable skill for a future career in organic chemistry.

The design process for the MCQs brought the student researchers on a different investigative path. The student researchers identified the potential audience for ChemPOV as students exposed to organic chemistry in the Singaporean education system. In this system, students are initially taught organic chemistry in secondary school, through junior college, with further specialisation in university — if students take chemistry-related courses. Naturally, the difficulty level of the MCQs and the core synthetic schemes of ChemPOV were stratified based on the content coverage across these distinct educational levels.

Reference was taken from the official Ministry of Education coverage across these educational levels (Singapore Examinations and Assessment Board, 2020a, 2020b), as well as undergraduate level pedagogical research (Zoller, 1990; Herron, 1975) in the team's identification of the testable content scope. Given the auxiliary usage of MCQs for ChemPOV, we created questions primarily focused on foundation concepts required for students to understand organic chemistry. Examples include 1) acid and base concepts for understanding reactions mechanisms, 2) nomenclature and skeletal structures to help visualise more complex organic molecules.

Game-based learning: A literature review

To gain a strong theoretical foundation in the game-based learning methodology the Senpai Learn research team was utilising, the student researchers conducted an extensive literature review on the topic.

They began this process with a wide net, first examining the general approaches that exist in chemistry education literature. These included the flipped-classroom approach (Ozdamli & Asiksoy, 2016), gamification of chemistry courses (Da Silva Júnior et al., 2022), peer instruction (Cortright et al., 2005), and game-based learning (Tobias et al., 2013).

In particular, they noted that game-based learning is a widespread methodology used at several other educational institutes and vocation-training environments. This approach leverages gameplay to deliver a fixed set of learning outcomes (Plass et al., 2015). Game-based learning has been empirically shown to have positive learning outcomes, increase student engagement and foster social connection (Shu & Liu, 2019; Romero et al., 2012). A commonly cited attribute of game-based learning is its ability to motivate students. This is delivered through captivating incentive structures, such as inter-player competition, points, and leaderboards, as well as game mechanics that create a high situational interest (Rahimi et al., 2021).

Another closely related reason for adopting game-based learning methodologies is that games offer educators a multifaceted platform to engage their students. The nature of this engagement is closely tied to the design of the game and the environment in which it is implemented (Ruiperez-Valiente et al., 2020). According to previous literature (Plass et al., 2015), these types of engagement include cognitive engagement (i.e., mental processing and metacognition), affective engagement (i.e., emotional processing and regulation), behavioural engagement (i.e., gestures, embodied actions, and movement) as well as sociocultural engagement (i.e., social interactions embedded within a cultural context). The student researchers connected ChemPOV's utilisation of a combination of these engagement methods — from in-game avatars fostering affective engagement to ChemPOV's multiplayer mode bringing sociocultural engagement.

While different educational games utilise varying cocktails of these engagements, all of them are ultimately aimed at fostering cognitive engagement in learners with the learning mechanic delivered through the game (Plass et al., 2015). The student researchers noted at the time that this was an especially important connection to the way ChemPOV was designed, with the primary source of cognitive engagement being the solving of partially filled organic chemistry synthesis schemes.

Furthermore, the use of games as a medium in education also allows instructors to provide an adaptable interface students can interact with. Adaptability in games facilitates learner engagement by means of customisability and personalisation (Hwang et al., 2012). A commonplace strategy most games employ to infuse adaptability into their infrastructure is by including delineated difficulty levels, possibly related to the learners' current level of knowledge or skill level (Plass et al., 2015). This was a key motivating factor for the student researchers to create a new difficulty level, featuring more advanced organic reactions, thereby catering to a wider group of learners.

Lastly, game-based learning offers an opportunity for students to learn without the fear of failure. Rather than being an unwanted outcome, failure is a crucial step in the learning process. In game environments, the repercussions of failure are minimised, encouraging students to take risks and learn from their mistakes (Plass et al., 2015). Flexibility to fail can also foster self-regulated learning, prompting students to adjust their strategies and enhance their conceptual understanding to advance in the game.

ChemPOV research trial on junior high school students

Motivated by the previously reported efficacies of game-based learning, the student researchers sought to bring ChemPOV into the teaching of organic chemistry for younger learners. They decided to conduct a preliminary trial of ChemPOV on their juniors from NUS High School of Mathematics & Science. This was primarily a result of the fruitful SCIENTIA collaboration between the Senpai Learn team and the student researchers — allowing ChemPOV trials to extend beyond the confines of the National University of Singapore. Furthermore, the student demographic suited the research interests of the team, given that students as young as junior high school students have never been given the chance to play ChemPOV with reaction schemes catered to their level of difficulty before.

Additionally, the student researchers noted that when they were first introduced to organic chemistry, many of their peers who disliked 3D-visualisation and the organic chemistry 'language' struggled to absorb it, which motivated them to make the learning experience for their juniors less challenging. As a result, it was decided that the research subjects would be Year 3 (Secondary 3, Grade 9) chemistry students from NUS High School of Mathematics & Science. These students have started learning basic organic chemistry spanning the Singaporean GCE 'O' Level syllabus (Cambridge O Level Chemistry 5070, 2019) for 10th-grade Singaporean students. They have also been introduced to the skeletal structure representation system. This is left out of GCE 'O' Levels and typically reserved for H2 'A' Levels instead, which are examinations taken by 12th grade Singaporean students. The student researchers split the Year 3 cohort of 176 students into a trial group with 87 students and a control group with 89 students. The trial group was involved in playing ChemPOV while the control group was not provided access to the game in the same time frame. Within the control group, the pre-game survey had 31 responses, while the post-game survey had 82 responses (Figure 1).

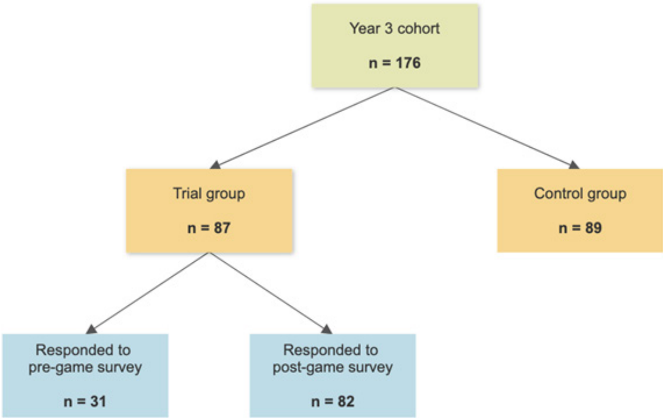

Figure 1: Flowchart illustrating the distribution of students in the trial group versus the control group, and the number of survey respondents within the trial group.

Furthermore, to assess potential shifts in academic performance after playing ChemPOV, the research team administered pre- and post-ChemPOV quizzes to 76 students in the trial group and 76 students in the control group. A total of 24 students did not attempt the quizzes (Figure 2).

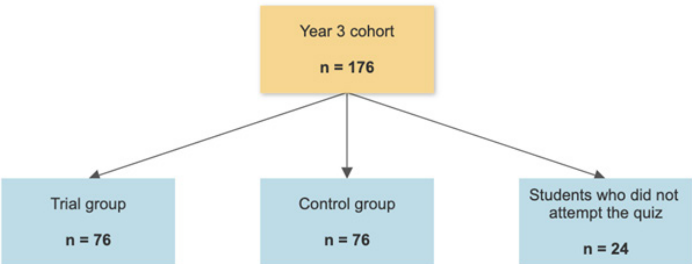

Figure 2: Flowchart illustrating the distribution of students in the trial group versus the control group who attempted both the pre- and post- quizzes administered.

The research team kept to a strict timeframe of milestones to ensure sufficient time between the various tests conducted on the Year 3 students (Table 2).

Measures, including vetting by multiple team members and the chemistry teaching staff at NUS High School, were taken to ensure that the pre- and post- quizzes were of similar standards of difficulty.

Table 2: Timeline of events before, after, and throughout the period of the trial and descriptions pertaining to each event.

Week	Event	Description
		Before the trial
6 months ahead	Pre-Trial	The student researchers gathered and began working on the ChemPOV project together. In collaboration with Senpai Learn, they began crafting synthetic schemes and organic chemistry MCQs for the game's usage.
4.5 months ahead		Administrative paperwork to allow the trial to be conducted on the Year 3 students was completed, alongside meetings with stakeholders and the teaching staff who had to ensure the quizzes and surveys were well-administered.
3 months ahead		The reaction schemes and MCQs were vetted by senior members of the Senpai Learn team and uploaded onto ChemPOV by partners from NUS Information Technology, who assisted Senpai Learn in programming ChemPOV on the back end.
1.5 months ahead		The game was played by the student researchers to ensure their readiness for the actual trial on the large cohort of younger students. The quizzes and surveys were also crafted and finalised during this period.
		During the trial
Week 1	Pre-Quiz	A short pre-quiz consisting of 10 multiple-choice questions was issued to the entire Year 3 cohort (n=176). The purpose of this assessment was to collect data on the students' initial performance in organic chemistry.
Week 2	Pre-Survey	A pre-survey was issued to the participants that would be involved with the game. The purpose of this survey was to gauge the interest of participants in organic chemistry and game-based learning before playing ChemPOV.
Week 3	Game	The research team arranged for a physical engagement session where ChemPOV would be played by the gameplay group in pairs or trios.
Week 4	Post-Survey	A post-survey was issued to the participants involved with the game. The purpose of this survey was to observe any change in attitude or perception of the students towards organic chemistry after playing ChemPOV.
Week 5	Post-Quiz	A short post-quiz consisting of 10 multiple-choice questions was issued to the entire Year 3 cohort (n=176). The purpose of this assessment was to compare their academic performance in organic chemistry before and after playing ChemPOV.
		After the trial
0.5 months after	Post-Trial	The research team compiled all the collected data and began data analysis and representation.
2 months after		The research team submitted the project to SCIENTIA programme's Research Congress, which included a full manuscript, an abstract, and a poster.
3 months after		The research team submitted their first abstract to an overseas conference for poster presentation and was accepted.
1 year after		The research team submitted their first abstract to an overseas conference for oral presentation and was accepted.
1.5 years after		The research team submitted manuscripts to peer-reviewed journals for publication, encompassing the data from the research trial.

Connecting with international chemistry educators about ChemPOV

As part of the holistic research exposure, to provide the student researchers with international experiences, and to encourage them to speak to other researchers about their work, the corresponding author encouraged the student researchers to attend international conferences on chemistry education.

The research team presented posters in the American Chemical Society's Spring Meeting at Indianapolis, USA in 2023, the International Union of Pure and Applied Chemistry's World Chemistry Congress at The Hague, Netherlands in 2023, and presented an oral presentation at the International Conference for Chemistry Education at Pattaya, Thailand in 2024. Their experience as the youngest participants at the IUPAC World Chemistry Congress was also featured in a journal (Kon et al., 2024).

The student researchers gained deep insights from the conversations they held with the experienced researchers at these conferences, had the valuable opportunity to present to numerous audiences from all backgrounds of chemistry, and obtained various takeaways from attending other symposia and conference tracks (Figure 3).

Figure 3: Diagram describing the experiences and personal sharing of each student research member of the ChemPOV team, each at a different conference where ChemPOV was presented to fellow chemists.

Analysis and discussion

Survey results

We display below a correlogram we generated based on our pre-game and post-game surveys (Figure 4). The gradient scale on the far right provides a colour code to the degree of correlation between any two variables, with as faint a colour representing a greatly positive correlation and as dark a colour representing no correlation or slightly negative correlation. The axis labels are described below (Table 3).

Table 3: Description of each axis label.

Axes Label	Description
interest	Interest level towards organic chemistry
engagement	Engagement level during organic chemistry lessons
enjoyment	Enjoyment level during organic chemistry lessons
grades	Personal satisfaction towards chemistry grades
anticipation	Anticipation level towards playing the game again in future (when the reactions have been adjusted to suit their syllabus)
external interest	Frequency of consumption of chemistry-related material beyond school
classmate help	Frequency in approaching fellow peers for assistance towards organic chemistry problems

In Figure 4, the magnitude of the correlation represents the degrees of correlation, with 1.00 or -1.00 indicating perfect correlation while 0 indicates no correlation. The sign (+/-) represents positive/negative correlations. The bottom triangle (in purple) and the upper triangle (in green) represent the pre- and post-survey responses, respectively.

We note that a number of factors surveyed are strongly correlated, with a correlation magnitude exceeding 0.50. Factors that correlate strongly across both surveys as well as the distinction in strongly correlated factor pairs between pre and post surveys are outlined in the table below (Table 4). We also note that there is very limited correlation between

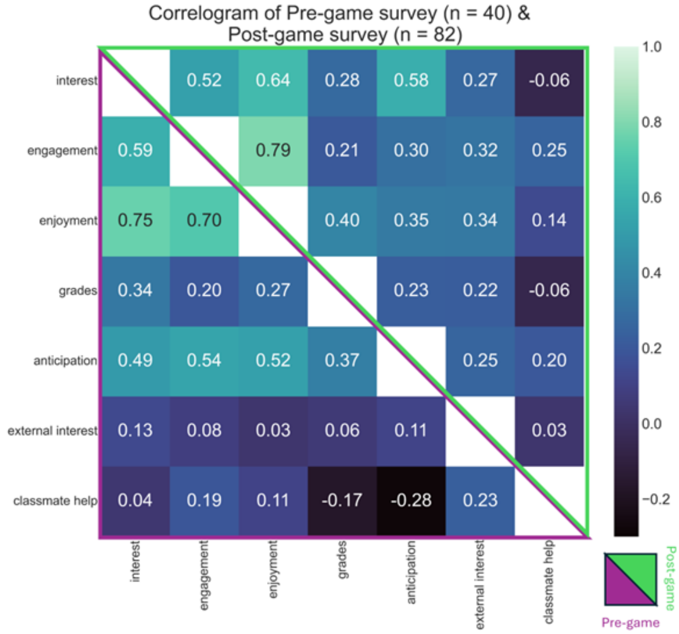

Figure 4: Correlogram displaying a heatmap, with central number within each grid representing the correlation between 2 of the variables obtained from a 5-point Likert-scale question in the pre- and post-ChemPOV survey (interest, engagement, enjoyment, grades, anticipation, external interest, classmate help).

grades, external interest, and classmate help and any of the other variables.

To observe the correlations found in Figure 4 in greater detail, a scatterplot matrix was plotted for each pair of factors from the pre-game and post-game survey data. These plots were coupled with a histogram illustrating distributions of each of these factors for the pre-game and post-game survey. The aggregation of these plots is presented below (Figure 5).

While we did more closely examine the variables which had noticeable changes between the pre- and post- game survey gradients.

Table 4: Summary of observed strong correlations from correlogram, sorted based on similarities and differences between the pre- and post-surveys conducted.

	Pre-Survey	Post-Survey
Shared strong correlations	- Engagement and interest. - Enjoyment and interest. - Enjoyment and engagement.	
Distinctions in strong correlations	- Anticipation and engagement. - Anticipation and enjoyment.	- Anticipation and interest.

Pre-survey and post-survey responses displayed in purple and green respectively.

Quiz results

Score distributions for pre- and post-ChemPOV quiz results for control and trial groups are plotted below (Figure 6). Additionally, the distribution of score differences between the post-ChemPOV quiz and the pre-ChemPOV quiz is

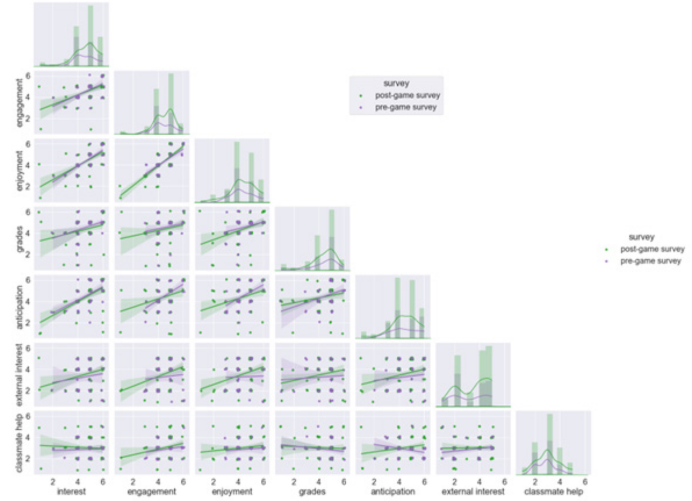

Figure 5: Pairplot (scatterplot matrix) displaying a grid of a) off-diagonal scatter plots, each representing the relationship between 2 of the variables obtained from a 5-point Likert-scale question in the pre-/post- survey (interest, engagement, enjoyment, grades, anticipation, external interest, classmate help). b) on-diagonal histogram and KDE plots for each of the aforementioned variables.

plotted for the trial and control groups. We observe a small right-shift in the distribution of score improvements for the trial group compared to the control group. Furthermore, we found that 59% of students in the trial group showed improved performance in the post-ChemPOV quiz as opposed to 56% in the control group.

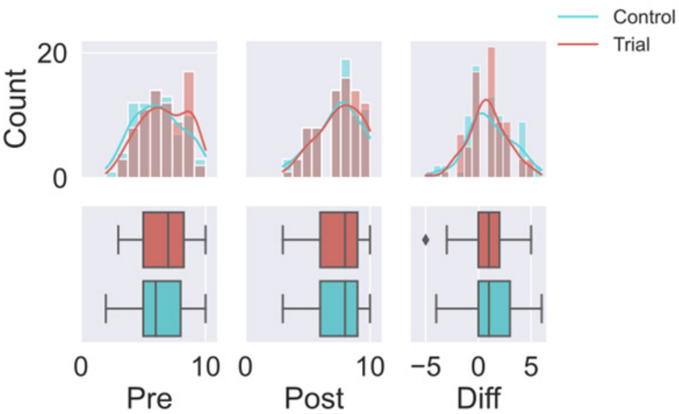

Figure 6: Histogram and boxplots of the pre-test, post-test and change in scores for each individual. (Red: trial group; Blue: control group; Brown: any overlapping area between both groups).

These results indicated to us that, in the context of high school students, academic performance in organic chemistry assessments does not appear to improve significantly after playing ChemPOV once. However, this finding could be confounded by the limited time students had to play ChemPOV as well as the modest two-week time interval between the pre- and post-ChemPOV quizzes.

Conclusions and recommendations

This study outlined the fruitful collaboration between high school students and university researchers. The student researchers, initially driven by their passion for organic chemistry and teaching, found themselves navigating the intricacies of academic research. From the process of crafting MCQs and synthesis scheme problems that challenged undergraduate organic chemistry students to presenting findings at international conferences, these young researchers experienced a steep learning curve that mirrored the very subject they sought to teach—organic chemistry itself.

The international conference experiences were especially transformative for the young researchers. From shifts in public speaking confidence, evolved appreciation for the interconnectedness of distinct chemistry disciplines and the reception of critical feedback from experienced academics, the students' familiarity with the way scientific research is communicated in academia and appreciation for the rigorous standards of academic discourse grew.

A significant outcome of this partnership was the transformation of the student researchers' perspectives on the role of failure in the scientific process. As one team member reflected after the IUPAC World Chemistry Congress, failure in research is not something to "begrudgingly accept, but also to welcome." This shift in mindset, from viewing failure as a setback to seeing it as an integral part of the scientific journey reflects the strength of the "to learn it, do it" principle of applied learning.

The ChemPOV investigative trials conducted by the young researchers, while focusing on a specific cohort of junior high school students, address broader questions about the efficacy of game-based learning in chemistry education. Their results hint at the potential for such interventions to influence student engagement and interest, even if immediate academic gains are not apparent. This suggests the need for longitudinal studies to fully capture the impact of game-based learning tools on students' long-term learning relationship with organic chemistry.

For educators and researchers considering similar collaborations, our experience was made most fruitful by the creation of a supportive working environment that allowed young researchers to take ownership of their work while providing guidance when needed. For meaningful synergies with younger students, we suggest researchers look for the following personality traits: self-disciplined, motivated, receptive to feedback and positive disposition. In our experience, these are the crucial character elements that laid the foundation for a strong and lasting partnership. Our team also observed that these traits are not exclusive to student researchers—much of what would make a productive research alliance with a colleague applies to collaborations with younger students.

During early mentorship phases, we found that having regular weekly meetings kept student researchers engaged and provided an avenue for them to seek regular feedback and grow as scientists. These factors transformed the students' journey crafting MCQs to presenting at international conferences into one just as much about personal growth as about scientific discovery. This positive research experience has kept the student researchers engaged with the Senpai Learn team's ongoing works, from the development of new chemistry education games to the crafting of manuscripts for journal article submissions, despite being occupied with full-time commitments. Their shared commitment to quality research in organic chemistry education is expected to keep this partnership strong for the foreseeable future.

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