Multimodal Discursive Teaching Practices in a Studio-Based Designed Chemistry Summer Program

by

Heather Catherine Thompson

Bachelor of Arts, 2008

University of Texas at Arlington

Arlington, TX

Masters of Education, 2012

University of Texas at Arlington

Arlington, TX

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Molly Weinburgh, Ph. D. Professor

This study investigates the instructional practices of a chemistry professor during an immersion summer program, with a focus on employing multimodal discourse within a studio-based learning environment. For this study, multimodal discourse includes natural language, gestures, mathematical expressions, symbolic visual representations, and manual technical operations. Studio-based design combines the lecture and laboratory in space and time. By integrating multimodal discursive practices, the aim is to enhance student engagement and facilitate meaningful interactions between students and instructors. Utilizing a case study methodology, the research demonstrates the effectiveness of the studio-based design in promoting active learning and supporting professors' teaching strategies. The findings highlight the versatility of the studio-based approach in fostering multimodal discourses, contributing to a more dynamic and interactive educational experience for students.

Chapter 1

Introduction

Chemistry is an essential part of our everyday lives and a "gatekeeper" into many science disciplines such as biological, medical, aeronautical, material science, environmental studies, and more advanced chemistry (Avent et al., 2018; Barr et al., 2009; Mervis, 2010; Moreno et al., 2021). It is considered the central science, tying other disciplines together (Balaban & Klein, 2006; Brown et al., 2006; Mahaffy et al., 2019). With chemistry being so interconnected to all disciplines of science, the need to study and understand chemistry is embedded in many science career paths.

Due to the universality of chemistry, students from various majors must enroll in and satisfactorily complete introductory courses such as general and organic chemistry (Avent et al., 2018; Moreno et al., 2021). While institutions view these courses as essential for building career skill sets, students view these courses as a way for instructors to weed-out unqualified students (Barr et al., 2009). When students fail these courses, they leave the science pipeline. In recent years, there has been more focus on why students struggle with chemistry and how to improve chemistry courses and student retention. This has led to investigating the disciplinary discourse used in chemistry by students and faculty, the design of the lecture-laboratory sequence, and the instructional strategies used by the professor.

Discourse in Chemistry

Meaning making and communication in chemistry require the use of unique discourse structures. Studies show students often lack the ability to navigate chemical discourse (Farheen & Lewis, 2021; Mathayas et al., 2019; Rees et al., 2013; Rincke, 2011; Tregust et al., 2003). Their inability to engage in the discourse blocks them from the deeper understanding that helps them succeed. Discourse is not just reading, writing, and speaking in science, but also using mathematical language and expressions, visual and symbolic representations, and manual technical operations, as posited by Lemke (1990) in his ground-breaking study. His suggestion that science used a 'hybrid language' constituted by several modes has resulted in the notion of multimodal discourse. Many researchers have examined engaging students in multimodal discourse (Unsworth et al., 2022; Weinburgh et al., 2017; Weinburgh et al., 2019), where learning is integrated within and across Lemke's four modalities. This is especially important in chemistry due to its nature of heavily using mathematical, symbolic, and shorthand notations (Lemke, 2004).

Lemke (2004) described all the modalities a student had encountered in a single chemistry lesson: natural language, mathematical expressions, visual representations, and manual technical operations. He further stated that the student "quite often had to integrate and coordinate most of these semiotic modalities either simultaneously or within the span of a few minutes" (p. 39). Different countries report having similar problems with the retention of students in introductory chemistry courses (Lafarge et al., 2014). Despite chemistry courses delivering instruction in the student's natural language, nearly all students are inundated with chemical vocabulary, visual representations, and mathematical expressions in one lecture. Students new to the discourse of chemistry lack the skills to integrate and process as quickly as needed in the lecture setting. Additionally, they must then use their newly acquired discourse along with manual-technical skills in the laboratory.

Jornet and Roth (2015) further explained that conceptual knowledge is gained when students understand "the relations between the original phenomenon and the ways it is made present again" (p. 9). Descriptions in written or spoken form can assist learners in understanding complex ideas. Gestures may also communicate significance or direct attention, thus reducing cognitive load. Mathematical formulas can help learners understand the relationships between different variables. Visuals, such as diagrams or graphs, can help learners comprehend abstract concepts by providing a concrete representation. Physical enactment, such as experiments, can help learners understand how a phenomenon works in the real world. Using multiple modes of representation helps learners connect different representations and develop a deeper understanding of phenomena being studied.

University teaching

While the focus has been primarily on students' understanding of chemical discourse, other studies have looked at how the courses are delivered to the students (Lafarge et al., 2014). With the structure of the chemistry course so heavy with discourse, it is not only important to study how students take in information but also how the discourse is presented. To achieve this, professors need to engage students repeatedly in scientific discourse and integrate the modalities together. One way to achieve integration of the modalities is to combine lecture and laboratory experiences together in a studio-style course. In a studio-style course, students can seamlessly transition from theory to practice in the same class. This approach allows for active, hands-on learning and encourages students to engage with the material holistically. By combining lecture and laboratory experiences, students can see the practical applications of the concepts they learn in the classroom, leading to a deeper understanding of the subject matter. Additionally, the studio-style course allows for immediate feedback and guidance from the professor, enhancing the overall learning experience for students.

It takes time for science educators trained in pedagogy, in general, to develop and refine their teaching skills. Chemistry professors, not trained in science education, would not know what this would look like. Additionally, it could be perceived as overwhelming to try and incorporate all these strategies at once. Consequently, chemistry content is traditionally taught one or two modalities simultaneously. Typically, the university chemistry course includes three hours of lecture time and three hours of laboratory time a week (Round & Lom, 2015). The lecture is a one-way transmission of knowledge that does not allow students to practice their discourse. Furthermore, manual technical skills with context are put on the back burner and often relegated to a disconnected laboratory experience. Therefore, more research is needed on how a professor incorporates multimodalities in a chemistry course.

Having the lecture immersed with laboratory experiences would help to strengthen the students' acquisition of the chemical discourse. Retention of knowledge in a traditional lecture is shown to be low and ineffective (Altmiller, 1973; Collison et al., 2012; DiBiase & Wagner, 2002; Gottfried et al., 2007; Greco, 2018; Kiste et al., 2017). Additionally, Kiste et al. (2017) found that in studio-based chemistry courses, student performance increased in addition to students expressing favorable attitudes toward chemistry. The physical and temporal divide between the two modes of instruction leaves students with a lack of context. Bringing the two modes together allows for more fluid movement between modalities.

Study Significance

This study extends the current research by examining a chemistry professor's instructional practices during an immersion summer program. By applying the notion of multimodality in a studio-based chemistry course, it may be easier to engage students in multimodal discursive practice. The focus of this study (e.g., the professor's instructional practices) differs from most other studies as they examine student attributes such as use of discourse, knowledge, and attitudes. Additionally, current research on studio-based laboratory chemistry course does not include multimodal discursive practices.

Research Questions

The focus of this research is on the instructional practice of a chemistry professor during an immersion summer program for high school students. The research questions are

1. How does the chemistry professor incorporate multimodal discursive practices into his teaching?
2. How does studio-based chemistry support the chemistry professor with incorporating multimodal discursive practices?

Definitions of Terms

For the purpose of this study, the following terms have specific meaning:

Active learning - an educational practice in which students participate in activities to construct knowledge.

Collaborative learning - an instructional model in which students work together in groups towards a common goal.

Laboratory. A designated space with equipment for experimentation.

Laboratory experiences – any event designed to provide students with a first-hand exposure to laboratory activities.

Studio-based chemistry – a term given to a science course where lecture happens in the laboratory space and does not have a separate time slot.

Summer program. An experience provided to students in a non-credit manner.

Chapter 2

Literature Review

The main goal of this research is to examine the instructional practices of a chemistry professor during an immersion summer program for high school students. To fully understand the instructional practices, related research is examined. The literature review includes multimodal discursive practices and studio-based (laboratory) instruction.

Multimodal Discursive Practice

Chemists, while having a similar language to other science disciplines overall, have their own unique language. They have ways of expressing the phenomena they study, especially abstract concepts that cannot be seen with the naked eye, in a variety of ways (Farheen & Lewis, 2021; Mathayas et al., 2019). While a chemist may communicate mostly in their everyday language, English for example, there are many words that are unique and concise to chemistry. For example, a chemist may describe a preparation of a solution. The word solution may mean the answer to a problem in everyday use, but in this case, it means a liquid in which a solute has been dissolved. Mathematics is used to demonstrate relationships, make predictions, and analyze data. Chemists even communicate with numbers using significant figures. The number of digits recorded for data tells the reader the accuracy and precision of the measuring device. However, words and mathematical expressions could not describe in detail the unique structures of compounds and how different molecules connect to form new compounds. Thus, symbolic visual representations are an important part of the communication of chemists. The manual-technical skills, which can only be gained in laboratory experiences, allow students to experience the reaction. These are all ways of knowing and communicating and have been developed over the years. Educational research has described this as multimodal discourse.

Over the last 50 years, increased interest in discourse related to science education and chemistry has been noted (Feez & Quinn, 2017; Unsworth et al., 2022, Weinburgh et al., 2017). Influential studies by Lemke (1990, 2004), Gee (2004), and Yore (2004) set the foundation for thinking about the complexity of science discourse, describing 'the language of science' as a medium for meaning-making through sociocultural practices (Martin et al., 2020). Furthermore, the 'language of science' is described "as 'a unique hybrid' of words, mathematical symbols, visual images such as diagrams and graphs, and the specialized actions of scientists in 'technological environments'" (Feez & Quinn, 2017, p. 196). Hybrid language is rooted in communicating ideas and semantics, or meanings connected to language. Lemke (1990) further contended that language is not just for communicating but instead using language as a tool for doing science. Just as students must make meaning of the scientific concepts taught to them, scientists had to make meaning of the world as they investigated it.

The notion of multimodality was further expanded and developed by researchers in the past decades and incorporated or merged with existing research. Unsworth et al. (2022) contends "that classroom practices must necessarily reflect the ways that knowledge and practices are built in the discipline" (p. 24). Scientific knowledge is generated through a "multimodal, representational re-description process" where data are translated, renegotiated, and refined (Unsworth et al., 2022, p. 22). Students recontextualize information as they switch between multiple representations of the different modalities allowing them to develop deeper meanings. As students cycle representations, the modalities should increase in complexities.

Gestures, as a way of communicating and making meaning, have been developed into the modalities by researchers such as Goldin-Meadow (2011), Hao & Hood (2019), and Mathayas et al. (2019). Gestures help students communicate when language or vocabulary are missing and reduce in use as language is developed (Roth, 2004). Additionally, more complex symbolism and modeling have also been included in multimodality. Symbolic representations and modeling help students to build mental models and conceptualize abstract concepts like those in chemistry (Farheen & Lewis, 2021; Unsworth et al., 2022).

Researchers like Talanquer (2011) and Unsworth et al. (2022), drew parallels between multimodalities and existing research of Johnstone's Chemistry Triangle. Talanquer (2011) summarizes Johnstone's Chemistry Triangle as "chemical knowledge and understanding of our world is generated, expressed, taught, and communicated at three different "levels", traditionally called the macroscopic, the submicroscopic, and the symbolic levels" (p. 179). Students must be able to navigate these different levels for meaningful learning to occur. However, most students and chemical educators have difficulties bridging the gap between the macroscopic and submicroscopic levels.

Researchers have recognized the interconnectedness and symbiotic relationship between these two fields of study, shedding light on the potential for a deeper understanding of chemical concepts through multimodal approaches. They argue that multimodalities significantly impact learning and understanding in chemistry education. Multimodalities allow students to engage with the content in various ways, enhancing their comprehension and demonstrating their knowledge in different forms. Engaging students in different multimodalities can help bridge the gap between the macroscopic and submicroscopic as well as make connections between abstract ideas and real-world examples. Moreover, multimodalities also promoted active engagement and participation in the learning process. Through multimodality, students could explore the content from different angles and perspectives, allowing for a deeper and more holistic understanding of chemistry.

Natural Language

Natural language centers around speaking, listening, reading, and writing and can range from the informal language spoken at home to the more formal concise language of chemistry. Language is a fundamental part of how students and scientist make sense of investigations and aids in knowledge development (Chen, 2019; Norris & Phillips, 2003). Through talking and listening, students can exchange and refine ideas while writing helps to strengthen and build structure to their ideas (Norris & Phillips, 2003). Research has shown that teaching practices should provide students with opportunities to use talk and text simultaneously like those demonstrated by Chen (2019).

The acquisition of the language of chemistry is not as simple as one, two, and done. A new language cannot be given to students and expect them to adopt it. Language takes time to develop and must be practiced. The study by Hosbein et al. (2021) investigated argumentation skills over two semesters in a general chemistry laboratory. The findings revealed that student argument improved following repeated opportunities over the course. Additionally, with improved scientific argumentation, students improved in conceptual knowledge and showed growth in scientific communication skills. Allowing students time to interact with each other and with the educator can help facilitate the learning of the language (Chen, 2019; Gee, 2004). While beginning to learn the language of chemistry, everyday language can help to facilitate and scaffold learning the more specialized language of chemistry by grounding thoughts in prior knowledge. This would only be a starting point; everyday language does not carry the same meaning as a specialized language and cannot substitute for the language of chemistry (Gee, 2004). Additionally, everyday language can be problematic due to its vagueness and misconceptions that can arise (Gee, 2004). The educator should facilitate the students through the continuum toward a more concise chemistry language. Furthermore, the new language learned can scaffold to increasingly more complex abstract language and knowledge (Chen, 2019; Unsworth et al., 2022; Weinburgh et al., 2019). Professors should be cognizant of the iterative process needed to learn the concise ways of talking and writing in chemistry when designing instruction.

Speaking and Listening

Speaking and listening are two of the most fundamental ways of communicating. When learning to talk science, students must master the thematic patterns of the specific science discipline (Chen, 2019; Lemke, 1990). Without understanding the thematic patterns, students will struggle with the concepts. The very concise language of science mixed with less concise words or everyday language can lead to many ways of talking about the same things. Educators should be cognizant of similar words or phrases when talking to students and include discussions about their relationships.

Research by Chen (2019) and Roth (2004) pointed out the importance of providing students opportunities to talk to other students and the instructor. Planning activities where the students can work in small groups encourages dialog. Student-to-student dialog allows for low-pressure practice. Additionally, these activities should encourage the student to ask the educator questions. Talking through chemistry enables students to refine their chemical discourse before committing their explanations to written form (Roth, 2004).

Reading and Writing

Written language encompasses both reading and writing text. Written language can also vary from informal, such as text messages, to more formal, such as scientific papers. Students most often engage in an informal written language outside of the classroom. In class, students mostly experience and interact with personal genres and narratives like those found in English class (Weinburgh et al., 2019). However, in a science class, students are presented with more formal text such as laboratory procedures, laboratory reports, or scientific explanations, known as factual and analytical genres (Weinburgh et al., 2019). "Factual genres make use of this simple present or simple past tense, or discipline specific, and incorporate vocabulary denoting sequence. … Analytical genres denote logical relationships such as cause-and-effect comparisons and conditional statements" (p. 14). Factual genres are typically found in reports and documents with procedures. They are used when planning and carrying out investigations. They can be identified by their use of simple present and simple past tense verbs expressing sequence or cause and effect (Weinburgh et al., 2019). Analytical genres are involved in questioning, argumentation, and interpretation. While factual language is involved with the actions of an investigation, analytical is more involved with the sense-making side of an investigation. An educator would need to know how to help facilitate the transition between informal text to formal text. Allowing students to edit and refine text will aid in this transition.

Talking and Writing Synergistically

Chen (2019) discusses many ways in which talking and writing can be used together with four instructional design principles. The first design principle is to engage students in public and private landscapes. Public landscapes allow for "teachers and students to work together as a community to solve conflicts and improve ideas" (p. 3). Private landscapes provide students time to reflect on their understandings and construct knowledge. The second design principle is to engage students in argumentation. Through argumentation students engage with their data, evidence, and experiences as well as negotiate ideas with others. The third design principle is to use talking and writing iteratively. Allowing students to talk before writing they have opportunities to build confidence, develop ideas, and to increase their scientific vocabulary. Giving students opportunities to write before they talk gives them time to activate prior knowledge and organize their thoughts. Talking and writing simultaneously "immediately freezes students' ideas on paper and allows for richer negotiations" (p. 5). The last design principle is to build uncertainty. Building uncertainty into laboratory experiences mirrors scientific practices and encourages deeper argumentation.

Gestures

Communication is not solely dependent on audible or textual artifacts (Goldin-Meadow, 2011; Hao & Hood, 2019; Mathayas et al., 2019; Roth, 2004). A great deal of communication can occur with body language or gestures. While gesturing is utilized by novices and experts alike, "gesturing plays an important role in how we think and learn" (Goldin-Meadow, 2011, p. 595). Gestures can consist of pantomiming, whole-body motion, hand movements, pointing, and facial expressions. Understanding the role of gestures used by students and educators can enhance learning.

Gestures are essential in the beginning stages of verbal chemical development by decreasing the mental cognitive load on the student (Goldin-Meadow, 2011; Mathayas et al. 2019; Roth, 2004). Roth described an interaction between two students who were able to explore phenomena of static electricity without having to know the technical words. Since they were not overwhelmed with the vocabulary, they were able to construct meaning to which words could be put later. As students' literacy develops, gestures are less prevalent.

Educators who are attentive to students' gestures can help them develop more complex discourse. Goldin-Meadow (2011) found that gestures can signal when students are ready to learn and demonstrate their current understanding. "Gestures express new levels of understanding before a student can put this new understanding into words" (Roth, 2004, p. 48). One student who was just learning English, was able to show her understanding of molecules even though she was not familiar with the word molecule (Mathayas et al., 2019). She was also able to show that she understood quite a bit about molecules and air pressure despite having the verbal language to accompany it. The interviewer was able to bridge the visual and verbal through the gestures. By engaging students in talk about chemical concepts or phenomena, students can utilize gestures in the absence of words. In those moments, the educator has opportunities to determine the development of students' ideas and what further supports are needed.

Mathayas et al. (2019) expanded on the use of preverbal gestures, by examining students' use of gestures while revising conceptual explanations. For example, one student was asked to construct an explanation of heat transfer. He used his hands to simulate the speed of the wiggling molecules. He also was able to identify the various regions of significance in the simulation through hand bumps. Through his movements he was able to make connections in the simulation shown to him that he was unable to make previously.

More recently, gestures have been categorized into sonovergent and semovergent. Sonovergent gestures must occur with words and mirror the rhythm of the words. These gestures are used to denote importance and signal unfamiliar vocabulary. This was demonstrated in the Hao & Hood (2019) study, where the educator used a strong downward hand movement for an important word or phrase and smaller repeated beats for the phase accompanying it. Semovergent gestures can be coupled with or without words. Although these gestures can be used without words, they must express meaning in place of words. Semovergent gestures serve as identification, shape, or positive and negative connotations. A gesture of pointing serves to identify something. Shape can be represented by holding up hands to create a circle or holding fingers close together to show something is small. Lastly, positive or negative connotations can be conveyed by waving a finger from side to side or nodding the head up and down.

Educators' gestures can be used to communicate to students in various ways. In small group discussions, gestures paired with objects and less formal words, such as this, that, or they, can help students comprehend explanations better. In lectures, gestures can bring emphasis to visual aids. The educator can also pantomime unseen phenomena to help students understand what is happening conceptually.

While gestures can be helpful, they can also be problematic. Gestures not in sync with talk can be difficult to follow, and important concepts can be missed. Additionally, gestures can communicate something completely different than what is being explained, such as pointing out length when discussing width. Lastly, gestures can communicate an entirely wrong scientific explanation.

Mathematical

It is broadly accepted that mathematics is the language of science (Bain et al., 2019; Lemke, 2004; Sherin, 2001). Chemistry as a science discipline would not be complete without mathematics as natural language cannot describe all the intricate degrees of measurement needed to carry our chemical reactions. A common example can be seen with the *mol*. This is a unit for an amount of substance but does not have a physical embodiment. Chemists rely on the ability to convert mathematically between tangible masses and the abstract *mol* concept (Unsworth et al., 2022). Bain et al. (2019) stated, "it is also important to note that mathematics is framed differently and used differently by mathematicians in comparison with how physical scientists use mathematics" (p. 2086). Although Lemke (2004) used 'mathematical expressions' as a broad mode of the unique hybrid language, Johnstone (2010) grouped mathematics with the symbolic. While chemistry uses typical mathematical equations, relationships, expressions, and functions, mathematics is also used symbolically (Bain et al., 2019). For example, variables in an equation with addition signs between them symbolically showing system parts of a whole (Becker & Towns, 2012; Sherin, 2001). Understanding the relationships shown in equations or expressions is known as a symbol template. The variables in equations are tied to real objects or concepts in chemistry, unlike solving for x in mathematics. Therefore, the variables and what they stand for have relationships; referred to as conceptual schema (Sherin, 2001). Additionally, chemical formulas and chemical equations represent ratio relationships despite not being in typical mathematical form.

Science is a data-rich discipline, and mathematics are crucial to data analysis. Graphical forms of data help scientists find patterns in phenomena. Bain et al. (2019) stated, "when characterizing graphical forms, the general term *registration* was used to describe the graph or the region in a graph attended to; thus, reasoning involving graphical forms occurs when an individual *registers* a mathematical idea to a graphical pattern" (p. 2091). For example, this could be recognizing a rising straight line as a direct relationship.

Mathematical fluency beyond solving an equation is needed to be successful in chemistry (Bain et al., 2019; Becker & Towns, 2012). There are several scaffolding techniques educators can use to help students. Becker & Towns (2012) suggests that educators utilize collaborative problem solving where students work in small groups. Similar to scaffolding group work for developing concise natural language skills, there is low-pressure to negotiate concepts and mathematical understanding. The educator also has opportunities to observe students' reasoning and provide supports or intervention when needed. Additionally, educators need to provide multiple opportunities for students to work with different representations of the objects or concepts under study to anchor them to the mathematical model (Johnstone, 2010; Unsworth et al., 2022).

Symbolic Visual Representations

Symbolic visual representations are not just ways for chemists to communicate but also to think about the submicro and abstract levels of chemistry (Ainsworth et al, 2011; Akaygun & Jones, 2014; Farheen & Lewis, 2021; Johnstone, 1993; Talanquer, 2010). These visual representations become mental models for explaining and predicting chemical behavior. Most students think at the macroscopic or tangible levels; therefore, symbolic visual representations must be anchored to the macroscopic. Ainsworth et al. (2011) summarizes that visual representations can help to clarify ideas and examine thinking. For students, thinking in this submicro level and with visual representations is difficult and takes practice and guidance from the educator (Farheen & Lewis, 2021). Farheen & Lewis (2021) describes the skills students develop as representational competency. There is a positive correlation between using visual representations and students understanding in chemistry as they develop their representational competency (Farheen & Lewis, 2021). Farheen & Lewis (2021) conducted a study examining students' ability to make predictions of chemical properties from visual representations of molecules. They found that how features of the visual representations were cued by professors impacted student predictions.

Symbolic visual representations can vary in simplicity and complexity (Weinburgh et al., 2019). These representations can include labeled pictorial diagrams, process diagrams, chemical formulas, graphs, and three-dimensional models (Farheen & Lewis, 2021). In chemistry, several different representations can serve to represent the same concept but different functions depending on the need and the model's limitations (Akaygun & Jones, 2014; Farheen & Lewis, 2021; Patron et al., 2017). For example, chemical compounds can be represented by chemical formulas, space-filling molecular models, ball-and-stick models, Lewis Dot Structures, Dashed-Wedged Line Structures, or Bond-Line Structures (sometimes referred to as skeletal structures). All the models convey the atomic components of a chemical compound but vary in describing the complexity of the compound in structure and dimension.

The Patron et al. (2017) study focused on educators' use of symbolic visual representations. They found that educators focused more on the use of symbolic visual representations rather than the features. Educators were more likely to use multiple representations than use the same representations multiple times. They focused on meaning-making with visual representations but not the meaning-making of the visual representations. This narrow focus is problematic since students will not learn the communicative power of the representations.

Manual-Technical Operations

Weinburgh et al. (2017) described manual technical operations as an "active process" "done with the hands" with "specialized tools as recognized within a community" (p. 37). Manual technical operations allow students to interact with and experience chemistry. For students to adopt the manual technical language they must have opportunities to collect data and engage with the tools themselves (National Research Council, 2006; Weinburgh et al., 2017). To facilitate students' adoption of manual technical operations, professors should consider embedding as many of the manual technical norms in an experience as possible. These actions can "take many forms from donning particular safety gear to the operation of highly specific tools" (Weinburgh et al., 2017, p. 37).

Weinburgh et al. (2017) created a three-dimensional meaning-making cube to describe "the complexity and interdependency of the components as tools (complex to simple), manipulation (gross to fine motor), and context (highly specialized context and everyday context)" (p. 39). For chemistry, a beaker would represent a simple tool that does not require fine motor skill, other than being careful not to break it, and is not specialized to chemistry (it is used in other disciplines). In contrast, a rotary evaporator (called a rotavap for short), is a complex tool, with lots of parts, that requires some finer motor skills, like those needed to secure a round bottom flask to the rotavap, and is highly specialized to chemistry.

As mentioned, students think in macroscopic and tangible ways (Johnstone, 1993). Students can utilize the macroscopic modes to anchor their understanding of chemical concepts as they begin to think more abstractly. As students begin to learn manual technical operations, the focus of the learning is on the movement. These skills need to be repeated to build fluency and competency. As students become more proficient with the tools less focus is on learning the movement and can then be connected to other modes of thinking (Weinberg et al., 2017). As students engage with and collect data, they manipulate the data in redescriptions using natural, mathematical, and symbolic language.

Opportunities to engage in manual technical operations should be frequent, iterative, and similar to authentic practice. Not all manual technical operations have equal weight and instead depend on the quality and context of the interaction. For quality purposes, there should be some meaning-making involved with the operations. For context purposes, the environment in which the interactions occur should fit the experience. Weinburgh et al. (2017) states, "tools, movements, and contexts … must interact in unique ways to be considered as the manual-technical operational mode of the hybrid language of science" (p. 45). Additionally, the manual-technical operations must be interconnected to the other modalities for meaning-making to occur.

Studio-Based Chemistry

Traditional lecture-laboratory

Laboratory experiences are considered a staple in science education. Laboratories can improve scientific thinking, practical skills, and understanding of science concepts taught (National Research Council, 2006; Weinburgh et al., 2017). Traditionally, an undergraduate chemistry course is offered as a separate lecture and laboratory section. Typically lecture meets two or three times per week for a total of three hours, and laboratory once a week for four hours. This separation causes a disconnect that lowers the construction of meaning and understanding of chemical concepts taught in lecture (Altmiller, 1973; Collison et al., 2012; DiBiase, 2002; Gottfried et al., 2007; Greco, 2018; Kiste et al., 2017). Over the last few decades, researchers have sought to reform the undergraduate chemistry laboratory experience. The reform that this study will focus on is the fusion of laboratory and lecture, frequently called studio-based design. In contrast to separating lecture from laboratory by both space (rooms) and time (days), the studio-based style merges them together.

DiBiase (2002) questioned the quality of the traditional laboratory experiences when separated from lecture. "The format of traditional laboratory experiments tends to be confirmation or 'cookbook' labs, which students are aware of what they will observe prior to beginning the experiment" (p. 158). Content presented in lecture is often asynchronous with content experienced in the laboratory. Students also produce correct answers, but this does not necessarily reflect learning.

Studio-based design

The design of a learning space can significantly impact the learning experience and can be part of an effective teaching practice. Modern pedagogical methods face challenges in teaching and learning due to the influence of physical spaces, prompting a redesign of learning environments as the paradigm shifts away from lecture-based teaching (Br et al., 2021). Studies of spaces beyond the traditional classroom have shown more opportunities for interactive and collaborative experiences among students and teachers. Br et al. (2021) explain that different approaches to teaching can be enabled by the space, especially when there is a quick transition between lectures, discussions, and project work. However, the space can only encourage changes in pedagogy but does not guarantee that the teacher will make the transition.

Br et al. (2021) conducted a study on learning spaces based on research in environmental psychology and learning processes. The researchers describe a new generation of learning spaces based on prior research on active learning classrooms, flexible learning spaces, and innovative learning environments. For this research, active learning classrooms and flexible learning spaces are of most interest. Active learning classrooms are described by the researchers as learner-centered and enable collaboration. They describe flexible learning spaces as areas that "can respond to different user needs and individual goals that change over time… The design of these spaces is directly related to the learning behavior that students are expected to exhibit in each area" (p. 5).

Furthermore, a review of research by Ellis and Goodyear (2016) defines key constructs for learning spaces. While there is a broad range of definitions for learning, the researchers describe three metaphors that directly relate to space. The first is in terms of the learner acquiring knowledge or skills and requires the least thought on space. The second metaphor holds the learner as a participant in which the space should include “learning how to appropriate the tools, and work out how to dwell in the spaces, that are involved in those practices” (p. 156). The third metaphor is learning involves knowledge creation where “collaborative creation of new knowledge, ideas, practices and artifacts” occurs and students understand the process involved (p. 155). The second and third metaphors require more consideration for the learning space. Furthermore, they define the difference between space and place. Space is a more encompassing term from a planning perspective and can include multiple places. Places are the spaces that are constructed for their intended purposes such as lecture halls or laboratories. To create spaces and places where learners are participants and create knowledge, learning spaces need consideration and redesign.

These new generation learning spaces as described by Br et al. (2021) would have specific notable aspects. Some of the aspects focus on the professor’s positioning, such as not having a “defined front of the room” where the teacher is stationed (p. 12). The researchers idealize close proximity between the professor and students which increases interaction and collaboration. Additionally, the professor can move around the space to address different student needs, monitor students, and shift between lectures and activities. Furthermore, the space should enable peer to peer interaction to encourage collaborative learning.

There is increasing interest between teaching practice and learning in the science education community. One focus on learning spaces is the combining of lecture and laboratory in terms of place and time. While there was no specific name for this combination or lecture and laboratory learning space, researcher have begun to call it studio-based. According to Wilson (2001) the Studio Course model implemented at Rensselaer Polytechnic Institute originated from reform the teaching methods in physics and calculus in the 1980s. During the course revisions, the researchers realized that something was still missing. Wilson (2001) states “Problems had been changed and curriculum revised, but there had not really been a fundamental redesign of the course” (p. 2). In order to achieve significant reform, the environment had to be redesigned with the course. In 1993 a panel of educators, architects, and industry professionals began to develop a studio style space that would combine lecture and laboratory.

The term studio originates from the educational studios where architects and artists learn their crafts. According to Wilson (2001), there are many variations on the studio-based design as it has been implemented at other universities. Although the studio-design is not prescriptive, there are similarities in implementation. The planning of space is more important that place. There is room for students and professors to move around and interact. Additionally, there is adequate workspace for students to participate in hands-on activities. The emphasis is on students playing an active role in their learning and a de-emphasis on lecture or the professor. Although the lecture is reduced in studio-based design, it is not entirely eliminated. While this style of teaching is occasionally referred to by other names, such as workshop or integrated, the term studio has been the most wide spread. It has been applied to many different science subjects including chemistry.

Although reform to change the lecture and laboratory structure of undergraduate chemistry has picked up speed in the last few decades, the idea of combining lecture and laboratory experiences is not new. Dewey (1938) contends that students learn by experience but not just any experience; learning depends on the “quality of the experience” (p. 27). It is the role of the educator to create meaningful experiences. These meaningful experiences occur socially through interactions and knowledge is constructed through a social process. This positions the educator as the guide or leader rather than the holder of the information. Many of the characteristics of active learning classrooms, collaborative learning models, and studio-based design align with Dewey’s experiential learning theory.

Altmiller (1973) expressed concerns with the traditional approach to teaching chemistry because “students are given no opportunity to act as scientists or learn as a scientist learns” (p. 249). He combined lecture and laboratory into two four-hour sessions per week to allow students to move between the laboratory experience and lecture. Students experienced the principles of chemistry before they were presented in a lecture or discussion. This format improved the alignment between lecture and laboratory and helped make concepts more concrete. The groundwork laid by Altmiller's combined lecture and laboratory format generated more interest from other researchers.

During the 1990s, when laying out the structure for studio-based delivery primarily in physics and chemistry, there were positive responses from both students and instructors. This led to increased acceptance and a more thorough assessment of the method across other science disciplines (Rees & Wineberry, 2020). “The approach has been most widely studied in physics, chemistry, and biology courses. Results from research in these topic areas have ranged from positive to neutral” (Rees & Winberry, 2020, Introductory section). In a systematic review of over 25 other studies, Rees & Wineberry (2020) found mostly positive and neutral results were reported compared to the traditional delivery method. Benefits gained from the integrated approach include student attitudes, motivational beliefs, and student engagement (Greco, 2018; Kiste et al., 2017). Some studies found improvement in conceptual understanding and learning outcomes, while others found no significant difference (Gottfried, 2007; Rees & Winberry, 2020).

Similar to Dewey's learning by experience, Round and Lom (2015) stated science coursework requires immersion to mimic the way real science happens. They posed the question if athletes are trained by immersion in their sport with lecture and coursework secondary, "why then do scientists train undergraduates in an inverse fashion" (p. A206). The summer immersion program is similar to an internship because it engages students in authentic scientific research. While their research specifically focused on student engagement, the researchers stated that the authentic research would be aligned with the instructor's enthusiasm. This suggests that the immersion program would also be beneficial to the instructor.

Kiste et al.'s (2017) study on student outcomes in a general chemistry class adds to the growing body of research on the studio-based model. The model was first introduced to their university in 1994 but was constrained in its implementation due to size limitations. Initially only offered to engineering majors, the program was expanded in 2013 with the addition of custom-built classrooms for the studio-based design. The framework for their study includes social constructivist learning theories that include active learning models, cooperative learning strategies, and computer simulations.

The course is implemented in either three 110-minute sessions or two 170-minute sessions per week. Enrollment options include 48 or 64 students, with one faculty member and one to two teaching assistants. "In these studios, classes frequently transition between laboratory work, computer simulations, small-group discussions, problem-solving, direct instruction, and formal and informal assessments" (p. 233). The classroom design includes workspaces equipped with computers with seating for six to eight located in the center of the room. In addition, the laboratory workstations are interspersed along the walls of the classroom, alternating with lecture spaces such as projector screens or dry-erase boards.

Overall Kiste et al. (2017) found an increase in student performance, a shift toward expert-like learning attitudes, and an overall positive opinion from students. Additionally, the researchers found that the educators in their study responded well to the studio-based style. The feedback from the instructors indicated that there was an improvement in the level of interaction between the students and instructors.

Nearly all current research on the combination of lecture and laboratory is focused on evaluating student outcomes. Some research included the educator’s reflections and notes but few studied laboratory immersions as an instructional practice. Bailey et al. (2000) mentioned that “Instructors new to this integrated form of teaching tend to fall back on traditional lecturing” (p. 198). This is also expressed by Bret et al. (2021), who found that while space can assist the professor, the place does not guarantee success in creating a new generation learning space. Additionally, some research focused on collaborative learning with reports of student-to-student interaction but did not include interaction between the educator and the students. The educator is essential to the role of guiding students through the construction of knowledge.

Summary

Often chemistry students must navigate between multiple combinations of the language modalities at a very rapid pace (Lemke, 2004). Educators may not be aware of the speed these changes occur because they are very well versed in chemistry and chemical discourse. Educators need to be explicit in teaching students the connections between the different modes of language (Lemke, 2004). For students to gain proficiency, they must also practice the language of chemistry often and allow them to reproduce the blending between them (Lemke, 2004). Studio-based chemistry also helps to build proficiency by providing the space for the different modes to occur.

Lemke (2004) contends scientific literacy requires that meaning is made conjointly. Texts are full of the words, math, and symbols that chemistry uses but can strain students if used alone because they lack context (Weinburgh et al., 2019). Natural language, mathematical language, and symbolic visual representations provide a resource for students to learn scientific literacy but should be situated in laboratory experiences, such as studio-based chemistry. Laboratory experiences provide excellent opportunities for students to interact with phenomena but are a missed opportunity if separated from other modalities. Laboratory experiences can embed all four modes of the hybrid language together like the simulated notebooks used by Magnusson and Palincsar (2004). The notebooks included text, data, graphs, diagrams, and illustrations. Students would then perform laboratory experiences to collect and add to the information in the notebook. The text provided two-way communication of language for student learning. The educator guided the students by providing an additional level of support in the students' language acquisition.

Studio-based chemistry allows students and educators to move between lecture and laboratory seamlessly. Combining space and time for both allows meaning-making to occur, similar to how Johnstone (1993) described the way chemists think. Strategically, moving between all four modes of language and allowing students to anchor them together will reduce the academic load on the student. This can help them be willing to accept the entry into chemical discourse. Revealing language when the students can actively engage with the language at the time of use helps to build a better understanding of the content (Weinburgh et al., 2019). Using the unique language consistently with meaning, can help to foster an understanding of relationships (Weinburgh et al., 2019, Wolpert, 1992).

Borte et al. (2020), in a systematic review of 66 articles, found many barriers to implementing student-active learning in higher education. Two areas of interest in Borte et al.'s findings are particularly relevant to this study: the barrier of space and the barrier of pedagogical development. The researchers emphasize that leaders must consider the design of rooms, buildings, and furniture to help facilitate student active learning and plan professional learning opportunities for staff. Furthermore, they state that "teaching staff must consider the relationship between expected learning outcome and pedagogical approach" (Borte et al., 2020, p. 11).

Altmiller's (1973) intention was to redesign the chemistry course to allow students to act and learn as scientists. This study addresses the limitations in the current literature on the relationship between multimodal discursive practices and space. There is a plethora of research on multimodal discourse in terms of how scientists construct knowledge and communicate. Additionally, there is emerging research on studio-based design for science classrooms, but most of the research is focused on student outcomes. This study attempts to serve as a model for teaching practices using multimodal discursive practices in the context of a studio-designed space.

Chapter 3

Methodology

The findings from this study may help provide a better description of how professors can incorporate multimodal discursive practices and successfully interweave them with studio-based chemistry. While both multimodal discourse and studio-based chemistry have a similar purpose of improving student understanding, it can be overwhelming for a chemistry professor to determine how to incorporate them together. This study does not seek to examine or quantify the students' gains of chemical discourse. Nor does it seek to assess the professor's knowledge of multimodality or studio-based courses. Therefore, a qualitative design approach is an appropriate fit for the purpose of this study. The following chapter describes the methodology in which the study is conducted.

Case Study Methodology

Case study methodology is widely used among the social sciences. Well defined design and implementation is often debated. In addition, what constitutes a case can be disputed (Schwandt & Gates, 2017; Yazan, 2015; Yin, 2009). Two prominent points of view, Merriam and Yin, are utilized to define the parameters of a case study. As Creswell (2013) explained, a case study is centered on what is to be studied. Creswell further describes this as "a real-life, contemporary bounded system (a case) . . . over time, through detailed, in-depth data collection" (p. 97). Schwandt and Gates (2017) contribute to the description of a case study as "an in-depth exploration . . . of the complexity and uniqueness of a particular project, policy, institution, programme, or system in real-life context" (p. 595). This study follows Merriam's view of a bounded system which is the professor and is limited to the teachings that occur during the intensive summer program (Creswell, 2013; Yazan, 2015). This study, more specifically, would be a descriptive case study with a purpose to "develop a complete, detailed portrayal" (Schwandt & Gates, 2018, p. 597). The purpose to provide a rich, holistic description of the professor's techniques further reflects the Merriam view (Schwandt & Gates, 2018; Yazan, 2015). Lastly, the Yinian point of view (Creswell, 2013) centers around the explanatory nature "how" questions. This study's primary focus is how the chemistry professor incorporates multimodal discursive practices in a studio-based style class, correlating to the Yin definition. Based on these parameters the case study methodology is an appropriate choice for methodology.

Context

This research was conducted at a private liberal arts university in the southwest. It is a residential university with an enrollment of about 12,000. The Upward Bound program provides support programming to low-income students high school students, under the age of 19, with the potential to be first-generation, college students. The Upward Bound program allowed students already to enrolled for the summer classes to self-select to participate in the research chemistry immersion program.

The teaching occurred during a four-week, university-based Upward Bound summer program. The Upward Bound program provides marginalized students with support and opportunities to enrich their academic potential. The summer enrichment program took place in the month of June where students were immersed in an organic chemistry research experience for half a day. During that time, the professor engaged students in lessons, instruction, or conducting laboratory experimental research. The professor planned out an authentic chemical research project for the students, in which new potential molecules were recycled from old medications and tested for antibacterial properties. He guided the students through the entire process of planning out the research, conducting laboratory experiments, testing the resulting molecules, and presenting the findings in a public forum.

The laboratory had two zones: partial safety zone (PSZ) and full safety zone (FSZ). The PSZ did not require as much personal protective equipment (PPE) and was separated from the rest of the laboratory by two workbenches that spanned the length of the laboratory. Most of the lectures took place in this area. The rest of the laboratory included an additional workbench with fume hoods that lined the walls. This area was where all chemical experiments were conducted as well as techniques were demonstrated. This area, having caustic chemicals allowed, was a full PPE area. Other areas where the experience was located included a conference room, a chemical research laboratory, a biology laboratory, and a lecture hall. For the context of this study, the conference room and PSZ will be referred to as the lecture areas and the FSZ and research laboratory will be referred to as the laboratory areas.

Figure 1

Map of the main lecture/laboratory room for the chemistry summer program.

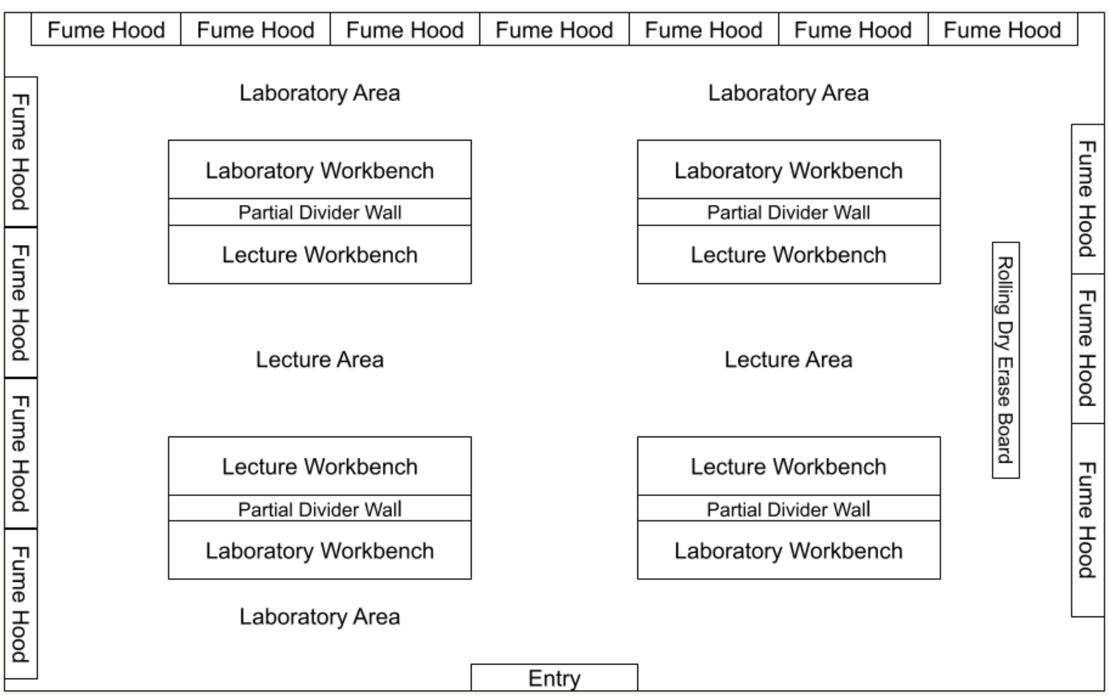


Figure 2

The lecture area (PSZ)on the right side of the room with a dry-erase board.

Figure 3

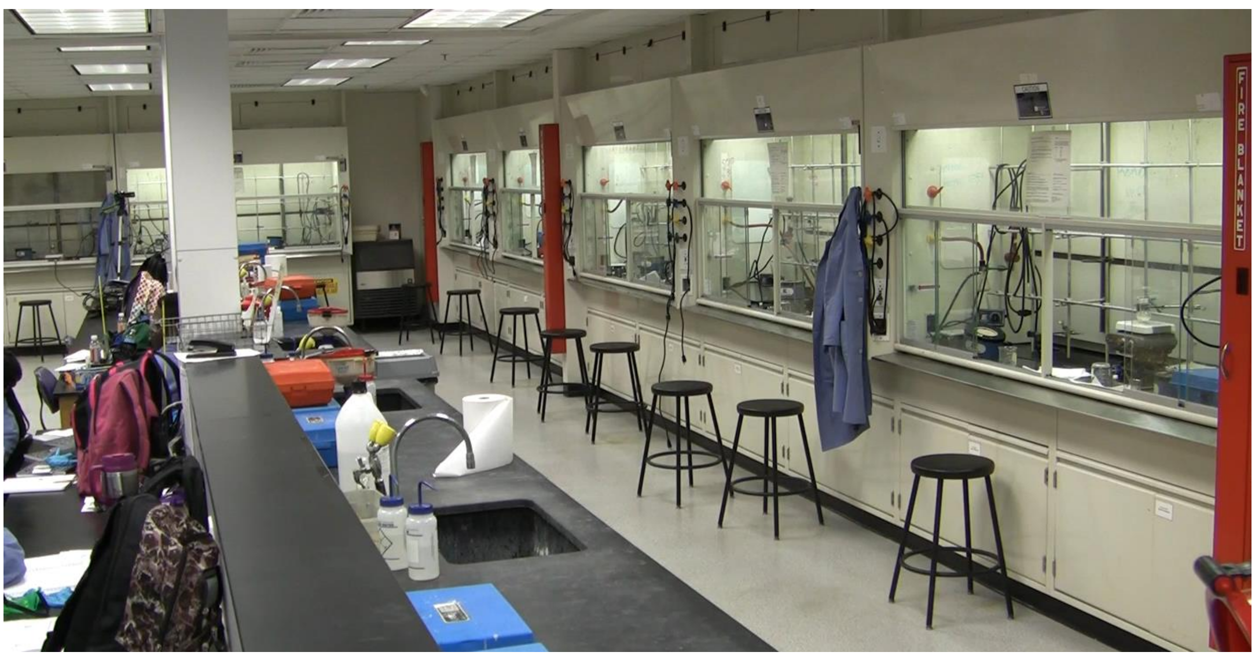
The lecture area (PSZ) facing away from the dry-erase board to the left side of the room.

Figure 4

The laboratory area (FSZ) facing to the right side of the room.

Figure 5

The laboratory area (FSZ) facing to the left side of the room.



Researcher positionality

In qualitative research, it is important to recognize and be aware of possible biases. As the sole researcher, I have experience in both chemistry and in science education. Additionally, I have a strong science background that was instilled in me from childhood. Being raised in a well-educated upper middle-class family with a heavy focus in math and science helped to form a more positivist viewpoint.

My post-secondary education was in chemistry. Earning a degree in chemistry with a math minor shaped me to view data in a more quantitative way.I have taught chemistry in the high school setting for 16 years. Working in a quantitative data driven school district teaching science further contributed to a positivist and quantitative viewpoint. After the first few years of teaching, I earned a graduate degree in science education. It was then that I became interested in how students learn and understand natural phenomena. During my graduate studies my philosophical stance has moved from a positivist viewpoint ingrained in chemists to a more constructivist found in educational researchers. However, it was not until my doctoral program that I began to shift to focusing on education in a more qualitative way.

I was a teacher's assistant in this immersion summer program and was present at every session. I did not assist the professor in developing the curriculum, however in some cases I led the class in mini lectures and quantitative data calculation. My position as a teacher's assistant allowed me to work very closely with the students and directly under the professor. My time with the students shifted my perspective to the instructor's view. In addition, I was a research assistant involved in examining the data for different research questions centered on the students. Conducting research with the focus on the students could hinder my views on the impact of the professors teaching. There was a potential for my viewpoint to negatively impact the validity of my study, but all care was taken to mitigate the impact.

Participant

Pseudonyms are assigned to the professor and university to protect confidentiality. This case study examines the teaching of one chemistry professor (Dr. S) who is a well-respected faculty member and is enthusiastic about teaching chemistry. At the time of this writing his main teaching focus is on graduate level chemical research and special topics. In the past he taught undergraduate chemistry and participated in outreach programs. He is well respected in both chemical research and teaching. He was asked by the Upward Bound Program to participate in this project. Dr. S had no formal instruction on multimodal discourse or studio-based chemistry courses.

Data collection

The data used in this study are archival (IRB #1604-048-1605) from a previous study that was a collaboration between the chemistry department, the college of education, and the Upward Bound program at a private university. The previous study investigated discourse practices and communities of practice of the students in the summer chemistry immersion experience.

Data used in this study were video recordings collected for 20 days. Cameras were used to capture as much of the activity going on during the "class." When possible, there were two cameras set up at opposite ends of the laboratory/lecture space. Occasionally, one of the cameras was moved to the chemical research laboratory to collect activity in that space. The video files were transferred daily to a secure server by the research assistants.

Data Analysis

Data analysis for case studies consists of creating detailed descriptions. (Creswell, 2013). This can be especially important if the setting is important as it is in this research. Data from the video tapes were collected and transcribed into detailed descriptions of the actions and interactions of the professor and the utilization of the space in the laboratory. In effort to analyze how the different modalities and studio-based design act together over time a spreadsheet (Appendix A) was used to organize descriptions. The data were already cataloged and sequenced by day into folders. Sequencing is maintained on the spreadsheet. All data were kept organized by creating a different sheet for each day. For easy retrieval, descriptions were also given markers consisting of camera, clip, and beginning time stamps.

Data were analyzed by reviewing the video using the frameworks of chemical discourse and studio-based chemistry course. Since both frameworks can be presented at the same time, the researcher watched each day multiple times using the frameworks simultaneously. Detailed descriptions of actions and interactions of the professor were recorded using a priori coding specifically based off the work of Van Rooy and Chan (2017). The categories include the five major modalities of natural language, gestures, mathematical, symbolic visual, and manual technical. Further sub coding occurred to indicate the location of the actions and interactions to develop the role studio-based design plays in the supporting of multimodal discursive practices. These categories include the laboratory area, designated by the full safety zone, the lecture area, designated by the partial safety zone, and crossing borders, where the professor moves in an out of both areas. Using direct interpretation, as described by Creswell (2013), data from the spreadsheets were reviewed to analyze each code separately and attempt to make connections between the multimodal discursive practices and studio-based chemistry. During interpretation, interrelated themes were categorized and descriptioned.

Chapter 4

Findings

This chapter presents a description of a professor's teachings in an immersion summer program through the lens of a case study. It is divided into two sections, addressing the research questions: (1) How does the chemistry professor incorporate multimodal discursive practices into his teaching, and (2) How does studio-based chemistry support the chemistry professor with incorporating multimodal discursive practices?

Multimodal Discursive Practices

This section describes Dr. S's teaching practices, specifically addressing research question one: How does the chemistry professor integrate multimodal discursive practices into teaching? For this paper multimodal discursive practices have been divided into five modes: natural language, gestures, mathematical expressions, symbolic visual representations, and manual technical operations. Each mode underwent individual analysis. Despite some overlaps, each subsection principally focuses on one mode. This division provides a comprehensive examination of Dr. S's multimodal discursive practices, offering insights into their integration within the teaching context.

Natural Language

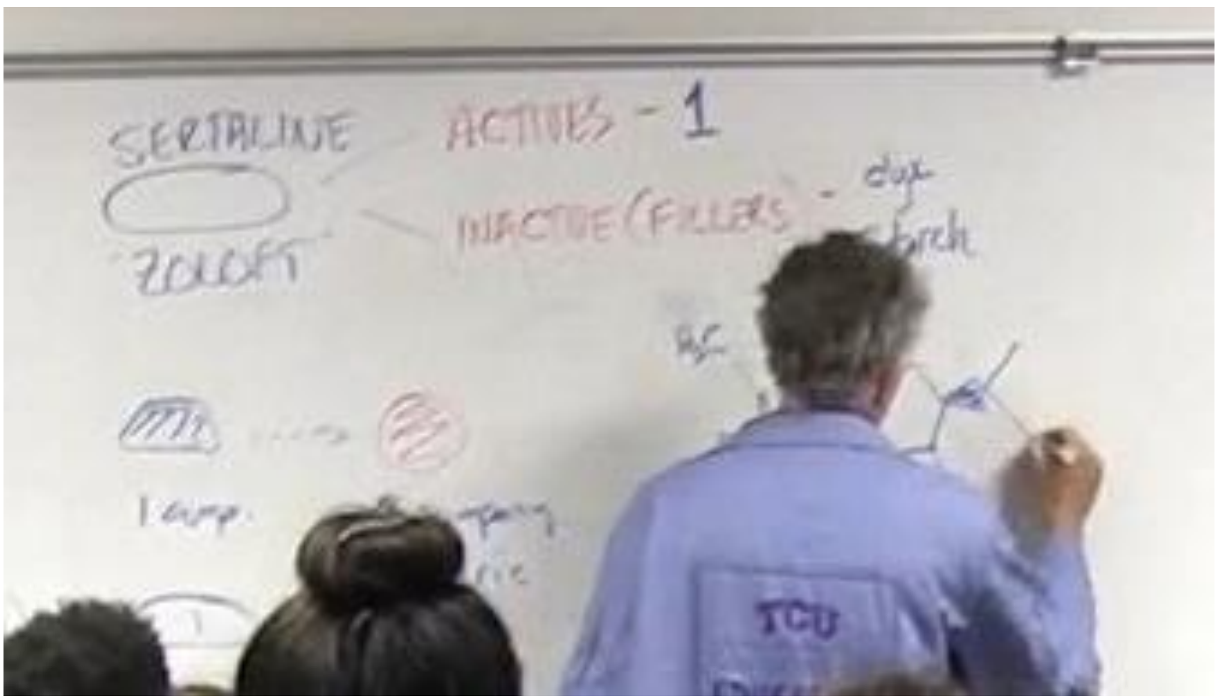
Dr. S predominantly employs natural language discourse throughout the immersion summer program. He articulates his actions verbally, providing detailed commentary on nearly every aspect of his instructional activities. Occasionally, he writes words on the board that accompany his explanations but uses the written words sparingly. In contrast, he has the students journaling and writing more than he does.

On day one, Dr. S introduces the students to the foundation of chemical research. During this introduction, he stands at the end of the table and engages in a more informal conversational approach. He talks and listens to students discussing what happens to unused medications. He asks students different questions, and as the students answer, he repeats and rephrases their answers. For example, he asks, "… when a lot of people change meds, don't finish their meds, and so what's the most common thing that happens?" He pauses to listen and repeats, "Throw them away," adding, "So where do they end up?" He pauses again, repeating "trash" and adding "and then ultimately, often times in water supplies." He then gives examples of what kind of research comes from medications in water sources. He transitions his focus to the medication they are using for research. He holds up the pills and askes, "What is a pharmacy going to do with these [pills] you think?" As students make suggestions, he focuses on one of the suggestions of proper disposal and responds, "How do you throw them away properly, though?" After listening to answers, he adds, "It turns out that typically with old chemicals, they just burn them, turn them into CO_2." Although the students are in a large group, they are engaged in the conversation. This more conversational introduction helps to ease students into the difficult lessons they will encounter later.

After students were introduced to the basics of chemical research, he focuses on the pill they will use in their research. He asks the students, "As you look at these pills, what do you think is in them? How would you describe the pill?" He allocates time for students to think and journal in their science notebooks. Afterward, he asked students to share their thoughts. As they respond, he makes suggestions and writes the words "physical property" on the board to emphasize it. Next, he suggests, "So, let's think about the chemicals inside this pill; what do you think?" As they talk through the process of understanding what is in the pill, he offers different terms that can be used for what the students are describing. He suggests, "So what we're going to call these kinds of chemicals are actives." He asks, "And so what do you think the other part, the big thing in the pill, is?" After listening to the student's answers, he responds, "Fillers, or inactives, right? And fillers is actually the technical term.” He writes the technical terms on the board, like "actives” and "inactives," to draw attention to them as he reveals them, as seen in Figure 6. This technique helps students gradually change their language from everyday to a more precise language of chemical research.

Figure 6

Dr. S writes emphasized words on the board.

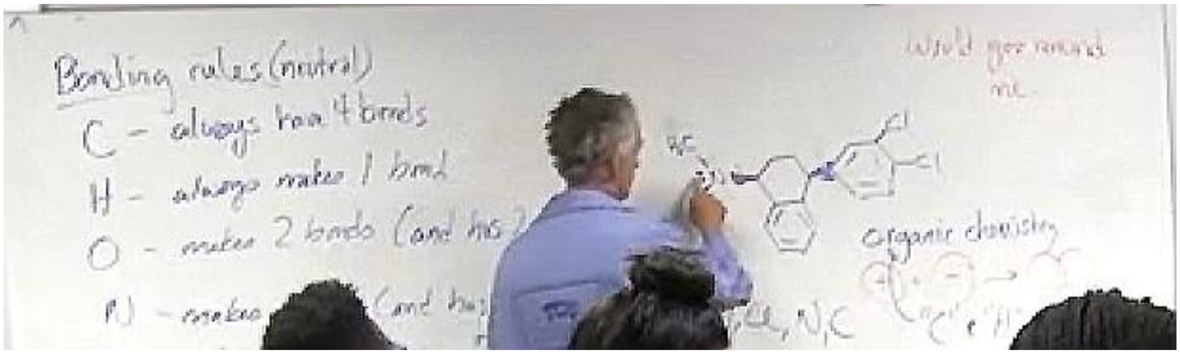


Dr. S employs this language transition approach throughout his teaching during the program. Another example of this language transition approach occurs when he talks extensively about thin-layer chromatography (TLC) plates, including how they work, what they are used for, and how to use them to perform laboratory tests. He begins the lesson with an analogy and discusses chromatography in general. He first introduces the word to students by breaking it down into its root words. He states, “What I want to talk to you today, before we start, and we try it, is something called chromatography. ‘Chroma’ for color and ‘graphy’ for plotting or separation.” He gradually guides the students through the ideas of molecules sticking together and to other substances and then relates the concept to the terms polar and non-polar molecules. He goes on to discuss the way molecules push and pull their way through the chromatography medium. He later transitions those words to the concept of capillary action.

He uses oral natural language to support the visual or manual technical operation when introducing tasks, such as drawing out molecules or performing laboratory practices. This is shown when he introduces the concept of skeletal structure. First, he calls the process of reading the diagram a translation. He then has the students create a list of elements in the molecule. While composing the list, he indicated the locations of the element symbols. Subsequently, he inquires, 'What's all this other nonsense?' gesturing towards the lines drawn in the middle of the molecule. Students hesitantly suggest bonds, to which Dr. S responds, "It's called shortcut. So, chemists will take shortcuts all the time because it would be a pain to write out every atom and label them." Next, he reviews the bonding rules used to construct and deconstruct the diagrams. He records (written natural language) each of the element's bonding rules as he discusses (oral natural language). He goes through each element to show where it is in the molecule and the bonds attached, as seen in Figure 7. He and the students created a chemical formula from the diagram through this process.

Figure 7

Dr. S translates a skeletal structure.



On day five, Dr. S relies on oral natural language to support his manual technical operation of extracting their compounds using the rotary evaporator, or rotavap, and a separatory funnel. First, he introduces the process while drawing diagrams on the board. He then walks the students to the other end of the laboratory to demonstrate the technique using the separatory funnels. Technical terms are introduced as he explains the parts of the separatory funnel. Procedural oral natural language is used as he provides safety tips. He then explains the transfer process of the different substances and the layering effect that occurs. Dr. S walks through the steps, stating, “I’m going to transfer this first bunch a goop to this sep funnel… and I’m going to make two layers, and one layer is the dichloromethane, and the other layer is going to be some water.” Swirling the chemicals in the separatory funnel, he adds, “I’m going to put this cap in and I’m going to slowly invert [the separatory funnel] because I’m worried about CO_2 gas being [ejected].” Continuing to vent the separatory funnel, Dr. S notes, “You hear that little pffft sound? If you were close to me, you might have heard it go pffft.” Demonstrating further, he rolls the separatory funnel around in his hand, explaining, “Ok, so, I’m actually just going to stir it gently. I’ve got my hand pretty tightly over the bottom, so it doesn’t come out.” Once satisfied with the mixing, he returns the separatory funnel to the ring stand, stating, “And now I’m going to hope it separates into two nice layers." Allowing time for the layers to settle, Dr. S points out, "There is a boundary right here" while pointing to the area between the layers, as shown in Figure 8.

Figure 8

Dr. S shows the layering effect in the separatory funnel.

Once the layers have been divided, Dr. S takes the students down the hall to the laboratory with the rotavap and again uses technical terms and procedural words as he explains how to set it up. While attaching the round bottom flask to the rotavap, he remarks "It's drawing a vacuum." Additionally, he warns "[students] just assume the vacuum will hold their flask on there, and they don't clamp." Dr. S then explains that the flask can fall off and spill into the water bath. As he turns a dial on the rotavap, shown in Figure 9, he explains "What I'm going to do is start spinning this thing." He adjusts the seal on the end of the vacuum tube, adding "So now I'm going to try to close this, with the hope that it doesn't explode all the way through… So, what I'm doing I'm watching my vacuum and I'm watching this [the flask]." Talking through the demonstration and using more familiar words with the technical words helps the students with meaning-making before they perform the laboratory procedures themselves.

Figure 9

Dr. S adjusts the settings on the rotovap while explaining the process.

Analogies have long been recognized as powerful tools for simplifying complex topics and enhancing understanding. They allow individuals to draw connections between unfamiliar concepts and more familiar ones, making it easier to grasp abstract or challenging ideas. Dr. S uses these analogies to assist the students in comprehending complex topics. For example, on day three, Dr. S begins discussing TLC plates by asking the students to propose a method of separating a bag full of bees and wasps. He then leads them through the concept of bees moving slower through a tube with flowers because they are attracted to the flowers, whereas the wasps would fly past the flowers. Students are familiar with the concept of bees and wasps, making for a vivid visualization tool. He connects the ‘bees and wasps’ concept to polar and nonpolar molecules moving across a TLC plate. By comparing the polar and nonpolar molecules to the bees and wasps, he helps students visualize and conceptualize this abstract idea. The analogy also serves as an anchor for the students as they become more familiar with TLC plates. He continues referring to this analogy when discussing TLC plates on days four, five, and seven.

Using analogies, Dr. S bridges the gap between complex topics and students' prior knowledge and experiences, making the content more accessible.

Dr. S spends most of the time at the beginning of the program talking and listening to the students in a whole group setting. He transitions to more one-on-one discourse with students and less whole group toward the end of the program. For example, on day one, Dr. S spends the majority of the day introducing students to chemical research, and they do a brief introductory tour of the laboratory. On day three, he splits time between working in the laboratory and discussing concepts at the board, with some group discussions lasting 40 or more minutes. On days six and seven, he still transitions students back to the lecture area between laboratory experiments at various points of the day. These mini lectures are often brief, approximately ten minutes before he dismisses the students to carry out more reactions. While students are working at the fume hoods, he can be seen going from group to group, checking in on students, talking, and listening to them. In the last few days, he mostly has a brief recap time at the beginning of the day, where he tells the group what tasks must be done before leaving. The rest of the day is spent with the students working and Dr. S helping where needed.

Gestures

In the studio-based learning environment designed by Dr. S, gestures play an integral role in his communication and assistance to students in constructing meaning. Dr. S frequently uses hand gestures with verbal discourse, except when performing specific laboratory techniques. These gestures serve various purposes, such as directing attention, synchronizing key points, mimicking actions, or pantomiming laboratory procedures. Whether guiding students through intricate concepts or demonstrating laboratory processes through gestures, Dr. S skillfully utilizes this non-verbal communication to guide learners and enhance their comprehension.

Directing Attention

To engage students fully in the learning process, Dr. S adeptly employs gestures that serve the crucial role of directing their focus. On day one, after the students have done their safety training, Dr. S gives them their first laboratory tour. As he stands in front of the laboratory door, Dr. S gestures with his hands and twists his shoulders towards the laboratory area while reiterating the safety rules that must be followed, as shown in Figure 10. After a follow-up statement about safety goggles, Dr. S turns and looks towards the laboratory, then immediately turns back to the students. He states, "So we'll go in, and I'll show you around," as he makes a waving pointing gesture into the laboratory.

Figure 10

Different ways Dr. S motions toward the laboratory.

As Dr. S is touring the laboratory with the students, he alternates between waving with an open palm and pointing to direct students' attention to various features and components. Dr. S tells the students, "Everyone needs to choose one of these," as he discusses the selection of fume hoods, gesturing and pointing to the available options, as can be seen in Figure 11. He continues, "Before we depart today, we'll come back, and we'll just hang your lab coat on whatever hood you have," as he taps on the knobs located outside the hoods. At the end of the tour, he uses a double hand wave and pointing gesture along with a shift in body weight towards the door with the phrase "let's move back to the library" to signal the students that they are leaving the laboratory.

Figure 11

Dr. S gesturing with an open hand and pointing.

On day four, Dr. S discusses ways to collect data to determine if the students' reactions worked. The first method he explains is Nuclear Magnetic Resonance (NMR) spectroscopy. He first brings out a three-dimensional model of the molecule. As he describes the "two chlorines on one ring, its got a blue nitrogen and a methyl group, a CH_3 on the other side," he uses different fingers and thumbs to touch each of the balls representing atom as he states them. As he shows the model to the students, he draws attention to hydrogens. Next, he draws the same molecule on the board and takes time to draw all the hydrogens. To draw attention to the features of the molecule, he taps on the board with the dry-erase marker or with his finger where the hydrogens are and traces the circular shape in the air in front of the carbon rings. Afterward, he passes out the datasheet from the NMR and reminds students that it is a "map of hydrogens." He explains "that all of these groups of lines, of peaks, correspond to different hydrogens" while tapping the paper at the different lines. He proceeds to draw the spectral lines on the board to match them to the different hydrogens in the molecular line bond diagram.

During this process, he occasionally taps on the board to count the number of hydrogens or points to hydrogen. He also uses the circling in the air motion to group various items. For the duration of his lecture on NMR, he utilizes gestures, moving back and forth between the line bond drawing and the NMR spectral drawing to connect the two concepts.

Synchronized

Dr. S employs a rhythmic use of gestures that synchronize with the cadence of his speech, amplifying the impact of his words and effectively emphasizing key concepts. On day one, while he was preparing to give the students a tour of the laboratory, he takes a moment to reiterate the safety precautions that must be followed in the laboratory. When discussing appropriate laboratory attire, D. S uses specific gestures synchronized with his words to emphasize their importance further. He states, "This is the last time we can ever go in this room with shorts, open shoes, and no goggles. He points downwards on the beat of the word "shorts," pointing outwards with the words "open shoes" and raising his hands while mentioning "no goggles." Each gesture is synchronized with the corresponding word, creating a visual connection for students, and accentuating their importance, as illustrated in Figure 12.

Figure 12

Examples of Dr. S emphasizing safety attire.

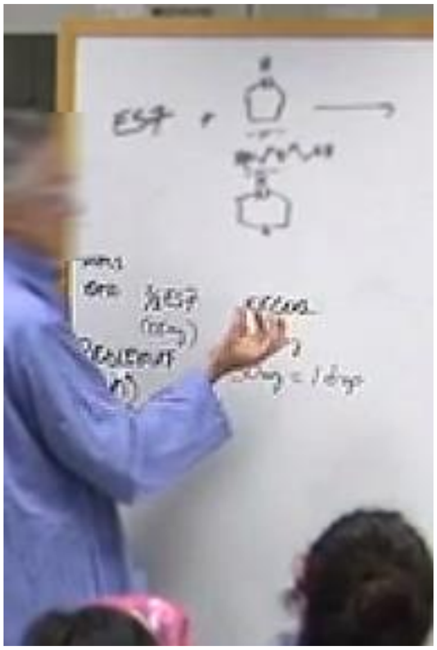
On day three, Dr. S. asks the students, "How many people think the reactions worked? How many people think the reaction did not work?" He then tells the students, "You have to be optimistic up until the point you are done setting up the reaction, and then you have to sort of believe it didn't work and have the reaction of the data to prove that it actually did work." As he divulges this dichotomy to the students, he waves his hand to the beat of the words he emphasizes. His hands move away from his body on the beat of the words optimistic, done setting up in a light waving manner. He then moves his hands in a tight downward movement but still away from his body with the words *believe*, *didn't*, and *work*. Lastly, he returns to the lighter movement with the words reaction and data but then switches direction and moves his hand toward his body with the word prove. These movements bring more importance to those words.

Mimicking

Furthermore, his ability to mimic actions through gestures adds a dynamic layer to his teaching and enhances students' comprehension through visual representation. On day one, during the laboratory tour, Dr. S shows the students the glassware they will be using throughout the summer program. He holds up a round bottom flask and announces, "This is a round bottom flask; this is what we will do most of our reactions in." He continues, "we'll put a stir bar in there and do the mixing." He twirls his finger around and below the flask as he says the word mixing. This circular motion Dr. S makes with his finger mimics the mixing the stir bar will do. On day three, Dr. S began discussing the chemicals they would mix in their round bottom flask. As he states that he is "going to add a drop to the round bottom flask," he mimics the shape of the round bottom flask with his hand, as seen in Figure 13. This gesture is not the typical way a chemist would hold a round bottom flask; instead, it takes the place of holding up an actual flask.

Figure 13

Dr. S makes a cupping gesture.



Pantomiming

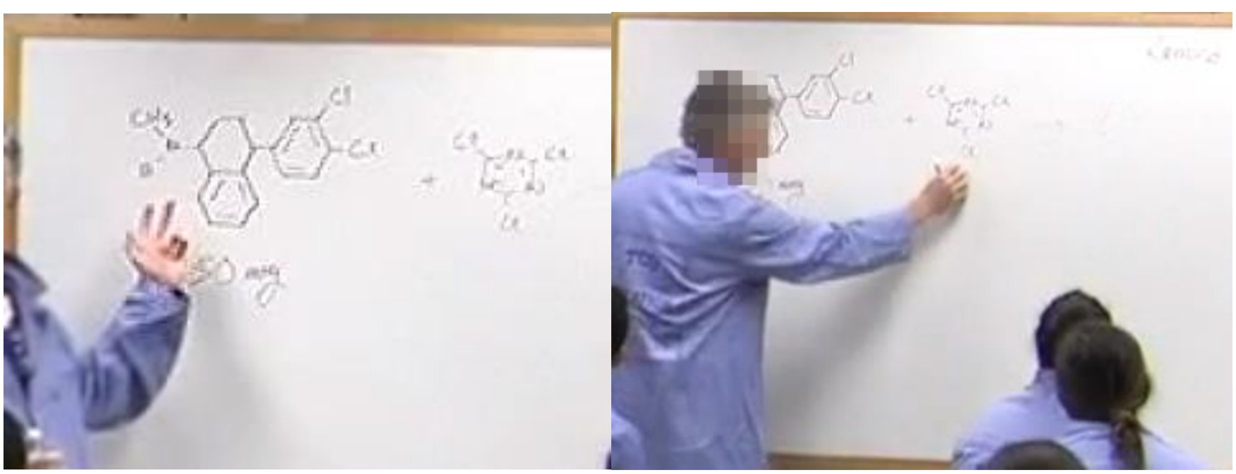
Lastly, in the laboratory setting, Dr. S's mastery of pantomiming laboratory procedures with gestures brings an additional dimension to the learning experience, making new techniques students learn more accessible. During his laboratory tour on day one, Dr. S discusses the importance of proper glove use. He states, "You have to assume that everything you touch will be transferring chemicals to your skin or your gloves." As Dr. S makes this statement, he pantomimes touching a workspace in front of him. He continues, "So, the other thing you have to do when you leave the room is just throw your gloves away and get a new pair." As he mentions throwing the gloves away, he gestures like he is pulling a glove off his hand and tossing it in the trash. On day three, students work in the laboratory area with mortar and pestles to grind up their pills. He discusses that grinding all the pills at once would be faster. While he is talking about grinding the pills, he pantomimes the process of using a mortar and pestle.

Mathematical

On day two, Dr. S begins a lesson on stoichiometry. He asks, "How much of this and how much of that do we mix?" while pointing to different molecules on the board. He explains to the students, "Everyone has access to one pill which is 50 milligrams of Sertraline." He emphasizes, "What we would like to do is mix them in about a one-to-one ratio." Afterward, he asked the students, "If we've got 50 milligrams of Sertraline, the question is how much of the cyanuric chloride do we have to weigh out?" He instructs the students to calculate the mass. After giving the students time to think about the question, he directs them by saying, "What we need to do is to convert this to some sort of common language." He elaborates on the common language, "One of these [Sertraline molecule] per one of those [cyanuric chloride molecule], the unit we use in chemistry because these [molecule] are really small and we use a lot of them, is moles." As he is explaining this, he points to the different molecules at different points in his sentence, as seen in Figure 14.

Figure 14

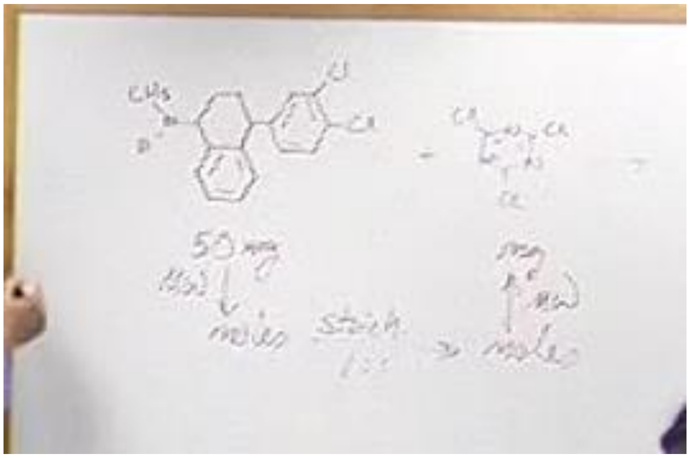
Dr. S points to Sertraline and cyanuric chloride molecules while describing the common language of moles.



After introducing stoichiometry, he visually maps it for the students in order to situate the mathematical expressions. He starts by asking, “So how do we get from mass, to moles, to moles, to mass?” He provides explanations as he draws the map, as seen in Figure 15. He begins with, “We can translate from milligrams to how many moles that it is.” On this first step, he draws a downward arrow from where he has written 50 mg on the board to the word moles. Next, he states, “And we can translate that into moles because we are going to use an equal mole ratio.” For this second step, he draws an arrow from the word moles written on the left to the word moles written on the right. Each of the words moles is below their respective molecule. For the last step he continues with, “And then from moles, we can translate that back into some number of milligrams.” He then draws an upward arrow going from the second word moles to where he wrote mg on the board. He provides further details about the map by explaining “So what’s the language of translation? Here it’s just the stoichiometry of the reaction.” As he says this, he writes stoichiometry above the arrow between the two words of moles. He reiterates the stoichiometry is “We’re going to use one of those and one of those, we’re doing a one-to-one reaction.” He briefly makes a side note and explains that in other reactions you might use a different ratio. Continuing with the reaction they are currently working on he asks the students “How do we convert from mass to moles?” The students respond with molar mass, and he answers them with “Molar mass, molecular weight, however you’d like to say it.” As he is saying this, he writes MW for molecular weight next to the arrow going from the 50 mg to the first word of moles.

Figure 15

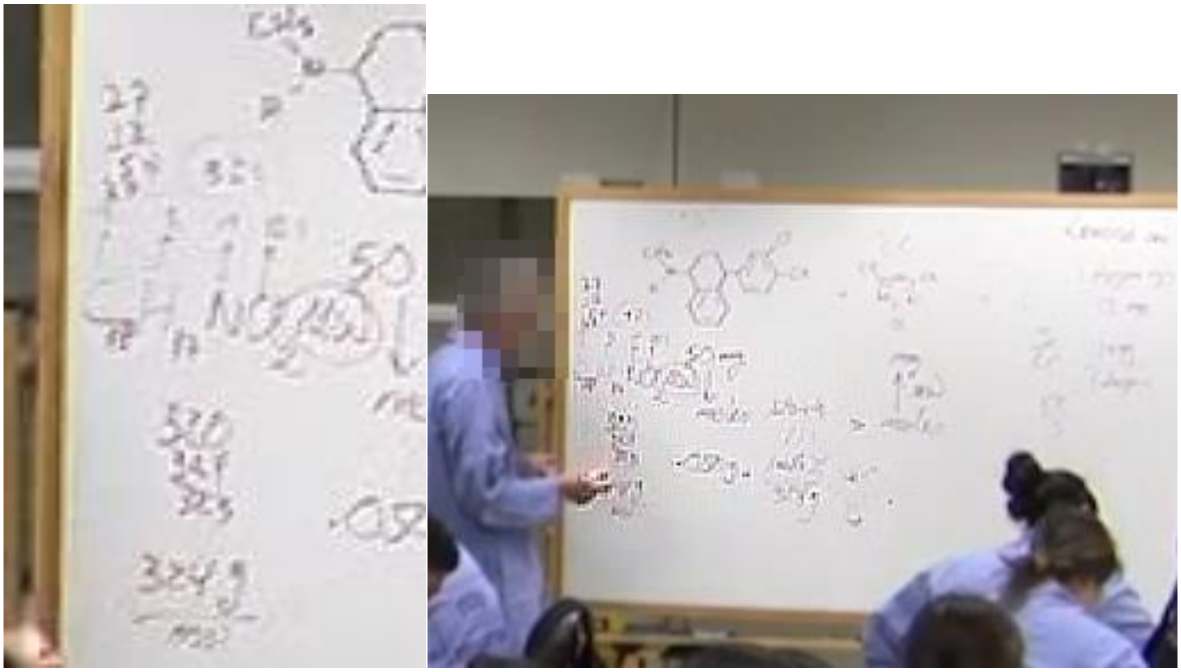
Dr. S maps out stoichiometry.



After mapping stoichiometry for the students, Dr. S breaks down how to find the mass of the molecule. He begins with writing the elements that make up the chemical formula on the board but leaves the subscript for carbon and hydrogen blank. He then askes “What was the C’s and H’s again?” When one student answers, he goes back through the line bond diagram and counts the carbons and hydrogens and then fills in the subscripts. Afterwards, he reminds students with the mass of each element is on the periodic table. He writes each mass above the element symbol and connects them with an arrow, as seen in Figure 16. He asks the students to calculate the sums of the masses. While giving them some time to do the calculations, he passes out periodic tables. A student tell him their calculations as he writes them on the board. Next, he goes through and “just to figure out a ballpark” calculates it roughly on the board.

Figure 16

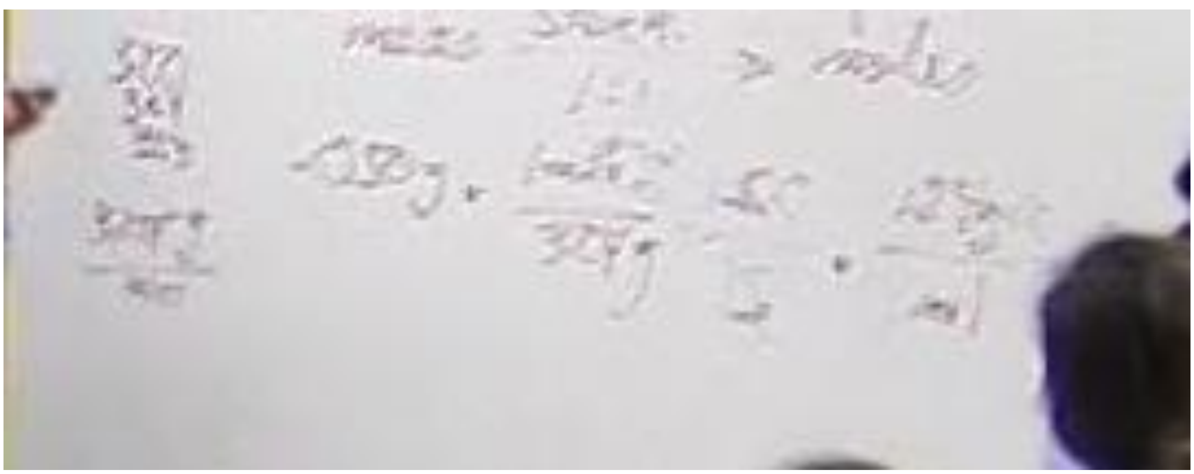
Dr. S calculates the molecular weight of Sertraline.



Once Dr. S has deconstructed all the stages of stoichiometry, he guides the students through the process of setting the required conversions, as seen in Figure 17. He rewrites the starting mass of Sertraline in grams instead of milligrams and explains they will multiply the starting mass with the molecular mass. Next, he writes the molecular weight on the board again, inquiring “It’s grams over moles, that’s the unit, right?” expanding on the concept of molecular weight over moles “… is equal to one.” To exemplify the meaning, he uses the similar but more familiar concept of one dozen eggs equaling 12 eggs and adds that they are unit conversions. Next, he explains what to do with the unit conversion when multiplying it with the mass, “It doesn’t matter if I say moles per 324 grams or 324 grams per mole, all I have to do is make grams cancel out.” When he fills in the stoichiometry, he reiterates that grams will be in the denominator. He reminds the students that the next step is to use a unit conversion for the one-to-one ratio of the two molecules. For the last unit conversion, he says he needs the molecular weight of cyanuric chloride. He skips over breaking down the mass and tells the students the molecular weight of cyanuric chloride. Shown in Figure 17, he finishes filling in the stoichiometry and states “Ultimately that’s going to tell me how many grams of [cyanuric chloride].” Then inquires, “What’s my answer approximately?” While students are doing the calculations, he shows them how to approximate the final mass of cyanuric chloride. After calculations are complete, he recaps “For every pill of Sertraline, we’re going to use 28 milligrams of cyanuric chloride,” while pointing at the different parts of the equation. Once the completing the calculation, Dr. S describes how they will transfer the 28 milligrams they calculated out into their round bottom flasks.

Figure 17

Dr. S does stoichiometric calculations.

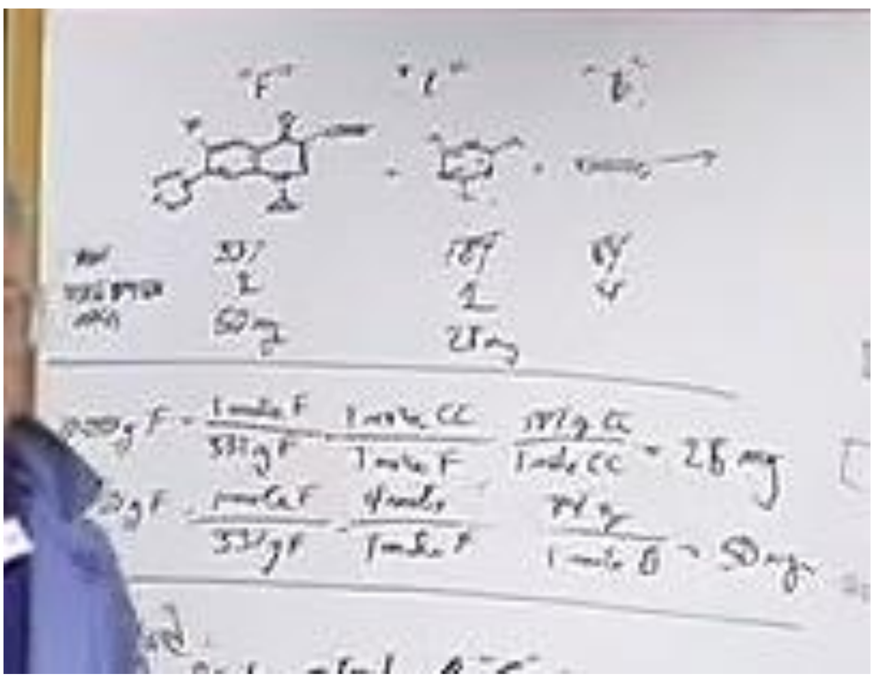


On day three, Dr. S introduces a new reaction for the students to perform with their molecules. He begins by recapping the stoichiometries covered in the previous days, reinforcing the foundational concepts as seen in Figure 18. Toward the end of the day, Dr. S proposes a new reaction to the students. He encourages them to choose a new branch from three possible molecules. They will be adding the branches from the molecules synthesized in the previous day’s reactions. He quickly guides the students through the stoichiometry involved in their new reactions. Once the students have established their amounts of chemicals, they move into the laboratory area to carry out their reactions.

On day five, Dr. S has the students repeat the process of adding more branches onto their molecules. The students must first determine mathematically their amounts of reactants needed. Dr. S conducts a comprehensive review of the stoichiometric calculations covered in the previous days, as shown in Figure 18. He involves the students and the laboratory teaching assistant in working on stoichiometric calculations for reactions with the new molecular additions. This session focuses on reinforcing the application of stoichiometry in varied reactions and scenarios.

Figure 18

Dr. S reviews previous stoichiometry.



On day seven, Dr. S incorporates a slightly different mathematical element by introducing the determination of ratios involving solvents for their TLC plates. However, these calculations are less complex compared to the detailed stoichiometries discussed at the beginning of the program. This inclusion varies the mathematical uses in their research when the options were limited. He walks around and shows the students two containers marked four to one and asks "Same thing? Four to one?" He states, "They all say four to one… but one of them is four to one hexane [to] ethyl acetate… the other one says four-part ethyl acetate to one part hexane." He explains that the ratio of polar to non-polar makes a difference in the outcome of the TLC plates. The exemplifies that writing four to one is not sufficient in chemistry and that more context is needed.

Symbolic Visual

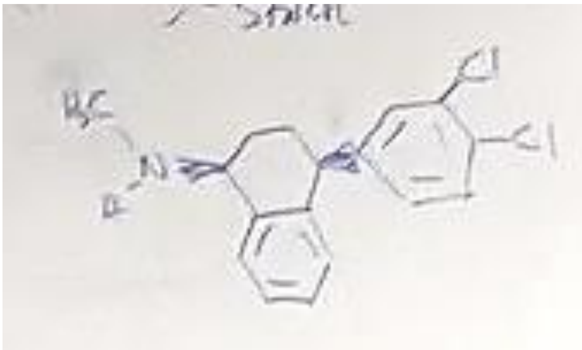
During the summer program, Dr. S uses a range of visual aids to enhance the learning experience. These include symbolic representations such as skeletal structures, intricate three-dimensional models, detailed drawings of laboratory equipment, and graphical representations of experimental data. These visual tools are utilized repeatedly to make connections to learning.

Skeletal Structures

Skeletal structures play a pivotal role in organic chemistry in terms of understanding and communicating essential aspects of molecules. The importance of these structures is evident as Dr. S begins on day one teaching the students how to construct and interpret skeletal structures. First, Dr. S probes, "What do you think the molecule looks like?" He follows with, "We can look it up. I can show it to you." He then draws on the board the skeletal structure for Sertraline, shown in Figure 19. He promptly asks, "Does that make any sense to anybody?" Continuing after a brief side note, "How do we translate Sertraline into something that's useful, into a molecular formula?

Figure 19

Sertraline skeletal structure.



To deconstruct the structure of Sertraline on the board, Dr. S asks, "What atoms are in Sertraline?" The students respond with hydrogen and chlorine as he repeats the elements' names back to the students and writes them on the board. When the students respond with “Carbon,” he asks, "Where's carbon?" Then, "Oh, right here," as he points to the H_3C in the upper left corner of the structure. Next, he questions, "What's all this other nonsense?" as he points and makes a circling motion around the center of the structure. The students respond with "Bonds," he tells them, "It's called shortcut. Chemists take shortcuts all the time because it would be a pain to write out every atom." He then explains to them that "Organic chemistry is the chemistry of molecules that contain carbon and hydrogen… But if all these molecules contain carbon and hydrogen, I don't want to write all the carbons and hydrogens down."

After explaining the bonding rules, as seen in Figure 7, Dr. S begins to count bonds on the explicitly written elements: nitrogen, chlorine, hydrogen, and carbon. Moving on, "Then we get to the shortcuts. So, it turns out that what organic chemists will do, is that they will use corners, ends of lines, to represent carbon atoms." He then identifies the corners of the lines and labels them with Cs for carbon. After picking out the carbons, he further explains, "The bonding rules say that carbon always has four bonds… By using the bonding rules, what I can do is come back and figure out where the hydrogens are." He demonstrates how to count the bonds on each carbon and marked any missing bonds as hydrogen. To finish up, Dr. S and the students count all the carbon and hydrogen and write the numbers in the chemical formula.

Dr. S puts various structures on the board to give the students practice deconstructing the skeletal structures. Students come up two at a time to attempt to determine the chemical formulas, as seen in Figure 20. He poses this as a race but also steps in and helps students when requested. When students finish their attempts, he reviews the structures and validates the formulas (Figure 21). As the practice progresses, more and more students become involved in trying to help their classmates deconstruct the structures.

Figure 20

Students deconstruct skeletal structures as Dr. S assists.

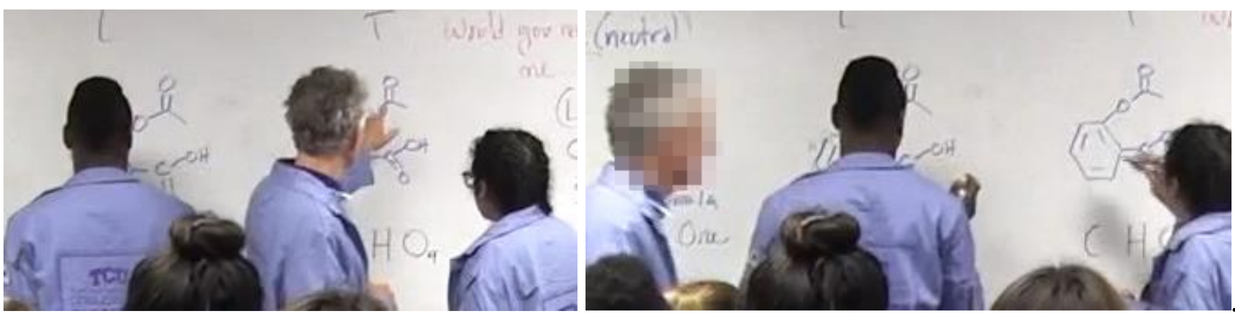
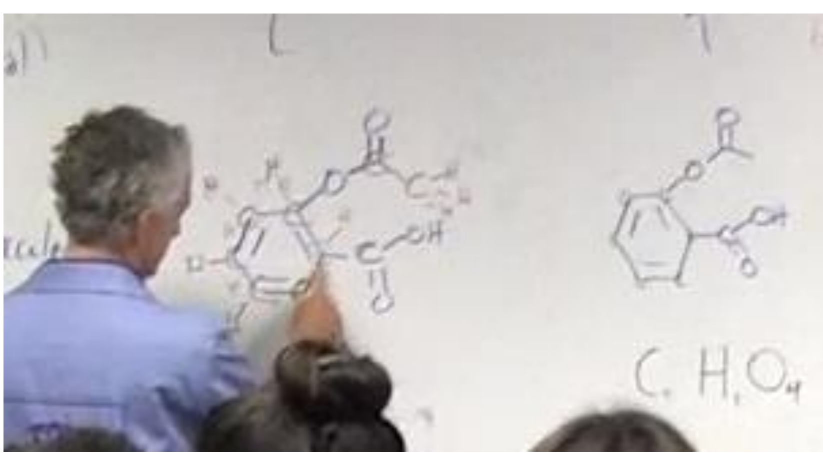


Figure 21

Dr. S reviews students' work.



Dr. S starts day two with "I'll remind you that the structure of Sertraline is..." he trails off while drawing the skeletal structure on the board. He continues, "Alright, so we're going to react Sertraline with a molecule that's called cyanuric chloride" and draws an additional skeletal structure of the new molecule. To put this in reaction formation, he adds a plus symbol between the two molecules and a reaction arrow to the right of the last molecule. The discussion precedes to the mathematics of the reaction. At the molecular weight portion of mathematics, he begins to write the molecular formula of the Sertraline molecule and asks, "What was the C's and H's again?" He goes through the structure and counts the ends of the lines. To give students more practice on day two working on skeletal structures, Dr. S writes similar reactions to the ones they will do in the skeletal structure format.

On day three, Dr. S discusses the evidence chemists can collect to determine if a chemical reaction occurred. He claims, "One of the advantages of the molecules that we're using is they have double bonds," and then points to the skeletal structure drawn on the board from the previous day; explaining, "The nice thing about double bonds in a molecule is that sometimes they interact with light." To further exemplify this point, he draws another molecule on the board and adds, "Red, of tomatoes, is a molecule that has, I think, 13 double bonds in it." When he finishes, he waves his hand down the length of the molecule and states, "Because there are so many double bonds, it's red." He then equates different colors to fewer and fewer double bonds as he erases double bonds from the tomato molecule’s skeletal structure.

Three-Dimensional Models

Starting on day four, Dr. S brings out a three-dimensional model of the Sertraline molecule, “I made a model of Sertraline, in case you guys have not thought about what it might look like.” This is yet another visual representation he provides for the students to anchor their understanding of the unseen molecules. As he is discussing the different atoms attached to the molecule and their directionality, he rotates the model back and forth, as seen in Figure 22. To emphasize the importance of the directionality, he states, “I could flip these two groups and get a completely different molecule.” As he says this, he twists the models to show that the groups do not move to different positions on their own.

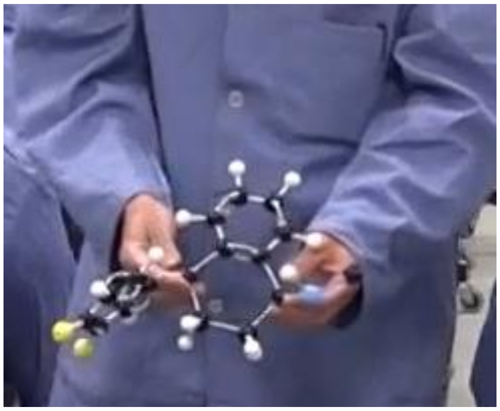
Figure 22

Dr. S turns the model in different directions to show the three-dimensional structure.

Dr. S uses the three-dimensional model to prepare a discussion on the NMR test, in which understanding hydrogen placement is crucial. Walking between the students, showing the three-dimensional model to them up close (Figure 23), he states, “I think in just looking at [the three-dimensional model], even looking at the two-dimensional sketch, what you recognize is every hydrogen… are different.” He emphasizes using the different representations to analyze. Dr. S brings out another three-dimensional model of triazine and demonstrates it replacing hydrogen on the Sertraline model. Dr. S puts the model down and draws the skeletal structure for Sertraline on the boards.

Figure 23

Dr. S shows the three-dimensional model of Sertraline to students.



While drawing the molecule, he stresses the importance of knowing a molecule's structure during research. He reviews some of the areas of significance, "As we saw in the [three-dimensional] model, the hydrogens are in a lot of different environments." He draws in the hydrogens usually assumed in a skeletal structure but is explicit in the three-dimensional model, "There are hydrogens that are attached to these rings, with single and double bonds" (Figure 24). He uses the three-dimensional model and the skeletal structure together to explain the environments and different significances of the hydrogens. He brings out the three-dimensional model again later while connecting the two-dimensional skeletal structure to the NMR data. He connects an additional piece to the model, stating, "If I pop off this hydrogen and replace it with a big ring that's aromatic…it's going to really influence the hydrogens it's close to." As he continues to explain the NMR data, he continually goes back to pointing to different atoms on the three-dimensional model.

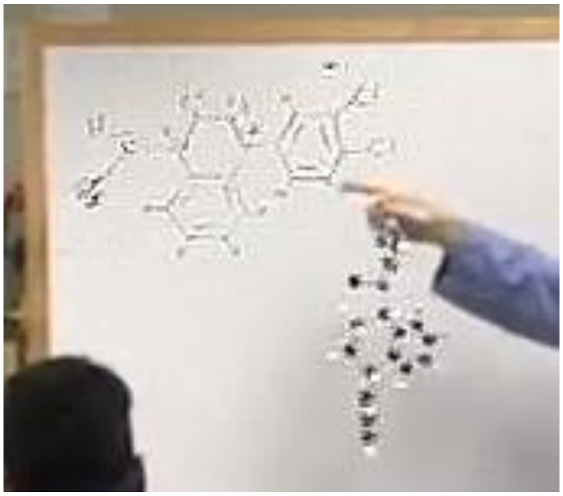
Figure 24

Sertraline skeletal structure with hydrogen drawn in on day four.

On day five, Dr. S repeats the process of anchoring the skeletal structure to the three-dimensional model. The skeletal drawing shown in Figure 24 is still on the board from day four. He is discussing why a graduate student thought the reaction did not work when the students did get it to work. He states, “He didn’t do what we did, we built a model.” Dr. S brings out the three-dimensional model again. He compares the skeletal structure to the three-dimensional model, as shown in Figure 25, and discusses how looking at it two-dimensionally can lead to false assumptions.

Figure 25

Dr. S connects the skeletal structure to a three-dimensional model on day five.



Drawing Laboratory Equipment

At different times during the program, Dr. S utilizes laboratory equipment diagrams to help guide students while introducing laboratory techniques. On day three, when Dr. S introduces TLC plates, he draws diagrams on the board. First, he draws a horizontal tube to assist in the analogy of bees and wasps (Figure 26). Inside the tube, he draws flowers to show that the bees would get stuck on them. Additionally, he draws a fan to show how the wasps can be assisted in moving through the tube faster. When anchoring the bees and wasps' analogy to actual laboratory equipment, he draws a vertical tube on the board to represent a chromatography column, shown in Figure 26. He adds, "We fill our column with ground glass, which has a fancier name, it's called silica." He uses the diagram as he describes, "We can dump on the top of this column, our two molecules… and then we can start pouring on the solvent, something like acetone, and acetone will push bees and wasps through this column." He then diagrams how wasp-like molecules will move through the column and can be collected in test tubes below.

Figure 26

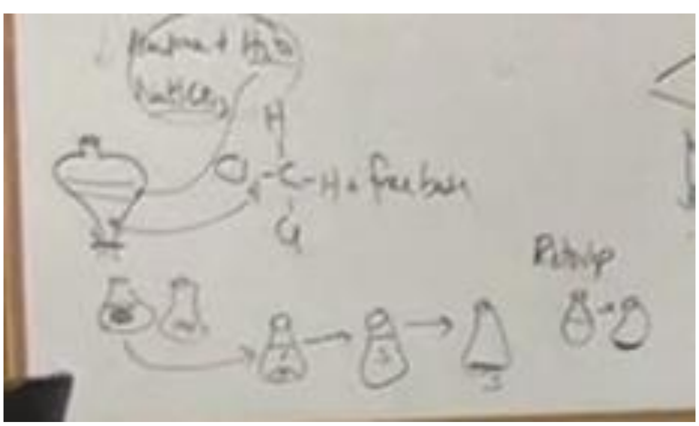
Dr. S diagrams the chromatography column and bees and wasps tube.

Dr. S transitions from column chromatography to discussing TLC plates. He states, "[TLC is] the same experiment, it's just faster and cheaper." He describes it as "A glass slide coated with Silica." He draws a TLC plate with a dot at the bottom on the board and describes, "We can put our… products on the bottom of the slide." He draws a wavy line representing a liquid at the bottom of the slide, stating, “We put the slide into a solvent and capillary action will have these things run up the slide, just like bees and wasps.” With his last statement, he draws lines going up the TLC plates.

On day five, Dr. S introduced students to removing water from the student’s reaction vessels and condensing the remaining liquid. He first explains the reasoning for the procedure, “I’m afraid the excess water and carbonate with decompose… the cyanuric chloride.” He draws a separatory funnel on the board, “What I want to do is put this material into a sep funnel with organic solvent” (Figure 27). Explaining the different chemicals and their purposes in the separatory funnel, he labels the layers on the diagram. Next, he describes collecting the material “Sertraline, in one tube, and water in the other” while drawing two flasks on the board. For the next few steps of removing the water, he draws three more flasks on the board. By the third flask, he states their goal is to “…end up with Sertraline [only]… by getting rid of the solvent.” The third flask shows a dramatically reduced level of liquid. He provides two methods of accomplishing this, “We could let it evaporate overnight…or we can put it on a machine called a rotary evaporator, or a rotavap.” He reiterated that the rotavap would reduce the liquid while redrawing the before and after round bottom flasks below the word rotavap, as seen in Figure 27.

Figure 27

Dr. S diagrams the separatory funnel and laboratory steps with flasks.



Drawing Laboratory Data

On day three, after the introduction and demonstration of the TLC plate test, Dr. S draws on the board the TLC plate results from the students' first reactions. He invites them back into the lecture area to discuss the results and directs them to return to the page in their notebooks with their reaction, stating, "We have to report our results. What everyone does is actually draw the TLC in their notebooks with a couple notes." As seen in Figure 28, Dr. S has already drawn the results from shining a UV light on the TLC plate he created during the demonstration. Dr. S treats the TLC plate with a stain and then draws it again with the stain spots also shown in Figure 28. Having both views on the board allows him to discuss the interpretation of the test results with the students.

Figure 28

Dr. S draws TLC plates on the board.

Dr. S distrusts an NMR printout on day four following his introduction using the three-dimensional model and skeletal structure. He recreates the NMR results on the board as students direct him where each peak is located (Figure 29). He refers to the skeletal structure drawn on the board every couple of peaks. He gets to the end of the spectrum and identifies a peak he calls "A critical CH_3 group." He explains, "The reaction we're doing happens right next door and if …

any hydrogens are going to be affected, I'd expect these hydrogens, maybe this one [points to hydrogen] to be most affected." After further discussion of the starting material NMR, Dr. S guides the students to look at an NMR of one student's molecules. Dr. S overlays new peaks of the students' results over his drawing of the starting material, as seen in Figure 30.

Figure 29

Dr. S draws NMR results on the board.

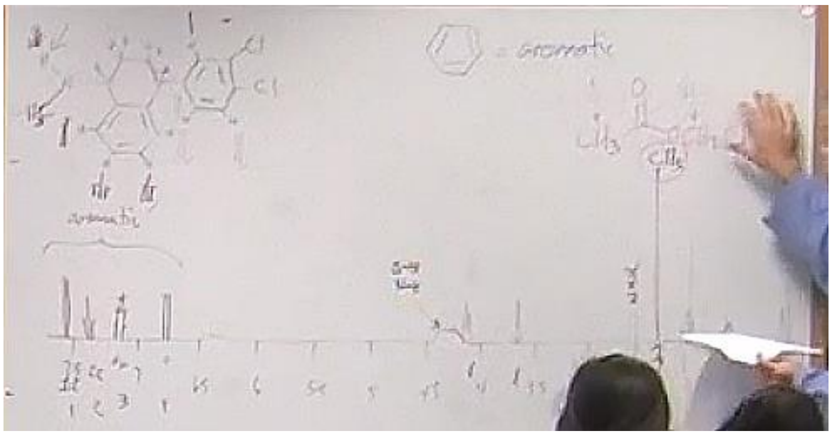
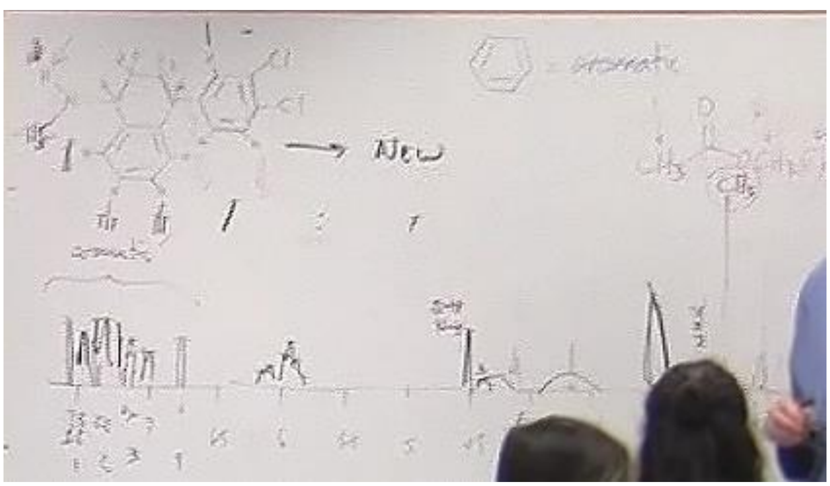


Figure 30

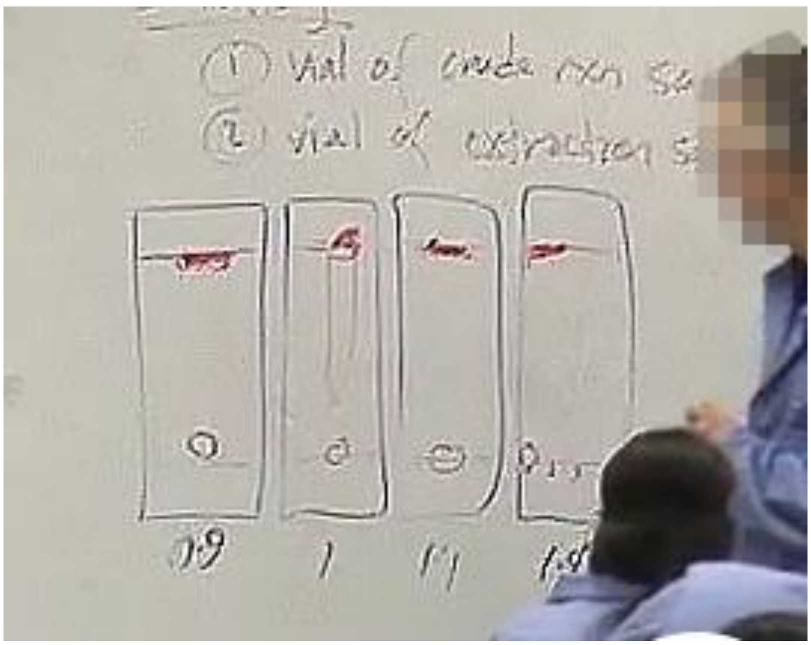
Dr. S overlays NMR results on previous results on the board.



As Dr. S stated earlier, TLC plates are an easy and inexpensive test for students to conduct with their reactions. The most utilized data that Dr. S draws on the board are TLC plates. During day four, Dr. S has the students test their reactions with TLC plates. He draws the different plates on the board, emphasizing the colors variations of the different amines show. Dr. S repeats drawing the TLC plates many times during the days when students try new reactions. He has students draw the TLC plates in their notebooks nearly daily. On day seven, Dr. S had students from four groups draw their TLC plates on the board. Dr. S asks questions to the groups and compares the TLC plates to one another, as seen in Figure 31.

Figure 31

Dr. S has student groups draw TLC plate results on the board.

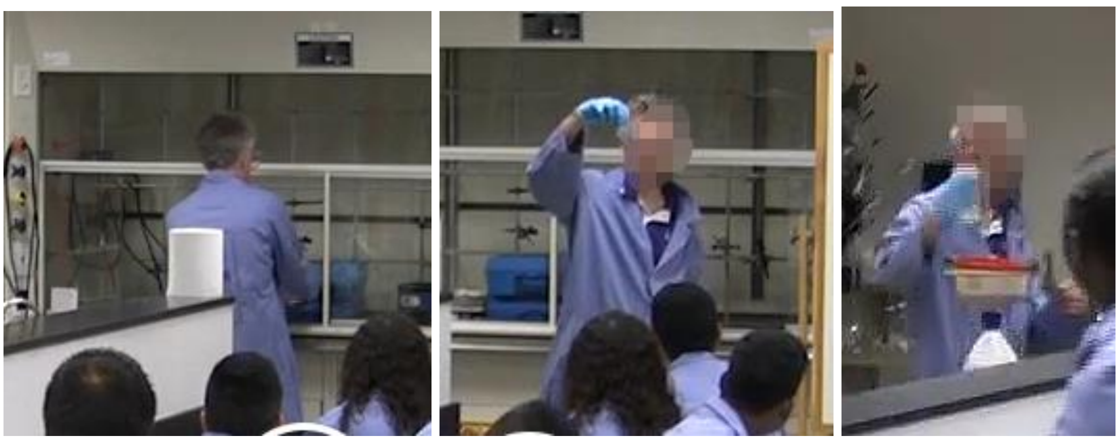


Manual Technical

In the initial days of the program, Dr. S focused on building foundational laboratory knowledge and skills with the students. On day two, following a comprehensive overview of the reaction procedure, the mathematics involved, and the underlying chemistry, Dr. S transitioned students into their first procedure in the laboratory. After having previously drawn a round bottom flask on the board as their reaction vessel, Dr. S puts on his safety goggles and gloves and retrieves one from a fume hood. He holds it up for the students to see then demonstrates how to clean it with acetone and the responsible disposal of the liquid in the waste container, as shown in Figure 32. He instructs them to set up their flasks on a clamp in the fume hood. Dr. S emphasizes the importance of safety, first by modeling his use of safety equipment and reminding them they needed to wear their safety goggles and gloves.

Figure 32

Dr. S retrieves a flask from the fume hood and shows students how to clean glassware.

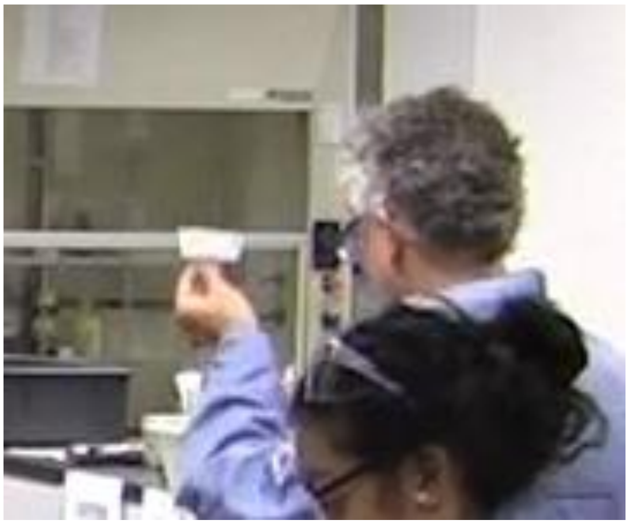


Later that day, Dr. S demonstrates the preparation of the pill used as the starting material. Introducing the mortar and pestle, he demonstrates the process of grinding the pill into a refined power. Next, he holds up a piece of wax paper (Figure 33) and shares a valuable tip, "Folding the wax paper in half is a neat trick; it allows you to actually use it like a funnel when you pour it into your flasks." He scrapes the powder from the mortar using a spatula and transfers the material to the weighing paper. Dr. S then showcases the meticulous technique of transferring the material into the round bottom flask, gently tapping the wax paper to ensure a controlled and gradual flow of the powder. Once the demonstration concludes, he releases students to the laboratory area, where they are tasked with replicating the process using their pills. Working in small groups, the students receive occasional guidance from Dr. S as he monitors their practice.

As the students master the procedure and prepare sufficient material for their reactions, they move to the fume hoods to proceed.

Figure 33

Dr. S shows a trick of folding the wax paper in half.



On day three, Dr. S engages the students with probing questions and reflections on the success of their reactions. He also elicits their thoughts and ideas on how they might be able to test their reactions. Following a lecture on testing procedures, he transitions the class to the laboratory area to demonstrate the TLC plate test. Before beginning the test, he holds up the glass (Figure 34) and describes the textures, drawing connections to his previous bees and wasps' analogy to help familiarize the students with the material. He explains, "On one side, it's glass, it's the solid support; it's the equivalent of that tube; on the other side, it's the ground glass, the silica, which is the equivalent to the flower beds." He then carefully shows them how to cut the glass into smaller strips precisely. Next, he demonstrates transferring a minute drop of the student's reaction product onto the glass. Emphasizing the importance of each step, Dr. S allows the drop to dry before employing an ultraviolet light lamp to inspect and display the preliminary appearance of the TLC plate before separation. Once prepared, the TLC plate is placed into a jar of solvent (Figure 34) to facilitate the separation of the molecules through the silica. During the setup of the TLC plate, Dr. S provides detailed explanations of the equipment used. Once completed, Dr. S shows the students the result of the TLC plate test. Afterward, he poses questions to the students on more ways they could test their materials. He demonstrates the test a few more times with the different materials suggested by students and examines and compares the outcomes. This interactive approach allows the students to actively engage with the testing process and comprehensively understand the TLC plate test.

Figure 34

Dr. S identifies TLC plate equipment, glass and solvent jar.

At the conclusion of day three, Dr. S strategizes with the students regarding the next phase of their reactions. After devising a plan, he instructs them to divide their products and initiate a second-stage reaction with a portion of their previous product. On day four, having thoroughly demonstrated the TLC plates the previous day, he directs students to their fume hoods to test their second reactions independently. While distributing TLC plates, he provides detailed instructions to "draw a line about a centimeter from the bottom" and to "make sure you use a pencil." Additionally, Dr. S reminds them that the TLC plate has two sides and emphasizes that "the side that we want is the gritty side." Throughout the process, he offers students guidance and reassurance. As he moves from group to group, he briefly pantomimes the motions of using the pipette to transfer the product to a TLC plate. Additionally, he reiterates the technique of holding the pipette and using thumbs instead of a pipette bulb, as shown in Figure 35. Once the students' TLC plates were finished processing and ready to be checked, Dr. S assists them with viewing the results under the ultraviolet lamp. He facilitates the interpretation of the outcomes and directs students to record their findings in their laboratory notebooks, ensuring a thorough understanding of the experimental results.

Figure 35

Dr. S pantomimes using a pipette.

On day five, Dr S reveals to the students a new piece of equipment, the rotary evaporator, or rotavap. Before moving students to the laboratory room with the rotavap, he describes the process on the board in the lecture area (Figure 27). Once students are gathered around the rotavap, he gives a detailed description of the various parts (Figure 9). While connecting his round bottom flask, he explains the crucial settings that needed attention. Simultaneously, Dr. S delves into the purpose behind each step of the procedure, cautioning students of potential issues that might arise if the procedure is not meticulously followed. As the excess solvent begins to evaporate from his reaction, he points out the bubbling in the vessel, providing insights into what students should observe during the extraction of their reactions. This hands-on demonstration familiarized the students with the rotavap and underscored the importance of attentiveness and precision in the experimental process. Remarkably, in the following weeks, the students quickly adapt to using the rotavap with ease and precision, requiring only a small amount of guidance from Dr. S.

In the second and third weeks of the summer program, Dr S directs the students to repeat their synthesis reactions several more times with slight variations in their starting molecules. Each repetition serves as an opportunity for the students to practice and reinforce the laboratory techniques they had learned the previous week. The students honed their skills with each iteration, and Dr. S needed less oversight. An integral part of his instructional strategy involves providing students with independent practice to foster their self-efficacy. What started as a structured learning environment transitioned into a space where students applied their acquired knowledge with increasing confidence. Gradually, the students become self-sufficient and autonomous in the laboratory. Notably, while the first week of the summer program leaned slightly towards lecture time, the dynamics shifted by the third week. During this period, a significant portion of class time is dedicated to the students working in the laboratory – carrying out new synthesis reactions, isolating products using the rotavap, conducting tests with TLC, and meticulously recording their findings in their notebooks. Dr. S's guidance and gradual shift ultimately empowered students to engage actively in acquiring manual technical knowledge and skills.

Studio-Based Chemistry

In the preceding section, each modality was examined separately to provide detailed descriptions. However, in real-life situations, these modalities rarely occur in isolation. While the focus was on describing each modality individually, in many descriptions, numerous instances revealed the overlap of different modalities. Dr. S's discursive practices are almost always intertwined, sometimes with three or four occurring simultaneously. The immersion summer program setting encourages more frequent engagement in various discursive practices. Therefore, the setting significantly contributed to the richness and engagement of the instructional environment.

A description of how Dr. S engages in the different modalities within this specific setting is provided to address question two: How does studio-based chemistry support the chemistry professor with incorporating multimodal discursive practices. Studio-based chemistry is a concept of integrating both the temporal and special aspects of a chemistry class, combining lecture and laboratory components. The summer immersion program can be subdivided into three distinct phases. These phases are distinguished by the duration spent in the two zones (lecture and laboratory) and the level of instructional involvement by Dr. S. The last week of the program, where students were testing biological factors of their reactions and preparing to present their findings, is not relevant to this paper.

The room where the summer immersion program took place is divided into two distinct zones. The first, designated as a full safety zone, serves as the laboratory area where experiments and tests take place. This space is equipped with fume hoods that line the walls and a laboratory bench for conducting experiments. The second zone, designated a partial safety zone, is dedicated to lecture lessons (Figure 6). It features chairs and two desk-height benches for student notetaking. At the end of these benches, a rolling dry erase board is available for Dr. S to use during lectures. For the purposes of this paper, the full safety zone is referred to as the laboratory area, and the partial safety zone is designated as the lecture area. Beyond the division of Dr. S's instructional time and space into lecture and laboratory, the concept of crossing borders is employed to address the unique circumstances afforded by the studio-based arrangement, allowing Dr. S to seamlessly move between the two spaces.

Phase One

The initial few days of the program mark the first phase. In this phase the students are acclimating to the new environment while immersing themselves in new material. Dr. S dedicates a considerable amount of time lecturing and teaching material at the board or demonstrating laboratory techniques. Notably, he occasionally brings materials from the laboratory to the lecture area for demonstrative purposes. For example, when Dr. S demonstrates grinding up a pill with the mortar and pestle, he transports equipment from the laboratory area to the edge of the lecture space, shown in Figure 36. Despite students remaining seated in the lecture area, this strategic integration of laboratory materials into the lecture setting enhances the learning experience. Following the demonstration, students transition to the laboratory area to practice the procedure themselves. It is during this initial phase, as students begin to learn laboratory techniques, that Dr. S provides the most guidance, instruction, and demonstration time. Despite the emphasis on lectures, Dr. S adeptly utilizes both spaces, facilitating a faster exposure of students to laboratory techniques and fostering a deeper connection to the learning process.

Figure 36

Dr. S demonstrates grinding a pill with a mortar and pestle in between the laboratory and lecture areas.

Phase Two

As the program progresses, a pivotal shift occurs on day five, marking the onset of the second major phase. In this stage, Dr. S transitions to less direct involvement with students during laboratory time who are now assuming more active roles in conducting experiments. Simultaneously, the pace of lectures accelerates, reflecting the students' growing comprehension of the lessons. Additionally, this phase exemplifies the dynamics of the studio-based classroom and its ability to facilitate multimodal discursive practices. The fluidity with which Dr. S can navigate through lectures and foster active student engagement exemplifies the unique strengths of the studio-based approach.

On day five, a notable instance highlights Dr. S's utilization of the studio-based space. During a discussion on the chemistry of the students' synthesis reactions, Dr. S introduced a three-dimensional model of the starting molecule, comparing it to the two-dimensional skeletal structure on the board. Demonstrating a graduate student's misjudgment, he revealed that the supposedly crowded area of interest shows considerably more space around it in the three-dimensional model. Dr. S then proceeds to draw additional skeletal structures on the board, emphasizing similar significant areas for comparable chemical reactions.

Less than ten minutes later, Dr. S explains a laboratory procedure designed to purify the starting materials. Utilizing a diagram of a separatory funnel, he guides students through the separation of excess nonpolar solvent with desired material and water containing excess unwanted material. Expanding on the lesson, Dr. S sketches multiple Erlenmeyer flasks, explaining their role in capturing the separate layers and then using a desiccant to remove excess water. To complete the preparation of the starting materials, he introduces the rotavap as the final step to remove excess solvent. Shortly after, he directs students to the other end of the room, where he performs a demonstration in the laboratory area while they remain in the lecture area. This strategic arrangement minimizes transitional time, allowing Dr. S to efficiently connect the lesson to the procedure. Within this brief interval, he engages students in various symbolic representations, pairing those representations with language through gestures, and seamlessly transitions to the manual technical skills immediately afterward.

Another example on day five illustrates how studio-based classroom design supports multimodal discourse teaching occurred in the final hour of class. Dr. S and the students have returned from using the rotavap to purify their starting materials. The skeletal structures of the starting material are drawn at the top of the board. Dr. S engaged the students in calculating the stoichiometry of their next round of synthesis reactions just below the skeletal structures. Meanwhile, students recorded both the skeletal structures and mathematical computations in their laboratory notebooks. After the mathematics discussion, Dr. S smoothly transitions students to contemplate the experiment on a larger scale. Identifying potential issues, he raises the concern that the reaction might heat up and poses the question, “anybody have an idea for how to control the heat of this reaction?” A student suggests keeping the reaction in cold water, a solution which Dr. S approved. He then illustrates how the students would set up their reaction with an ice water bath on the board. Subsequently, Dr. S moves into the laboratory area, sets up, and runs the reaction. During the process, he reiterates the mathematical aspects. After a few minutes, Dr. S tests the reaction using a TLC plate. Upon completion, a student views the TLC plate under the ultraviolet lamp. When a faint spot appeared, Dr. S takes the TLC plate and draws the results on the board for the students to copy into their notebooks. At the board, Dr. S guides the students through analyzing the TLC plate results. In this instance, Dr. S is able to engage students in all modalities in a relatively short period of time.

Phase Three

Throughout the remaining time of the program, Dr. S assumes the role of a guiding facilitator, primarily directing students through iterative processes and the experimental journey. While not directly participating in multimodal discursive practices during these instances, Dr. S employs an instructional strategy that consistently immerses students in multimodal discourse. His emphasis on ensuring meticulous documentation of processes in their laboratory notebooks underscores the integration of various modes of communication. Dr. S's approach, marked by strategic guidance and a commitment to fostering student engagement, fortifies the foundational principles of the studio-based classroom, making it a conducive environment for comprehensive learning experiences.

Chapter 5

Discussion

The following chapter provides a discussion with possible explanations of the findings based on the guiding research questions. Key discussion points include the professor's incorporation of different multimodalities in his teachings and the ways in which the studio-based design of the summer program supports his discursive practices. There is a plethora of literature on multimodal discourse but less on studio-based design. This research specifically addresses how multimodality is supported by studio-based design. Additionally, this chapter addresses the limitations and outlines the possibilities for areas of future research.

Interpretation of Multimodal Discursive Practices

Researchers suggest incorporating multimodal discourse into teaching practices can assist students in navigating the complexities of science language (Farheen & Lewis, 2021; Feez & Quinn, 2017; Hao & Hood, 2019; Lemke, 2004; Mathayas et al.; 2019Roth, 2004; Talanquer, 2-11; Unsworth et al, 2022)). In the environment of the summer immersion program Dr. S demonstrated these multimodal discursive practices and skillfully incorporates them together throughout his teachings. His teaching practices serve as an example of engaging students in multimodal discourse. Additionally, the data showed that Dr. S provided many opportunities for the students to engage in multiple discourses with the same concept or process. Unsworth et al. (2022) suggest that not only does this mirror the way scientific knowledge is generated, but allows students to develop deeper meaning.

In the previous chapter, each modality was described in-depth, but Dr. S's use of multimodal discourse is more dynamic and embedded within the studio-based design. His ability to connect his words with symbolic representations, such as the skeletal structures, through gestures can aid students while they develop their chemical language. Additionally, the skeletal structures and 3-dimensional models Dr. S used supports students in conceptualizing abstract concepts and build metal models, as suggested by Farheen & Lewis (2021) and Unsworth (2022). Through his approach, Dr. S provided opportunities to equip students with essential scientific knowledge and fosters their ability to communicate and comprehend scientific concepts.

Natural Language and Gestures

Dr. S uses natural language and gestures throughout the program and connects to every other aspect of his multimodal discourse. One explanation may be that he is well-versed in the discipline of chemistry and in laboratory work. His use of multimodal discourse can reduce barriers for the students to enter chemical discourse. He accomplishes this through blending everyday language with technical terms and by gradually easing students into chemical discourse. As other researchers have suggested, the use of everyday language can provide a foundation for the more complex and abstract language of science (Chen, 2019; Unsworth et al., 2022; Weinburgh et al., 2019). Gee (2004) suggests that this can be problematic, but Dr. S seemed to negate that by quickly replacing everyday words with the more precise words of chemistry.

Dr. S provided many opportunities for the students to build their chemical discourse through discussions with him, talking to each other, and writing in their journals. On the first day, Dr. S emphasized the importance of the journals to the students. While he was lecturing, Dr. S wrote on the board and would stop and have students write in their journals. Chen (2019) suggests that students should have the opportunity to engage with talk and text simultaneously. Chen also suggests that students should be able to talk with each other and the instructor before writing. The data showed that Dr. S would talk to students more conversationally and guide students through thought processes before having them write. The iterations between talking and writing could aid in building scientific vocabulary. Additionally, Dr. S uses journals as a way to transition students into the more factual and analytical structure needed for their scientific report. This strategy can be beneficial to students as a way to ease students into the more formal writing required in science as described by Weinburgh et al. (2019). This can be seen on day one when Dr. S has students write down their thoughts on pills on the first day. Later in the program, Dr. S has students recording processes and recording results of experiments as laboratory reports in their journals.

Dr. S's gestures seem to play a pivotal role in simplifying complex ideas, such as stoichiometry and skeletal structures, without overloading students with information. Dr. S attempts to quickly transition the students from very limited chemical knowledge to being proficient in chemical discourse. By the end of the summer program, students appear to confidently engage in chemical discourse with little assistance from Dr. S as they work in the laboratory and present their final results.

Gestures are a crucial aspect of communication, helping to establish a connection between language and mathematical, symbolic, or manual technical elements. Dr. S uses gestures to guide his students and make his language more accessible. He simplifies complex concepts by using vague terms and gestures instead of the technical terms, which can reduce cognitive load as suggested by Goldin-Meadow, (2011) and Mathayas et al. (2019). With this technique, Dr. S can explain complex chemical concepts, and laboratory techniques like the rotavap, to his students without overwhelming them with too much information at once.

Dr. S utilized both sonovergent and semovergent gestures in his lesson as described by Hao & Hood (2019). An example of his sonovergent gestures occurred on day one. As Dr. S is about to tour the laboratory for the first time with the students, he iterates the importance of safety attire that must be worn in the laboratory. As he is describing the most important clothing items, he moves his hands in time with his words, adding stress to each word individually. In addition to moving in time, he uses his hands to direct attention to the area the clothing if worn. He pointed downward for shoes, moved his hands out at thigh level for shorts, and directed his hands toward his eyes for goggles. An example of semovergent gestures occurs during the lesson describing the main laboratory procedure. Dr. S holds his hand up and forms a shape similar to the round bottom flasks while discussing their use. The palm of his hand creates the bowl shape of the flask and his fingers for the shape of the neck of the flask. These gestures could aid Dr. S in communication with the students both importance of his words and anchor his words on more tangible thoughts.

One lesson by Dr. S exemplified the use of natural language and gestures to guide students through stoichiometry using multimodal discourse. He anchored the mathematical concepts to a concept map that utilizes visual and symbolic modalities. In every step of the stoichiometry process, Dr. S utilized natural language as he focused on the technical math terms of stoichiometry, such as moles, molar mass, grams, and ratio. He first illustrated the reactants' skeletal structures. Then, he guided students through converting mass to moles and back, using gestures, such as pointing, to connect his language to the mathematical and symbolic aspects on the board. Instead of naming the compounds used for the reaction, he refers to them as "these" and "those" while pointing to their skeletal structures. Dr. S then leads students through setting up conversions, clarifying unit conversions, and emphasizing the cancellation of units. Finally, they calculate the approximate mass of cyanuric chloride needed, preparing students for carrying out the reaction in the lab. The lesson focuses on mathematics, not the compounds' names by use of generic identifiers.

When Dr. S introduces the skeletal structures, he refers to the lines as nonsense while waving his hand around them when asking students what they think. The students respond freely, offering their prior knowledge that lines in chemistry represent bonds. Dr. S uses this starting point to elaborate on the concept of skeletal structure at the level needed for organic chemistry. He explains that organic chemistry is primarily concerned with carbon and hydrogen and that the lines are simply a "shortcut" to represent those atoms and their bonds. He then shows the students where carbons and hydrogens are implied to be in connection with the concept of bonds. Calling the lines shortcuts aids the students in understanding that the lines are representations of carbon and hydrogen. The line constitutes a ‘language’ that other chemists can easily understand. Dr. S’s gestures and simplified language could decrease the cognitive load on the first day of the program as suggested by Goldin-Meadow (2011) and Mathayas et al. (2019).

Another example of Dr. S strategies for easing students into chemical discourse is seen on day five when he is explaining how to use the rotavap. The rotavap has many components, so it can be overwhelming for students before they become familiar with it. Therefore, before taking students to its laboratory room, Dr. S provides a brief overview, using natural language, of the rotavap and its uses. Once in front of the equipment, he demonstrates how to use it while attaching a round bottom flask with reactant chemicals he is preparing for the students. To facilitate the student’s understanding of each adjustment he makes on the rotavap, Dr. S uses the words "this thing" or "this" with a pointing gesture, drawing attention to each part. He also focuses on what each part is doing and what the students should expect rather than using technical words. Once again, the students were not overwhelmed with complex terminology but could still understand the procedure for using the rotavap.

Gestures can serve multiple purposes besides reducing cognitive load; they can aid communication and comprehension. Dr. S seamlessly integrates hand gestures with verbal discourse to direct attention, emphasize key points, and pantomime laboratory procedures. For instance, during the laboratory tour on day one, Dr. S skillfully orchestrates his gestures to direct attention to crucial garments and emphasize the safety rules for laboratory attire. He points out different room features during this tour, which helps the students connect his descriptions to the actual features. While explaining the concept of NMR spectroscopy, Dr. S utilizes tapping and pointing gestures to connect the three-dimensional model to the skeletal structure and then to the data on the result page. His gestures are synchronized with his speech, helping to accentuate key concepts. Dr. S helps students connect explanations to future experiments by mimicking actions such as mixing chemicals. Additionally, pantomiming laboratory procedures, such as using a pipette to transfer chemicals, he reinforces previously demonstrated concepts to his students.

Blending Formal and Informal

Dr. S employs a teaching approach that combines informal conversation with structured lessons to facilitate discourse transition. A good example is on the first day of class when the students are required to have proper safety training before entering the laboratory. Therefore, the primary focus of the first day's lesson is to introduce the students to the language of chemical discourse and the symbolic visual aspects of multimodal discourse. Dr. S begins by using a more conversational approach standing at the table with students to introduce the fundamental questions and observations that fuel chemical research. This promotes engagement and helps them feel less intimidated by the concepts. This teaching style is effective as it enables the students to enter into chemical discourse in a more relaxed manner.

Very evident is the move from informal to formal language. Once the students have formulated their questions and observations, Dr. S introduces them to skeletal structures. Understanding this concept is essential as the students will use it throughout the program. Though he transitions to a more instructional approach by teaching at the board, he still maintains interaction with his students. He asks them questions and invites them to share their thoughts on what molecules might look like and how they could be represented. Dr. S illustrates the skeletal structure of the main compound of their research. As he guides the students through the process of interpreting the skeletal structures, he adds bonding rules that make up the foundation of the skeletal structures. Essential concepts are explained and connected to the skeletal structures, such as carbon always forms four bonds. The students, intrigued by the visual representation of molecules, actively participate in the discussion. They share their interpretations of the skeletal structures and ask probing questions to deepen their understanding.

Dr. S then switches back to a more informal approach and employs a game to get the students involved in interpreting skeletal structures themselves. Students attempted to determine the number of atoms of each element in an example compound aided by other students on their team. When students needed assistance, Dr. S would guide them through the process. By the end of the session, Dr. S had successfully introduced skeletal structures to his students, laying the groundwork for further exploration in organic chemistry.

Another example of blending informal conversations with structured lessons is in Dr. S's use of analogies. When introducing the concept of TLC plates, Dr. S skillfully draws parallels between separating bees and wasps and the movement of polar and nonpolar molecules across the TLC plate. His approach during the analogy is more conversational. He asks the students questions, and the students provide their thoughts. Dr. S guides the students through the analogy before beginning the lesson on TLC plates. By leveraging familiar concepts, such as bees and wasps, Dr. S assists students in visualizing and conceptualizing abstract ideas, effectively bridging the gap between complex topics and students' prior knowledge. Once the analogy has been developed with visuals, Dr. S transitions back to a more structured lesson on the TLC plates followed by a demonstration in the laboratory.

Another way Dr. S moves students into the disciplinary discourse is by using alternate words for the technical terms. For instance, he uses the word "goop" to describe the chemicals he is transferring to a separatory funnel, which allows the students to focus on what he is doing and the name of the equipment in his hand. In sentence following the use of “goop”, he uses the names of the chemicals and draws attention to the layering effect in the separatory funnel. Alternating between non-technical and technical names draws attention to what is most important at that moment. Quickly returning to the technical terms reiterates their importance and keeps the everyday language from being problematic, as suggested by Gee (2004). This opens a space for the students to use descriptive terms as a communication tool as they are learning the more precise technical term.

Interpretation of Studio-Based Chemistry

Historically, science content and science skills have been separated into lecture and laboratory. In the immersion summer program created by Dr. S, students engage in multimodal discourse, where studio-based design plays a crucial role. The students can quickly grasp new chemical concepts and laboratory techniques in this environment. Lectures, demonstrations, and experimentation are seamlessly integrated to ensure maximum comprehension and retention. The program goes beyond traditional teaching methods, as Dr. S engages students in multiple modalities, fostering a comprehensive understanding of chemical principles.

Anchoring Modalities Through Repetition

An example of how studio-based instruction played out in this program can be seen with skeletal structures serving as an anchoring point for the manual technical operations performed in the laboratory and reinforce mathematical concepts daily. The studio-based framework provides a unique space to cultivate student acquisition of chemical discourse.

Dr. S spends a significant amount of time during the first few days in the partial safety zone lecturing and teaching at the board, while moving into the full safe zone to incorporate laboratory demonstrations and experiments into his lessons. This studio-based approach to teaching was incredibly effective, as it allowed for a seamless integration of hands-on demonstrations with theoretical instruction. For example, Dr. S brings a mortar and pestle from the laboratory to the lecture area for a demonstration. After the demonstration, students move to the laboratory area to practice using the mortar and pestle, with Dr. S providing them with guidance and instruction.

One significant advantage of the studio-based design is that Dr. S can quickly perform demonstrations without students needing to wear full safety equipment. This setup allows him to perform laboratory techniques within the full safety zone while students remain in the lecture area, making the learning process more streamlined. For instance, Dr. S lectures on purifying starting materials on day five. He explains the process on the board and then demonstrates the separatory funnel procedures. While he performs the separatory funnel procedure in the laboratory area, students remain in the lecture area where they do not need to have on safety glasses, gloves, and lab coat. Dr. S elaborates further on his previous lecture during the demonstration. Once he finishes and has the separate wanted layer of starting material, the students transition into full safety gear to move to a different laboratory area where Dr. S can show them how to use the rotavap.

As the program progresses, Dr. S shifts from giving lectures and demonstrations to the role of guiding and monitoring the students. By the beginning of the second week, the instructional time utilized by Dr. S is more evenly distributed between lectures and laboratory work as he moves back and forth between the full safety and partial safety zone. During this stage, Dr. S's role shifts from showing examples of multimodal discursive practices to facilitating students' active engagement in them. While lectures are utilized to reflect students' increasing understanding as well as introduce new material, the iterative process that the students engage in through their laboratory experiments is an essential part of the learning process.

In each iteration, students conduct a reaction, purify it, condense it in the rotavap, and then test their products using the TLC plate. Throughout this process, they record their skeletal structures, mathematical calculations, and diagrams of their TLC plate results in their notebooks. This showcases the effectiveness of the studio-based classroom, which allows students to participate in multimodal discourse daily.

Overall, the summer immersion program created by Dr. S demonstrates the versatility and effectiveness of the studio-based classroom design in promoting active learning and facilitating meaningful interactions between students and instructor. Dr. S uses a language transition approach to help students gradually change their discourse from everyday to the more precise language of chemical research. He uses natural oral language and gestures to support mathematical and symbolic discourse and manual technical operations when introducing tasks. By employing clear and accessible language, Dr. S fosters understanding and engagement, ensuring students can grasp the material more easily. Dr. S's approach helps students ease into the difficult lessons they encounter throughout the summer program.

Limitations

The purpose of this study is not to draw generalizable conclusions but rather to describe the multimodal discursive practices utilized by a chemistry professor and how they are supported by studio-based design. However, this research has several limitations, including a small sample size, the researcher's involvement, and limited data sources for triangulation. It should be noted that this research is solely focused on the teaching practices of one professor, as there were no other professors to observe in the summer immersion program. Additionally, the program was not repeated, which resulted in only one professor being a participant.

It is important to mention that the researcher participated as a teacher's assistant to the professor during the program, which could lead to bias on the researcher's part. Although the role of teacher’s assistant provided close interaction with the students and on occasion some direct instruction, the researcher did not play an active role in the design of the summer program. Any instruction given by the researcher was omitted from the data. Additionally, several years had passed between the participation and the analysis of this research, and the researcher attempted to remain impartial by relying only on observations from the collected data.

The limited data sources, made it challenging to provide triangulations through the data collected. Some recordings were not available at the time of the research. However, the recording provided a plethora of data, and the missing recordings belonged to time frames of little interest. Triangulation for a sequence of events was attempted by cross-checking video time frames and student recordings in their notebooks.

Future Research

Over the last few decades, there has been a growing interest in studio-based design in science classrooms. While this approach to design has been around for some time, it is becoming increasingly relevant as reform in undergraduate chemistry courses continues to grow. Studio-based design offers a unique framework for fulfilling the goals of this reform. By integrating knowledge and laboratory skills, this approach to education can help students develop the foundation they need to become successful scientists and researchers. Moreover, studio-based design aligns with the growing recognition of the importance of integrating multimodal discursive practices. There are three potential areas for research related to the growing interest in chemistry course reform. These include expanding the number of professors, comparing discursive practices in traditional and studio-based classrooms, and evaluating the retention of students in science who go through studio-based design chemistry classes.

It would be beneficial to replicate the current study using a more extensive and diverse sample of chemistry professors. This will allow researchers to gain further insights into the natural occurrence of discursive practices within the discipline. By increasing the number of participants, researchers can evaluate the generalizability of the findings and identify any potential variations based on individual teaching styles or backgrounds. Additionally, examining the effectiveness of studio-based design across multiple instructors can help determine its adaptability and scalability within undergraduate chemistry education.

Another area of research is comparing studio-based design and traditional classroom environments. This research could help to evaluate how different teaching methods affect students' multimodal discursive practices. Researchers can measure the effectiveness of studio-based design in fostering chemical discourse by examining the development of discursive skills in both settings. Additionally, this study could highlight the potential benefits of incorporating studio-based methodologies into current curricular frameworks. Most undergraduate chemistry courses do not focus on chemical research, but the studio-based design could be adapted to fit into current curricular programs.

A third area for future research is that it would be valuable to conduct studies that track the long-term impact of studio-based design on student retention in science-related fields, particularly chemistry. Researchers can follow cohorts of students over multiple semesters to assess their persistence in scientific disciplines, including their likelihood of continuing advanced coursework, pursuing graduate studies, or entering scientific professions. Such studies may also reveal correlations between studio-based instruction and factors contributing to student retention, such as engagement and a sense of belonging in the chemistry community. By doing so, we can gather valuable evidence about the effectiveness and sustainability of studio-based design in increasing students' discursive practices and promoting retention in science-related fields.

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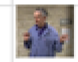
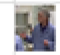
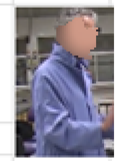
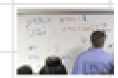
Appendix A

Camera	Clip code	Time	general	description	mm codes	SB codes	image
106	203		S not in Camera, voice only				
	204		S not in Camera, voice only				
	205		safety by safety officer				
	206		safety by safety officer				
	207	0	S touring lab	S enters lab room, discusses safety, gestures hands toward lab while saying "in the lab"(1), gestures down when commenting shorts, out for shoes. and back up when stating googles, this is all done in beat with each word.	nls, g	lab	
	208	0	S touring lab	S discussing choosing fume hoodwhile gesturing/pointing to fume hoods, tells students they will hang their lab coats on the fume hoods while touching the knobs outside the fume hood,	nls, g	lab	
		1.57	S touring lab	S discussing the 2 different secions of the lab/where it is safe to touch objects and where it is unsafe while making a touch gesture, then discusses leaving the lab and throwing away gloves while pointing out of the lab and then pantomiming taking of a pair of gloves	nls, g	lab	
107	12	20.22	s at table	talking about pill while holding up a pill	nls, g	lec	
		25.4	s at board	S at board writing "physical property" while talking and listening to students describe pill	nlt	lec	
		30.27	s at board	s at board discussing contents of pill writes actives and inactives on board, gestures to drawing of pill on board	nlt, s, g	lec	
		37.24	s at board	draws line bond structure of sertraline then explains the drawing. while pointing at different parts	nlt, s, g	lec	
	13	0	s at board	continues to explain the line bond drawing from previous clip		lab	
	13	23.1	s at board	S draws new stuctures and allows students to decifer them, watches the students gestures toward elements written board and reiterates numberof bonds per element	nlt, g	lab	
		25.3	s at board	S counts elements from a line bond drawing while pointing to corners of the line bonds and elements	nls, g, s	lec	
		35	s at board	S counts elements from a line bond drawing while pointing to corners of the line bonds and elements	nls, g, s	lec	
	14		safety training			lec	
	15		safety training			lec	
	16		touring lab	not in camera or bad angles		lec	
	17	5.1	touring lab	S holds up round bottom flask while explaining its name	nls	lab	

Note: nls = natural language spoken, nlw = natural language written, nlt = natural language, g = gestures, m = mathematical, s = symbolic, mt = manual technical, lab = laboratory, lec = lecture, cb = crossing boarding

VITA

Educational work experience:

Lake Ridge High School
From August 2018 to present
Mansfield Independent School District

R. L. Paschal High School - Science Teacher
From August 2008 to June 2018
Fort Worth Independent School District

Tarrant County College – Adjunct Instructor
Department of Community Education and Engagement
From the summer of 2019 to Spring 2021

Texas Christian University – Program TEA Application Writer - Summer 2017

Texas Christian University – Lab Assistant
TRIO organic chemistry summer program - Summer 2016

Research:

Creating an Acid and Base Learning Progression
Presented at Texas Christian University Research and Pedagogy Festival 2016

Learning Progression - the Acid Base Concept
Presented at NARST - National Association for Research in Science Teaching International Conference 2017

Thinking with Theory: Examples from Qualitative Inquiry
Presented at SPE – Society of Professors of Education Annual Meeting 2017

Middle School Laboratory Experiences in Japan and U.S. Schools
Presented at Texas Christian University Research and Pedagogy Festival 2017

Hybrid Discourse Practices as Entry into Chemistry Research Community
Presented at SSMA – School Science and Mathematics Association Conference 2017

Students become Chemist as Antidepressants become Antibiotics
Presented at Texas Christian University Research and Pedagogy Festival 2016

Awards:

Werner Schulz Award for chemistry teaching winner for 2021 from the DFW ACS
https://acsdfw.org/awards/