ABSTRACT

CHRISTIAN, CAROLINE. Examining Chemistry Students Visual-Perceptual Skills using the VSCS tool and Interview Data. (Under the direction of Maria T. Oliver-Hoyo).

The Visual-Spatial Chemistry Specific (VSCS) assessment tool was developed to test students’ visual-perceptual skills, which are required to form a mental image of an object. The VSCS was designed around the theoretical framework of Rochford and Archer that provides eight distinct and well-defined visual-perceptual skills with identified problems students might have with each skill set. Factor analysis was used to analyze the results during the validation process of the VSCS. Results showed that the eight factors could not be separated from each other, but instead two factors emerged as significant to the data. These two factors have been defined and described as a general visual-perceptual skill (factor 1) and a skill that adds on a second level of complexity by involving multiple viewpoints such as changing frames of reference. The questions included in the factor analysis were bolstered by the addition of an item response theory (IRT) analysis. Interviews were also conducted with twenty novice students to test face validity of the tool, and to document student approaches at solving visualization problems of this type. Students used five main physical resources or processes to solve the questions, but the resource that was the most successful was handling or building a physical representation of an object.
Examining Chemistry Students Visual-Perceptual Skills Using the VSCS tool and Interview Data

by
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Chemistry

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DEDICATION

I dedicate this work to all the students I have had over the years, that have inspired me to pursue this degree. I also dedicate this work to all the teachers, mentors, and educators I have ever met, who encouraged me to reach for my dreams but especially to Maria Oliver-Hoyo – the greatest mentor, teacher, and educator that I have ever had the pleasure of knowing. Lastly I dedicate this work to my husband, my rock, my best friend, my soulmate, and my one true love – Patrick.
Caroline Christian is an educator because she likes to make a positive difference in students’ lives. She is a scientist because she is intrigued by the natural and physical world and hopes to find truth in the world by studying chemistry. She loves chemistry because it is in everything around us: everything we make has been influenced by a chemist, everything we do is controlled by our bodies’ biochemical processes, and everything that is living or nonliving has chemical properties.

She was born in Illinois on November 30, 1977, the second child to Bill and Alice Christian. When she was seven years old, her parents divorced and she moved to a small cottage next to a park. During these early years of her life she attended St. Andrews Lutheran School in Park Ridge, Illinois. It was at this small, private school that she got her early love of learning, teaching, and her good study habits. These habits have followed Caroline her whole life, turning her into a lifelong student, always thirsty for new knowledge. Peter, Caroline’s brother, got accepted to the University of South Florida when Caroline was eleven, so this prompted the whole family to move to Florida. While in Florida, Caroline developed her love for singing, singing in two duet and four solo competitions, five musicals, countless ensemble and choir competitions, and even made it to three all-state invitationals. She also found a new love in tenth grade, chemistry.

She attended Concordia University in River Forest, IL with a dream of becoming a high school chemistry teacher, but she quickly changed her career focus and decided instead to pursue college teaching. Caroline next went to the University of Illinois in Urbana-
Champaign for Ph.D. studies, where she got her first true taste of teaching. She was
responsible for a twice weekly discussion section, and then a 4-day a week lecture section
where the students only saw her to teach them chemistry. Needless to say, Caroline loved
this interaction, and unfortunately her Ph.D. studies suffered for it. She decided to get a
Masters’ Degree in Chemical Biology after four years of doing biophysical chemical research
on a pathogenic bacterium – *Vibrio Cholera*. Then another teaching opportunity opened up
for Caroline – a Masters’ degree in Education, where Caroline would be certified to teach
middle and high school science. Caroline’s love for teaching lead her to complete this
program in May of 2005, and graduate with two Masters’ degrees from the number six
school in the country for chemistry programs.

Then another schooling opportunity opened up for Caroline, to pursue her dream of
becoming a college chemistry instructor somewhere warmer, at North Carolina State
University in Raleigh, NC. When she arrived, she came just as she had done three previous
times in her life, with a chance to reinvent herself with no one who knew her. After about a
year and a half of searching, she finally found a project that suited her – development of a
Visual-Spatial Chemistry Specific assessment tool. Here she has found her place, where she
wakes up every morning enthusiastic for the day to begin, yearning to go to work, and
willing to learn new things. Caroline will be receiving her first Ph.D. degree with the
completion of this dissertation and its defense, and she is excited to be working on the next
phase of her life, teaching students. She eventually hopes to get a job with a school board
developing assessments.
ACKNOWLEDGMENTS

I would like to acknowledge the help of my mentor, Maria T. Oliver-Hoyo, for helping me understand this topic, decide upon an assessment framework, listening to me at numerous group meetings, and helping me to revise pages and pages of text. She has been a generous and wonderful mentor, advisor, and friend. I would also like to acknowledge the help of the professors that have implemented the assessment in their classrooms, and the members of my committee, Dr. Jones, Dr. Ghiladi, and Dr. Whitten.

I would also like to thank the present and past members of my research group for listening to my group meetings, and giving me advice on how to make my research stronger.

A big advantage of my research study is the use of statistical consultants at North Carolina State University. I would like to acknowledge all the help that I received from the consultants: Dr. Brian Reich, Q Burkhart, Danny Modlin, Muhtar Osman, Stacey Wood, Woohyeon Kim, and Murilo Brizzoti.

I would also like to thank some special people who helped me articulate concepts by listening – Holly, Patrick, Maria, Stacey, Anita, Anne, Dr. Nancy Penrose, the students in the ENG 641 class, and Laura.

I would also like to thank my mother, without whose constant love and support I would not be where I am today.

Finally, where would I be without the one constant force in my life, pushing me to do right, to be a better person, and to find my hour of peace a week, Dear Lord, thank you for bringing me on this fantastic journey that I call life.
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CHAPTER 1. Introduction

Visual-perceptual skills are needed to form a mental image of an object, whereas visual-spatial skills are subsequently needed to compare that object to others in space. Both skills are important for college chemistry students because of the various ways that chemical structures are represented in textbooks, lectures, and online media. Interpretation of molecular representations requires visual-perceptual skills because a mental image must first be rendered to understand these images. Visual-spatial skills are also necessary to truly understand molecules, atoms, and their interactions due to the need to compare different molecular images to others in space, since most images have no background. In this dissertation, the student abilities necessary to mentally model such molecules will be described as visual-perceptual skills, while the tools that are used to test these skills will be referred to as visual-spatial assessments. Although the focus will be on visual-perceptual skills, to actually solve questions on a tool designed to monitor these, one needs to compare objects to others, resulting in the use of visual-spatial assessments.

Chemists’ model molecules three-dimensionally based on experimental research and data, and usually represent them either as a space-filling image, a ball-and-stick object, or a line drawing. Space-filling models symbolize most accurately what the atoms look like in molecules by representing their electron clouds. Ball-and-stick models represent how the atoms are connected together with balls signifying the atoms, and sticks denoting the bonds between atoms. In line drawings used in organic chemistry, two-dimensional lines represent carbon to carbon bonds, and students must mentally interpret what the molecule looks like in
three-dimensions in order to understand the structure-function relationship of the molecule.

In Figure 1.1, the three different representations of an organic molecule are shown.

![Figure 1.1: Space-filling, ball-and-stick, and line drawing representations of the molecule n-butane](image)

Since line drawings are the most simplified way to represent molecules, they are often the most confusing to chemistry students. A fundamental step in visualizing these representations of chemistry molecules is to form a mental image of the molecule invoking visual-perceptual skills. These important skills make understanding the different representations of chemistry molecules an achievable goal.

**1.1: Visual-perceptual skills**

A logical step in understanding how students view these representations of chemistry molecules is to assess the students’ visual-perceptual skills. Various studies have implemented visual-spatial assessments to connect college students’ visual-perceptual skills and chemistry achievement. Baker and Talley studied the correlation of academic ability with visualization skills as compared to achievement in freshman chemistry. They found a relationship between freshman and senior status in an undergraduate chemistry curriculum.
with general academic ability and visualization abilities. They determined academic ability by a standardized College Board exam, the ACT, assessed visualization abilities with the Paper Folding and the Surface Development tests, and measured chemistry achievement by the students’ grade on the final exam. Baker and Talley found that upper class students who major in chemistry may be superior in visualization abilities as compared to freshman students. Visualization abilities might act as a catalyst in enhancing the functioning ability of the student to deal more effectively with undergraduate chemistry problems. Problem solving ability and visualization skills were studied more closely in research by Carter, et al., who found that spatial abilities, tested with the Purdue Rotation of Visualization Test and the Embedded Figures Test, were more positively correlated with complex problems rather than with questions that tested rote memory or simple algorithms. Rochford and Irving also discovered a positive correlation between the spatial visualization abilities of college students and their chemistry achievement as measured by their scores on tests and exams. The spatial abilities were tested with a specially designed assessment, the Visualization of Pictorial Molecular Structures. In addition, Rochford and Irving noted that students with weak spatial abilities underachieve in chemistry classes and are more likely to fail. These studies show that chemistry visual-perceptual skills are positively correlated with chemistry achievement and problem solving skills.

Rochford and Archer theorized that there were eight important visual-perceptual skills needed by engineering students. The theoretical framework of these skills and definitions is listed in Table 1.1.
Table 1.1: Definitions of eight theoretical visual-perceptual skills proposed for chemistry.  

<table>
<thead>
<tr>
<th>Visual-perceptual skill</th>
<th>Definition (Ability to)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual association</td>
<td>Relate concepts written as text to their representation in pictures</td>
</tr>
<tr>
<td>Visual constancy</td>
<td>see diagrams of objects that are the same size, shape, or color from others that are not</td>
</tr>
<tr>
<td>Visual discrimination</td>
<td>perceive dominant features in objects and to discriminate one object from another</td>
</tr>
<tr>
<td>Visual figure ground</td>
<td>distinguish objects from their background</td>
</tr>
<tr>
<td>Visual form perception</td>
<td>represent in two- or three-dimensions objects that are three-dimensional</td>
</tr>
<tr>
<td>Visual memory</td>
<td>recollect the dominant features of a diagram</td>
</tr>
<tr>
<td>Visual orientation</td>
<td>rotate the positions of objects in space in relation to other objects and the observer</td>
</tr>
<tr>
<td>Visual sequencing</td>
<td>See objects in a particular order</td>
</tr>
</tbody>
</table>

The foundation of this theory is based on case studies of students assessed as having average intelligence and who exhibited one or more learning deficits.  
Examples of these problems and the skills that encompass them include: motor-memory dysfunction as in the visual memory skill category; reversals, insertions, and deletions in the visual discrimination skill set; and the “...inability to identify figures presented in fragments or to visualize missing portions” in the visual association skill group.  
The researchers hypothesized that students who lack these visual perceptual skills may fail courses in their scientific academic careers.  
In other research, Rochford’s group found that for anatomy students, a positive correlation exists between scores on a specialized visual-spatial assessment and failure rate of the class.  
Thus students who lack these visual-perceptual skills failed the anatomy classes in greater numbers.  
The study concludes that students who have these difficulties overcome them by compensating with their strengths, such as students with an auditory input disorder supplementing with visual input.  
Rochford also advocated helping these students by clearly
identifying the visual-perceptual skills needed for mastery of the material, so that the
necessity to help students’ problems might be eliminated as students would take care of the
obstacle themselves. Although this was originally conceived of as an engineering skill set, it
is the claim of this dissertation that these skills are also needed by college chemistry students.
However, visual-perceptual skills are often overlooked in chemistry classrooms and
chemistry instructors are rarely trained or made aware of the relevance of visual-perceptual
skills in chemistry. Development of an assessment tool that could test these skills could
ultimately be used to screen students’ visual-perceptual skills and monitor their skill
development to empower students to improve their own visual-perceptual skill set.

1.2: Visual-spatial assessments

Various terms in the literature have been used to describe this dissertation’s two main
concepts: visual-perceptual and visual-spatial skills. Consider these from an expert’s
dissertation, “As I formally present my theory of spatial cognition in chemistry it will
become apparent that visualization [visual-perceptual skills] can occur independent from
spatial reasoning [visual-spatial skills] and that neither are necessarily reflected by a
student’s visuo-spatial ability as measured by standardized visuo-spatial ability
psychometrics [assessments]”. Researchers have used new terms and have recycled old
ones to describe the same processes, which is why the terms used in this dissertation are
listed in brackets. Steiff’s words describe the purpose of this research, which is the need for
a new assessment, one that can test the fundamental skills students need to use when looking
at a molecular structure. We propose that the Visual-Spatial Chemistry Specific (VSCS) tool can fill this gap, by assessing visual-perceptual skills.

Previous visual-spatial assessment tools were written for a variety of purposes. For example, Thurstone developed several different assessment tools, versions that are still in use today, to test intelligence in the belief that people possess several different types of intelligence. As a pioneer in the field, his book contained a variety of tests for visual-perceptual skills which he considered to be a part of an individual’s primary mental abilities. In one study 240 volunteers took fifty-six different general visual-spatial assessments that were analyzed using for the first time factor analysis on the data, which is a term he coined. Thurstone hypothesized two visual-perceptual factors or skills: the skill to see in two-dimensions and the skill to see in three-dimensions. Both of these skills were tested with a number of visual-spatial assessments and it was concluded that although Thurstone had considered them separate categories for visualization in flat and solid space, the analysis did not show a division. More recent assessment tools that are based on Ekstrom et al. Educational Testing Services assessments test students’ achievement in school, and include math, language, and spatial visualization tests. In this set of assessment tools, the most common one used today in chemistry classrooms to test students’ spatial ability is called the Purdue Rotation of Visualization test, or the Purdue ROT. A figure of one of its questions is included in Figure 1.2.
The ROT questions assess visual orientation skills as described in the Rochford framework, or the ability to rotate or reflect the positions of objects in space in relation to other objects and to the observer. This dissertation argues that chemistry students need more than just visual orientation skills. Table 1.1 includes the visual-perceptual skills Rochford and Archer theorized to be important to engineering students, and that are theoretically important to college chemistry students as well.

The purpose of this research is to determine if Rochford and Archer’s visual-perceptual skills can be validated in college chemistry classrooms by developing a visual-spatial testing tool, the VSCS assessment, that will test these eight skills, and to determine which (if any) of the skills predominate as well. This study will be performed using a statistical technique called factor analysis. A history of factor analysis and some recent developments will be discussed in the literature review section. This section will also include a listing of research that has sought to improve visual-perceptual and visual-spatial skills by the use of specific interventions, and a discussion of what could be implemented in
conjunction with the Visual-Spatial Chemistry Specific Assessment tool. Specifically the
Think Aloud method was chosen to interview students answering the visual-spatial questions
and to understand mental models of students. Think Aloud is a process that has been tested
and validated.\textsuperscript{12} The methodology section will discuss how the statistical methods were used
to analyze the data from the VSCS, and how the interviews were conducted. Results and
discussion sections will follow. The appendix will include the complete assessment tool as it
is currently written and tested. This dissertation will concentrate on the validation of the first
assessment tool developed to test eight distinct chemistry visual-perceptual skills, the results
and interpretations of its analysis and implementation, and a discussion on the implications to
chemistry instruction.
1.3: REFERENCES


CHAPTER 2. Literature Review on Possible Interventions

A considerable number of research papers describe spatial ability interventions, or studies that seek to improve students’ visual-spatial or visual-perceptual skills.\textsuperscript{1-5} These two types of skills are defined in this dissertation as: visual-perceptual skills are the fundamental skills required to produce a mental reproduction of an image, whereas visual-spatial skills are the concurrent skills needed to compare that image to other objects. This literature review will focus on:

- Interventions to help improve students’ spatial abilities subsequently broken into three sub-sections:
  - Chemistry specific interventions where chemistry students have participated or have used molecular images.
  - Science fields other than chemistry that have used unique interventions.
  - Non-science fields’ interventions that use different techniques.

- A historical perspective of the think aloud method which is an interviewing and possible intervention technique.

All research studies discussed in this review have been performed with college students, unless otherwise stated. The research in the interventions sections has been published over several decades, and the studies are listed here in chronological order since the ideas highlighted have been influential in this order. Literature papers chosen may describe
complete research studies and/or interventions (process or activity aimed at improving
visual-perceptual or visual-spatial skills.)

2.1: Intervention studies

Spatial abilities are particularly important in a variety of fields; however high school
and college instruction do not usually address these types of skills, emphasizing instead a
verbal teaching approach. Typically little or no time in chemistry class is spent in the
development or explicit use of spatial abilities. It has been argued that background
experiences and gender may cause students to have low spatial abilities, but it has also been
shown that these abilities can be developed and learned during formal educational
experiences. Since the 1930’s, theorists have suggested that visual-perceptual skills are
important for learning, and beginning in the 1970’s research interventions have been
published. The research interventions in this section of the literature review will be broken
down into three sections: first, research that specifically targeted chemistry students or used
chemistry molecules to help students develop their spatial skills; second, studies from
different science fields; and third, interventions from non-scientific fields such as art.

2.1.1: Chemistry-specific interventions

In chemistry, a number of interventions have been proposed to help students increase
their visual-perceptual skills. These authors either specifically aim their interventions
towards college chemistry students or use chemistry molecules to help students at a lower educational level, such as high school.

2.1.1.1: Molecular Models

Foundational research by Baker and Talley found visual-perceptual skills were correlated with academic ability as measured by scores on the standardized American College Testing (ACT) program.\textsuperscript{11} Forty students in two freshman chemistry classes and twelve senior majors were tested. The visual-perceptual skills were measured once in the chemistry students’ academic careers with two of Thurstone’s visualization tests: the paper-folding test and the surface development test.\textsuperscript{10} The significant difference in visualization test scores suggested that upper-class students majoring in chemistry were superior in their visualization abilities as compared to freshman. They postulate that visualization acts as a catalyst to enhance the ability of chemistry students to work undergraduate problems.

Talley and Solomon found that 73.7\% of a college instructor’s behavior operated at the abstract level, but 75.2\% of the college instructor’s presentations were built on rote knowledge.\textsuperscript{12} Based on this research Talley introduced physical molecular models in a freshman chemistry class for science majors.\textsuperscript{1} Molecular models come in different shapes and forms, but they usually have balls to represent atoms and sticks that represent bonds. One hundred and two undergraduates in a freshman general chemistry course were divided into two equal size sections for the control and experimental groups in this study. Both groups were given two common visual-spatial pre-tests (Paper-Folding and Surface
Development tests, both in Thurstone, 1938), and both classes were taught by the same professor. The experimental class was taught using molecular models and a strong visual approach. The control group used a lecture approach, stressing verbal descriptions and textual cues. At the end of seven units of instruction the two sections were given the same test of fifty items that followed Bloom’s taxonomy of learning domains: ten basic knowledge, ten comprehension, five application, five analysis, five evaluation and fifteen analogy questions. Talley found that the experimental group had statistically higher test scores on all the questions except for the knowledge questions, where the control group had higher scores, and the comprehension questions, where the scores were statistically equivalent. The researchers took this to mean that the control group was operating at a knowledge/comprehension level, whereas the experimental group was operating at a higher cognitive level. This research suggests that working with molecular models promote students to operate at a higher cognitive level.

Another research study introduced molecular models to high school students in a stoichiometry unit. Whereas the Talley study used model kits with college students, Goodstein and Howe used miniature marshmallow, candies, and Styrofoam balls as atoms, and toothpicks for bonds. The students performed four experiments during the six week instructional period in 2-hour laboratory periods. The labs were involving (1) counting large numbers of particles indirectly, (2) determining the percentage of water in a hydrate, (3) verifying Avogadro’s number by a monomolecular layer method which was performed by the control group only, and (4) validating the ratio of reactant \( \text{Na}_2\text{CO}_3 \) to product \( \text{NaCl} \). The experimental classes had the students manipulate models of atoms, ions, and molecules.
whenever possible. The teachers of the control classes used models only sparingly, and the topics covered in the experimental and control classes were the same. The students were also tested on their level of logical thinking, to assign them to a concrete learning style or a formal operational style. The classes were taught by two different instructors who taught one experimental and one control class each. At the conclusion of the 6 weeks of instruction a test was given that included two questions that were not specifically covered in the textbook or during the lessons. The scores on these two questions showed that the formal operational learners did benefit from the intervention of the molecular models, but the concrete learners did not. This research suggests that students need to be at a certain cognitive level, before they can be expected to benefit from using molecular models.

2.1.1.2: Depth Perception studies

The next two research studies are foundational to researchers who used molecular or chemical images to study depth perception. Deregowski used five three-dimensional wireframe figures represented on paper, therefore students perceived the figures to be in two-dimensions or three-dimensions (Figure 2.1). All the students in this study were boys from a Kenyan primary school aged ten to eleven years old. The researchers asked students to make one of the models out of bamboo splints with plastic balls on the corners. If the students made it two-dimensionally, the researchers gave them stereoscopic goggles (two different orientations of plane polarized film for each eye), and let them build the other four models. Stereoscopic goggles will show the diagrams in a three-dimensional fashion. If the
students made the first model in three-dimensions, then the researchers let the students build two out of the four remaining models without the goggles.

![Figure 2.1: Five diagrams used to test if stereoscopic goggles were a way to teach African boys’ pictorial depth perception](image)

About thirty percent of the boys built the first structure in a two-dimensional way, which indicates that the students did not understand the picture was a three-dimensional picture just drawn two-dimensionally. This research study did not give any data about how the 30% of students did after the intervention with the stereoscopic goggles. The researchers concluded that presentations of stereoscopic pictures may serve as a method for teaching pictorial depth perception, and that perception with the stereoscopic goggles can generalize this experience to ordinary drawings.

Stereoscopic (three-dimensional viewing) and planoscopic (two-dimensional viewing) depth relationships were studied by Seddon as early as 1977, and his research was strongly influenced by Deregowski. In this first research study, interventions were
conducted where the researchers used a specially designed pre- and post-tests to study two different groups of Nigerian secondary school students’ ability to understand depth relationships in pictures. Figure 2.2 portrays a portion of this specially designed frameworks assessment tool that shows the beginning of Seddon’s work with molecular-type structures employing cubic and hexagonal structures and testing vertical, horizontal, and diagonal displacements.

Figure 2.2: A portion of the frameworks test used by Nicholson and Seddon to assess the spatial abilities of African students17
The researchers wanted to compare the effectiveness of stereoscopic versus planoscopic pictures to determine how the different representations were perceived by different cultural groups. Stereoscopic pictures were analyzed with special glasses to induce three-dimensional viewing. The effectiveness of three different interventions was studied by using (1) models, (2) stereoscopic, and (3) planoscopic pictures of the frameworks test questions in Figure 2.2.

Two cultural groups were tested, the Yoruba and Hausa tribes in Nigeria, which are distinct by language, religion, and geographic region. For the first group of students, with 235 Yoruba students, the comparisons were between the planoscopic pictures, stereoscopic pictures and the models of the frameworks test questions observed within a viewing box. The second group, which was 158 Hausa male students, compared the planoscopic, stereoscopic, and the planoscopic used in conjugation with the models in viewing boxes. Figure 2.3 is a schematic of the viewing boxes that were used in these interventions.

Figure 2.3: Representation of the design of the viewing model boxes

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The researchers split each group of students into three experimental groups and a control group. (1) The experimental intervention completed by one set of students involved viewing models, where the students had to observe a model of a framework test question and answer questions about the model. The models were built with plastic rods, metal connectors and polystyrene balls and were put in boxes, with the questions printed on the inside of the box (Figure 2.3). The models could not be rotated; instead the students could only see the models in the orientation in which the experimenter had placed them in the box. The reason for putting the models in the viewing boxes was so that the students viewed the frameworks from the same viewpoint, and the three-dimensional nature of the diagram was maximized. The students were asked to view the model and determine the answer.

For the (2) planoscopic and (3) stereoscopic interventions, diagrams were projected on a screen by an overhead projector for the students in the same room; the only difference was that the first group wore glasses that could view the stereoscopic images on the screen. The students assigned to the planoscopic group enjoyed the same novelty of wearing the glasses, except a lens was removed, rotated 180 degrees, and glued back into the frame, so that “[t]he effect of this adaptation was to align the axes of polarization for the two filters in parallel directions...[to be] entirely planoscopic”.16 From the posttest scores, the researchers found that both group of students who received the stereoscopic diagrams intervention had significantly higher scores on the framework test than the students who received the planoscopic diagrams, although the stereoscopic intervention was similar in results to the models intervention for both of these particular groups of students.
2.1.1.3: Organic visualization training

Small and Morton’s intervention\textsuperscript{18} was designed to clarify unanswered questions from Talley’s study on molecular models.\textsuperscript{1} They first wanted to determine if motivation or enhanced interest in Talley’s experimental classroom affected the students’ achievement. Small and Morton claim that the classroom activities and the atmosphere differed in the two classrooms, so the effect of the models could be invalid. The researchers also wanted to see if organic students would benefit from spatial training, since Talley’s study involved general chemistry students. Finally, Small and Morton claimed that students who are just given a model kit, and no training on how to use it, will be less likely to use this kit when developing their chemical knowledge. This study was designed to determine if visual-spatial training, regardless of the instructors, labs and classrooms would improve performance in chemistry.

Advanced organic chemistry students received organic visualization workbooks and were trained on how to use the workbooks. Sixty-seven students were split into two groups, using SAT scores and five visual-spatial assessments as covariates and equalizers among the students; the experimental group received workbooks on how to use the spatial model kits, while the control group received a nomenclature workbook, and both went to special training sessions on how to use their respective workbooks. The results of this study determined that although the exams were written with no special spatial agenda in mind, the students who received the spatial training did better on the spatial test questions. On the nonspatial test questions, there was no difference in score between the experimental and control group. The authors did the classification of spatial versus nonspatial test questions. Small and Morton
also claim the results obtained were long-term, because the training of the students stopped in
the eighth week of the term, yet the final exam did not occur until the fifteenth week of the
course.\textsuperscript{18}

More recently, high school organic chemistry students were exposed to physical and
computer molecules into their formal instruction.\textsuperscript{19} The researchers surveyed fifty teachers
and found that only a minority (17\%) used physical models with individual students. The
research population was 276 students from nine high schools in Israel: 154 were in the
experimental group, and 122 were in the control group. The students in the experimental
group conducted learning tasks and investigated the molecules three-dimensional structure by
building and drawing physical and virtual models. The students in the control group used
models rarely and then only for teacher demonstration. There is no mention in the research
study of the length or frequency of the intervention. Both groups of students were given a
pre- and post-organic compound visualization questionnaire, where the students had to
transform between one- (molecular formula), two- (structural formula and ball-and-stick
drawing), and three-dimensional (space-filling) representations. No significant differences
were found in the pre-course questionnaires scores, but by the post-questionnaire the
experimental students outperformed the control students significantly. The organic
molecules highlighted helped the experimental group students define and implement
isomerism and functional group concepts, more so than the control group. The researchers
recommend incorporating physical and virtual models in organic chemistry classrooms,
which shows that organic chemistry students can benefit from specialized training in spatial
awareness\textsuperscript{18} as well as using physical and virtual models in classes.\textsuperscript{19}
2.1.1.4: Depth cues training

In the following three research studies Seddon uses chemistry molecules to test depth perception and visualization skills of high school aged students from different cultures. The first research study describes two separate interventions that introduce the concept of depth cues.\textsuperscript{20} Depth cues are used to give the appearance of depth in a 2-dimensional drawing of a molecule (Figure 2.4).

Students were given the same two pre- and post-tests: cues test (Figure 2.5) and the frameworks test (Figure 2.2). The researchers tested two different groups of students with two different interventions. Since the four separate cues tests are difficult, Seddon tested to see how many of the depth cues tests students would pass.\textsuperscript{20}
Figure 2.5: Four example depth cues test questions from Seddon, Adeola, El Farra, and Oyediji\textsuperscript{20}

The researchers gave students different intervention programs, a cues program which is represented in Figure 2.5 and a frameworks program in Figure 2.2. For intervention one (cues program) the researchers tested 235 Nigerian males and females aged ten to seventeen at one secondary school who were in the top twenty percent of general ability and 152 students in the middle range of ability at a college for training teachers where the average age was twenty-one. Seddon et al. did not subdivide these students by gender. All these students spoke English, as opposed to the students in intervention two (frameworks program) who
only spoke Arabic; thus the researchers translated all the materials. These were 470 boys aged fourteen to fifteen from two single sex secondary schools in Kuwait who were in the top twenty percent of general ability. For both interventions, the students viewed models in boxes with the questions and answers posted next to the box (Figure 2.3). The answers were hidden, so the students could only look after attempting the problem. The model boxes were lit so the students could see the shadows the models cast, but they could not rotate the model. The group of English-speaking students received one model of each of the four different depth cues, and the Arabic-speaking students received models of the frameworks diagrams. Students did improve their scores on the depth cue test in which they were given instruction, but they did not improve their scores on the depth cue test for which they were not given instruction. It appears that these skills are nontransferable for this particular group of students. If the students were given the frameworks intervention, they did improve their scores on the framework and the depth cues tests. If the students received both interventions, they scored superior on the frameworks test as compared to the students who were given only one intervention.

In a second research study 245 mostly male Nigerian students received the molecular rotations test first (Figure 2.6), and if the students failed this test, they then took the four cues tests (Figure 2.5). If they passed the molecular rotation test, they were not included in this study.
The students in the three experimental and one control groups were determined by the number of depth cues tests the Nigerian students passed. In the first intervention the researchers were investigating how the students analyzed a task as to its component parts. All three experimental groups were given the same molecular rotation questions, but they got the questions in different formats.

- Experimental group 1 – received all 36 questions as diagrams. Diagrams are pictures of the questions.
- Experimental group 2 – received 12 questions as models and 24 questions as diagrams. Models are ball-and-stick figures in a box which could be rotated.
• Experimental group 3 – received 12 questions as shadows, 12 questions as models, and 12 questions as diagrams. Lights in front of the model box showed students the figure in shadows.

• Control group – received no questions.

At the end of the intervention, all the students completed the molecular rotations test as the post-test (Figure 2.6). The students who employed the models improved their scores on the post-tests as compared to the students who were given just diagrams, and the students who received the shadows and models out performed the students who had only received the models. Therefore, the researchers postulated that seeing the rotating model and the shadows of the rotating model do help students in realizing how the depth cues change due to the effects of rotation.\textsuperscript{21}

In this same research study by Seddon, et al.\textsuperscript{21} a second question aimed to determine how much of a rotation would best help students understand the different depth cues (Figure 2.4). This intervention, however, did not use models of the rotation questions, instead used an overhead projector to project a slide show of the molecules dissolving while rotating into place on the screen. The researchers tested 252 students of less overall ability than in the first intervention but were still male Nigerian students. These Nigerian students were given no pre-tests, because it was assumed that most of these students would fail at least one cue test (Figure 2.5). The researchers assigned students to one of two experimental and one control groups. The first experimental group saw the depth cues in static structures as their intervention, whereas the second experimental group saw the depth cues in a slide show changing as the structure rotated. During the intervention this group was broken down even
further to a group who saw the angle by which the structure was rotated changed progressively. The total rotation occurred through an angle of 90°, and the first group students saw the structure 10° increments until the full rotation was reached. The second group of students saw the rotation in three 30° rotations dissolving into the full 90° rotation. The results of this second intervention showed that the students who received the rotations intervention did significantly better than those who just received the static depth cues intervention. The post-test results also improved when the rotations were parsed in smaller angle increments.21

A third research study by Seddon and Moore tested younger students to examine the effectiveness of combining models with the use of a television to present the sequences of rotations of the molecules to an entire class.22 The researchers tested seventy-four 14-15 year olds at an English comprehensive school, and gave them the molecular rotation test as both a pre- and post-test (Figure 2.5). Seddon and Moore used two experimental groups; one that received the intervention as physical molecular models and viewed rotating molecules on television, and one group that only viewed the molecules on the television. The control group did not view any molecules as an intervention. The researchers found surprising results in that the use of models had a distinctly deleterious effect which cancelled out the beneficial effects of the videotape. The students may have been unable to simultaneously manipulate the rotating models and watch the diagrams moving on the television screen. The researchers caution teachers to temper the use of physical models and rotating diagrams, and use models considering students’ working memory and avoiding memory overload. Working
memory is addressed in Cognitive Load Theory by emphasizing the inherent limitations of working memory on learning during instruction.23

2.1.1.5: Designing molecular representation in textbooks

High school students in Israel were found to not understand the equation

\[ 2\text{Cl}_2\text{O} \ (g) \rightarrow 2\text{Cl}_2 \ (g) + \text{O}_2 \ (g) \]

or more generally the structural aspects of chemical reactions, such as the structure of a molecule, the nature of a gaseous state, and the interactive nature of a chemical reaction.24 The researchers gave the students chemical equations, asked the students to draw what they thought the equations meant, and the drawings were analyzed. Most of the students had a macroscopic understanding of the equation, or a static microscopic description in mind, but the researchers expected the students to have a dynamic microscopic representation. Ben-Zvi et al. developed a new textbook used by tenth-grade students in Israel, where models were used extensively in many units of the textbook, and stressed the dynamic nature of reactions particularly indicating movement of particles. The researchers found that this textbook alone did not increase the students’ scores on in-class or spatial examinations. They thus postulated that students need model kits along with the representations of models in a textbook to be able to understand the dynamic structural aspects of chemical reactions.24
2.1.1.6: Elementary steps in solving a rotation task

Researchers tried to enhance college students’ visual-perceptual skills by pre-testing students using a molecular rotation question (Figure 2.7), which assesses the visual orientation skill set in the theoretical framework of Rochford and Archer.\textsuperscript{25}

The researchers determined where the students had problems with this question, and reworked the question into six smaller, simpler steps, which included\textsuperscript{26}:

“(a) visualize which atoms in diagram 1 are in the plane of the paper, which atoms are farther away, and which are closer to us than the plane of the paper, by making use of the depth cues (overlap, foreshortening of lines and distortion of angles) provided in the diagram [Figure 2.7];

Figure 2.7: An example rotation question by Tuckey, Selvaratnam and Bradley\textsuperscript{26}
(b) recognize the orientation of the Y-axis;

(c) recognize the meaning of the phrase "rotation about the Y-axis";

(d) visualize, three-dimensionally, how the positions of the various atoms would change when the molecule is rotated about the Y-axis;

(e) indicate on paper, using the depth cues, the three-dimensional structure of the molecule that would occur after the rotation;

(f) compare the diagram obtained in the last step with diagrams 2, 3, 4, and 5 given in the question, and select the one that matches’

The researchers then tested students with the full question shown in Figure 2.7 together with shorter and easier questions that test these specific steps. They found that most of the students had trouble identifying the axes and planes, understanding the meaning of the phrases "reflection in a plane" and "rotation about an axis", and visualizing the positions of the atoms after rotation or reflection. In addition, many students were unable to make use of the depth cues provided to visualize three-dimensional structures (Figure 2.4). After the researchers identified all the problems the students were facing, the students received a one-time two-hour long remedial intervention that consisted of explaining the axes, depth cues, and the operations of rotation and reflection. The students’ scores and understanding of these concepts increased significantly on the post-test which was equivalent to the pre-test but asked different questions. The researchers did not do any longitudinal studies to see if the knowledge was retained after days or weeks of instruction. This research only tested one type of visual-perceptual skill, visual orientation skills.
2.1.1.7: Electrochemistry and Dual Coding implemented by computer software

One chemistry-based intervention centers around Paivio’s Dual Coding theoretical framework.\(^{27}\) Dual Coding theory explains human behavior and performance by invoking educational theory and looking at three realms: education, affective skills, and perceptual-motor processes.\(^{28}\) Some chemical education researchers have used Dual Coding theory as a theoretical framework for their visual-spacial research.\(^{27,29}\) According to this theory two important systems are required to teach: nonverbal imagery or imagens, and verbal linguistic or logogens.\(^{27}\) Both of these systems are used to explain the senses; however the systems are different in internal structure because they describe two parts of one whole. One system can trigger activity in the other, but the pathways are usually incomplete, which is why it is imperative to teach with both systems. This is especially true in the highly visual subject of chemistry. For example, in organic chemistry, visual representations of hydrocarbons and other molecules are used interchangeably with verbal descriptions of them. If the pathways in human performance are incomplete in regards to their verbal and nonverbal systems, then teachers must make these connections explicit for students. In this study the researchers used computer animations to teach electrochemistry to 415 students in an introductory college chemistry class.\(^{27}\) The researchers tested two groups of students - one was shown computer graphics animation representing electrons and ion movement in batteries, the other was shown static pictures of the same phenomenon. The researchers gave the students pre- and post-tests on flashlight and battery knowledge (Figure 2.8), and tested their visualization aptitude with the Purdue Rotation of Visualization test. The researchers found that the
students who received the computer graphics instruction improved their scores on a content test on flashlights and batteries. Furthermore researchers found that students with higher visual-spatial skills, as measured by the Purdue Rotation of Visualization test, were superior on both the pre- and post-test on content as compared to the lower visual-spatial ability students.

![Example pre- and post-test questions from Yang, et al](image)

In conclusion, studies of chemistry-specific interventions have been published over several decades, and have implemented various ways to help students improve their visual-perceptual skills. These interventions have included using molecular models in classes to
teaching students specific ways to view and treat the molecules. All the interventions have included a way to test the students’ pre- and post-visualization abilities. All of these studies have been done in chemistry classrooms or have used molecular drawings, but work done to increase students’ visual-perceptual skills has also been conducted in other science fields. The next section highlights four interventions used in science fields other than chemistry aimed at improving visual-perceptual skills in students.

2.1.2: Visual-perceptual interventions in science fields

Other science fields have also introduced different visual-spatial intervention studies, although these are rather recent as compared to the chemistry studies. The first is a physics education study which was conducted because of the high dropout rate in many entry level college physics classes. The researchers elucidated which visual-spatial abilities are most utilized in college level science courses such as physics. The experimental group was given eleven additional hours of instruction where the students used visualization exercises. This group of students drew scenes by viewing them through a small hole cut in a piece of cardboard, drawing dominant lines of the scenery and reducing the scenes to proper perspective. They also completed a short course in geometry involving lines, angles, planes, solid figures, and geometric transformation. In addition a "relative position and motion" module was assigned where the students had to locate positions of objects relative to a fictitious observer. In this part of the intervention the students needed to learn how to reorient their perceptual framework with respect to observers with different orientations. The
second group of students, the placebo group, received the same amount of time, eleven hours, but lectures on the history of physics. The final two groups were the control groups where the students had no extra hours spent on any topics and one of the control groups, a liberal arts class, had no physics students. All the students in this study were given several instruments that tested perception, orientation, and visualization. Most of the assessments came from Ekstom et al. *Manual for the Kit of Factor Referenced Cognitive tests*\(^{32}\) and included: three perception tests which emphasized perceptual speed (identical pictures and number comparison tests) and disembedding ability (see Figure 2.10), two spatial orientation tests which stressed rotation skills (card rotation and cube comparisons), and two spatial visualization assessments which emphasized sequencing skills (paper folding and surface development tests). The results obtained showed that the experimental group improved in all the visual-spatial tests, while the other groups did not. The professors who taught the classes labeled the final exam questions as a spatial question, a propositional question, or as a content problem. The students in the experimental group did better on the spatial questions, the lab grade, and the course grade as well. The questions that were propositional in nature and the content problems did not have any significant differences between the groups of students. The researchers further determined that students who dropped the course had poorer visual-spatial skills than the ones who stayed in it as tested using the assessments from the *Manual for the Kit of Factor Referenced Cognitive tests*\(^{32}\) at the beginning of the semester. Although this study took a first step in splitting visual-perceptual skills into important categories, there was no real framework of skills that was documented.\(^{31}\)
2.1.2.1: Biology and manipulating physical models

The next two biology education studies were conducted because of research claims that visual-spatial skills can not be taught. Lord defined visual-spatial skills as the ability to form and control a mental image. Lord’s research included eighty-four college undergraduates enrolled in a major’s biology class that were placed randomly into either an experimental or a control group. Every student was given several pre-tests / post-tests from the Educational Testing Service’s *Manual for the Kit of Factor Referenced Cognitive tests* which included orientation tests that measured rotation skills (cube comparisons), a Group Embedded figures assessment (see Figure 2.10), spatial visualization instruments (surface
development tests), and an author generated assessment tool meant to measure direct success of the intervention “The Planes of Reference Test”. The two groups followed an identical weekly routine of biology lecture, seminar and laboratory. The experimental group was given a 30-minute interaction exercise during each of the 12 laboratory sessions. This interaction exercise consisted of giving the students a solid object (blocks and spheres for the first six weeks, and prisms and cones for the subsequent weeks) and asking them to draw what they would see when cutting the object in a specific way (Figure 2.11).

Figure 2.10: An example of the interaction exercise from Lord

Numerous times in the session the students were asked to close their eyes and imagine what an object would look like when cut in different ways. The control group worked in the same
lab classes as the experimental students; however, they did not receive any additional instruction. The results of this study revealed that the experimental group had significantly increased scores on the spatial visualization, spatial orientation, and planes of reference tests, but not the Group Embedded figures test. This result conveyed that this intervention is not powerful enough to affect disembedding ability in science students. However, Lord found that students’ visual-perceptual cognitive potential can be enhanced through carefully planned interventions.35

Another study used the same shape cutting interventions, but dealt with the notion that men outperform women in tasks involving visual-perceptual awareness.36 Two hundred and fifty students at a two-year college were randomly picked, half male and the other half female, and were drawn from two groups, half from science majors and half from non-science areas. The students were given three pre-tests: the Group Embedded figure test (Figure 2.10), a spatial visualization test that involves choosing blocks that are the same based on only three of their sides (cube comparison), and a spatial orientation assessment that involves folding a piece of paper into a distinct shape (surface development test). The results of the pre-tests on the science and non science students showed that the men in sciences performed better than the women in sciences only on the spatial visualization test; women in sciences achieved better results on the spatial orientation assessment and on the Group Embedded figures assessment. All science majors performed higher than the non science majors on all the assessment tools. The science majors from this study were all enrolled in a biology class and were randomly placed into three groups: experimental, placebo, and control. The experimental group received the same intervention as the previous Lord study
(Figure 2.11), the placebo group was given thirty minute presentations each week on the historical significance of pursuing lab investigations, and the control group had no additional instruction. The result obtained at the end of the semester on the post-test indicated the experimental group had improved in spatial aptitude. The women also gained greater scores in their spatial perception scores than the men. Lord’s study indicated that women with poor spatial skills are less likely to migrate towards college science majors than women who have developed strong visual-perceptual thinking before college. The results of this study also showed that college females majoring in a science field develop their visual-spatial skills faster than college males when given specific interventions designed to enhance their spatial abilities.36

2.1.2.2: Geology and computer-based modules

Researchers tested students in a geology course, using a laboratory based geo-spatial content test and two visual-spatial tests, the cube rotations and the surface development tests, to see if visualization can be taught in a geological context, and if doing so will lead to improved course grades.37 Pilburn, et al. implemented computer based modules that would allow them to embed visual-spatial learning in the context of authentic real-life, complex problems. There were one hundred and three students in this study: forty-four in the control section, and fifty-nine in the experimental section. The students came from four sections of a beginning geology course taught by four different teaching assistants. Both groups experienced the computer based modules, but the experimental group underwent two
additional computer-based intervention modules on topographic maps and interactive three-dimensional geological blocks. Results showed that spatial visualization skills improved (higher scores and lower times to completion), but that the students’ spatial orientation skills did not. Although scores of the male students were initially superior to those of the female students, this experience equalized their performance. Females benefitted from both conditions, but females in the experimental group benefitted more, and the experimental group as a whole profited more than those in the control.37

The studies in this section have used varied techniques, from manipulating physical objects to computer software, to observe effects on science students’ visual-perceptual skills. It might not come as a surprise that Roe, in 1951, reported that sixty-four eminent scientists had superior scores on visual-spatial tests.38 The interventions in this section have shown that although similar assessment types have been used for visual-perceptual skills with various fields of science, no single assessment tool exists that is specific to a particular science field. Besides science fields, studies have also looked at improving visual-perceptual skills in other liberal arts academic fields. For example, science college undergraduates were shown to have significantly higher scores on visual-spatial assessments than their liberal arts counterparts.39

2.1.3: Studies on visual-perceptual skills in non-science fields

Non-science fields have also considered visual-perceptual skills as related to their discipline, and have developed interventions to help students in their courses improve on
such skills. Stericker and LeVesconte conducted research to study gender differences in spatial ability; the authors postulate that gender differences are caused by early environmental variation. Training on visual-spatial skills was provided on three exams, but tested on four to see if any transfer occurred. Stericker and LeVesconte also wanted to determine whether training can be used to equalize men and women’s scores, or whether women improve more than men. The researchers involved fifty female and forty one male psychology students who participated and took four assessments as pre- and post-tests: DAT-Space Relations, Group Embedded figures test (Figure 2.10), Shepard-Metzler rotation test, and a Space Relations Test of the Primary Mental Abilities. The researchers tested the students with six one-hour long sessions which consisted of:

- Collection of background data and introduction of the study (one hour)
- Pre-testing and random assignment of control and experimental groups (one hour)
- Training of the experimental group on the DAT-Space Relations, Group Embedded figures, and the Shepard-Metzler rotation tests only (three hours)
- Post-testing of all students (one hour)

Students in the experimental group were organized in tables of four students, with two who scored above and two who scored below median on the tests. For the first few minutes of each intervention session, the researchers returned the tests to the students, went over the test, and then provided the correct answers. The students spent twenty minutes on each test in the three-hour sessions, and the researchers made available:

- Paper cut outs of the DAT-Space Relations models
- Overhead transparencies of the Embedded figures
• Styrofoam models of the Shepard-Metzler objects

The results of the study indicated that the intervention significantly improved the scores on all the post-tests, including Thurstone’s Space Relations Test of the Primary Mental Abilities\(^\text{10}\) where no training was given. Women did increase their scores to be comparable to men’s scores, which the researchers concluded to indicate that spatial skills can be learned and that biological differences are not the reason for discrepancies.\(^\text{40}\)

2.1.3.1: Drawing and visual-perceptual abilities

Even though Orde’s paper is not about an intervention activity, she makes a strong argument that drawing ability and visual-perceptual ability are connected, and formulates a hypothesis that both can be developed through education in general and drawing in particular.\(^\text{43}\) Orde defines the terms “drawing”, “spatial” and “visual-perceptual abilities” and indicates their connection to information processing and intelligence. The debate is ongoing whether “the ability to draw and spatial ability are gifts of nature or products of nurture”.\(^\text{43}\) Orde discusses Clark’s Drawing Abilities Test, as a tool to measure visual-perceptual ability. The researcher maintains, “[d]rawing and spatial abilities share common conceptual ground, common training, and common outcomes”.\(^\text{43}\) This paper points out that drawing does play a significant role in spatial ability development, both through tactile and kinesthetic experience.
Blasko et al.'s study describes VIZ, (http://viz.bd.psu.edu/viz/), a free and open portal visualization website for assessment and training of visual-spatial skills that tests three skills that have been postulated by two different meta-analyses to be important visual-spatial skills: spatial perception, spatial visualization, and mental rotation skills. Spatial perception is defined as the ability to determine spatial relationships among objects despite distracting information; this skill is measured by Piaget’s water-level test. Spatial visualization is defined as the ability to manipulate complex spatial information when several stages are needed to produce the correct solution, a skill measured by the paper-folding test. The Shepard and Metzler mental rotation task is used to assess mental rotation, which is defined as the ability to mentally manipulate three-dimensional objects in order to imagine them in a different perspective or orientation. The researchers found that males do much better than females on the mental rotation tasks, and slightly better than females on spatial perception. In spatial visualization females and males are almost equal in score.

The researchers validated the VIZ website by giving it to different groups of students either in a computer lab or from home. Males and females were randomly assigned to three groups: self-training, lab training or control. The forty students in the self-training group came to campus to take a pre- and post-test on the VIZ site with the rest of the participants, but for the four weeks in between were told to use the site to complete spatial tasks at home. The thirty-six students in the lab training group came to the lab once a week for four weeks to complete the same spatial tasks. The thirty-two students in the control group came to the
lab and surfed the web each week. Although women and men experienced similar improvements in mental rotation skills, the researchers claim that the females in the self-training group achieved higher scores and were more comfortable than the females in the mixed gender lab situation.

The researchers have also used the website to test the spatial abilities of incoming engineering students, and found the tests to be a significant predictor of course grades, cumulative GPAs and retention rates. The intervention the researchers implemented was directed towards students who scored at the 60th percentile or lower on the VIZ website. These students went through supplemental instruction sessions throughout the semester where they used paper-based, hands-on, and computer-based exercises to visualize and sketch three-dimensional objects in a two-dimensional format and vice versa. After the semester was over, the students were given post-tests using the VIZ website and findings showed that scores increased on all three main assessments: the mental rotations task, the paper-folding test, and the water level test. Interestingly, the authors did not separate out these scores by gender.44

2.2: Think aloud interviewing method

The think aloud method was the interview technique chosen to probe students’ thoughts processes about the visual-spatial questions on the VSCS assessment tool. Students were told that only their thought processes and their methods were important, not getting the correct answer. This next section gives a brief history of the think aloud method and
describes the ways that this interviewing technique can be used with students responding to visual-spatial questions.

2.2.1: History of the think aloud method

The think aloud method was developed from the introspection framework, which speculates that events that take place in an individual’s subjective experience can be observed just as events that occur in the outside world. A principle observed by the psychologists who developed this method was that only trained observers were to be used because only they would be able to interpret events correctly in a subjective experience. The fundamental problems with this method included the fact that none of the data would be reproducible if the data were only accessible to the person being studied, and that the processes of consciousness and introspection are separate. This caused problems because the observer would have to examine their own feelings on conscious development, which the framework could not solve satisfactorily.

Dealing with introspection led psychologists to the other extreme of behaviorism which became popular in the 1930’s. Behaviorism banned theorizing about processes that could not be observed outside the body; it instead focused on explaining people’s behaviors as their thought processes. According to this framework there is no difference between thoughts, feelings, and behaviors. Think aloud drew from both of these frameworks of cognition and behavior and assumes a simpler process: verbalization instead of observation and interpretation. Think aloud assumes that the verbalizations are the contents of working
memory, or short-term memory, and not the entire cognitive process. Think aloud processes are different from introspection and behaviorism in two regards: “The think aloud method avoids interpretation by the subject and only assumes a very simple verbalization process, [and] the think aloud method treats the verbal protocols that are accessible to anyone as data, thus creating an objective method”.

Currently the think aloud method is accepted by psychologists as a useful method for inciting verbalizations from subjects, and also for analysis of the thought processes and patterns. There exist, however, some issues that could threaten the validity of a study using think aloud. The first concern occurs if the subject changes answers because of being asked to think aloud. At present, there is not much evidence supporting that the think aloud process changes people’s responses as would be inevitable in knowledge acquisition and experimental settings. A problem may arise if the subject would interpret the directions incorrectly and might give incorrect information regarding cognitive processes. Again, there is no evidence that the think aloud protocol leads to this kind of error other than the occasional spoken language error.

Possible memory errors on the part of subjects that would invalidate an interview study are essentially absent in the think aloud method, because the subject has the question or topic at hand and is asked to think aloud about it. Difficulties in the interviews may occur when subjects have problems with their working memory. Subjects may pause to find a word to describe something, with the result that the next step in their cognitive process is lost, because of the memory used to find the missing word. Verbalization becomes a cognitive process by itself, which could cause the interview to be incomplete or even hinder
A problem may arise because the verbalization takes place concurrently with the cognitive process, and subjects frequently will skip steps in their verbalization. Because it takes longer to verbalize, people need to slow down their cognitive processes to synchronize them with the verbalization. When this synchronization doesn’t happen, gaps appear in the interviews where subjects needed to think about something, but did not verbalize it.

2.2.2: Rationale for choosing the think aloud method

The interviews conducted to understand how novice students solved visual-spatial questions from the Visual-Spatial Chemistry Specific assessment tool involved simple directions. The technique avoids interruption of the subjects that are being interviewed. Although there have been reports of using the think aloud method asking the students questions during the interview process, this was not the way that it was originally intended to be. In Van Someren et al.’s book *The Think Aloud Method: a Practical Guide to Modeling Cognitive Processes* they summarize that the method involves “the subject [being] asked to talk aloud, while solving a problem ... this request is repeated if necessary during the problem-solving process thus encouraging the subject to tell what he or she is thinking”. They also note that this method eliminates suggestive prompts or questions during the interview as the subject should simply concentrate on the task on hand. Because this is often difficult for subjects, however, Van Someren et al. also advocates stopping after 15 minutes if the student is uncomfortable with the think aloud process.
The setting where the interview takes place should also be a neutral, comfortable location so as to set the subjects at ease. The students must also be informed their performance is not going to be discussed at all either during or after the interview, and that their comments may be used in future research studies.\textsuperscript{48} When transcribing the data it is best to only type the words that the students use and not include any data about emotions since these have been shown to be unreliable data.\textsuperscript{48} It is also suggested that a pilot study be done before the real interviews take place; this way the pilot subjects can be asked if the test questions were confusing, too difficult or too easy.

2.3: Conclusions

This literature review concentrated on possible interventions that could be used to increase students’ visual-perceptual skills. The first type of intervention discussed was using molecular models in chemistry classrooms, which have shown to increase students’ visual-perceptual skills and promote higher order thinking skills.\textsuperscript{1, 13, 19} The second type of intervention was using models of structures and either have the students build them or view them to answer specific questions about the molecular structures.\textsuperscript{15, 17, 20, 21} A third type of intervention used computer animations, software, and modules to increase students’ visualization abilities.\textsuperscript{27, 37} Other hands-on techniques have been used in fields other than chemistry, such as visualizing how blocks are cut in a biology setting.\textsuperscript{35, 36} To explore gender differences in visual-perceptual skills, techniques have been utilized that let students handle physical models of the traditional test questions.\textsuperscript{40}
One of the major lessons of this literature review has to do with gender differences. Although it has been proposed that males are superior in their spatial ability, the studies in this literature review have shown that females, who on pre-testing have lower spatial scores, can reach or even exceed males’ spatial ability when given proper intervention techniques. Most of the intervention techniques that have helped females reach this equal footing with males as described in this literature review, have been hands on. Students have been given a molecular model, a block, or a diagram of test question, and have been asked to manipulate it in some way. Another lesson to be learned from this literature review is that carefully constructed computer animations can increase students’ visual-perceptual abilities. Different computer animations have been implemented in chemistry, geology, physics, and engineering courses and all have increased students’ test scores and their spatial abilities.

The think aloud method is a simple technique to implement, because all the tools needed to solve the problem with are in front of the student and all they are asked to do is to think aloud about the problem. Tools are an important part of the think aloud process, and examples of the tools that are needed to solve the visual-spatial questions on the VSCS assessment were the questions themselves, a model kit, extra paper, pencils, and a small paper box. Although the think aloud method was not employed as an intervention technique in this research, it has potential as an intervention technique and has shown to help chemistry instructors conceptualize the topic of equilibrium. The process of showing how students can use tools such as molecular models or a physical representation of a visual-spatial question are important interventions that could be used in chemistry classrooms.
2.4: REFERENCES


CHAPTER 3. Methodology

3.1: Research Design

The Visual-Spatial Chemistry Specific (VSCS) assessment tool was designed around eight visual-perceptual skills that were hypothesized to be important to engineering students by Rochford and Archer. The theoretical framework the VSCS assessment is based on clearly defines each visual-perceptual skill, specifically describes the kinds of manifestations for trouble areas, and has never been used in a chemistry context before. The questions that make up the newest version of the VSCS tool come from a variety of sources, including some that were developed from this researcher’s lab.

Webassign, an online homework system that gives immediate feedback to the students, was utilized to distribute the VSCS assessment tool. Writing questions in simple HTML coding is fairly easy to instructors, and the program is equally user friendly to students. The one thing that webassign can not do, is to show different questions of an assignment on different screens: the assignment opens synchronously and in its entirety. This posed concerns with the memory questions, which would require at least two different screens to test students’ memory of molecular structures. This problem was addressed by placing the memory questions on a different website, where the first molecular picture would appear and then disappear leaving in its place four possible choices. (See Chapter 4 for questions and choices.)
3.2: Implementation

Version I of the VSCS assessment tool was discussed in previous research. Version II of the VSCS assessment was given to general chemistry (both sequence of courses), organic, and physical chemistry students. This version was given at the end of the spring, summer, and fall semesters of 2009. The classes that participated were volunteered by the chemistry professors assigned to teach those courses in this timeframe. Version III of the tool was given at the beginning of the Spring 2010 semester, so for this reason no general chemistry I class was asked to participate due to the fact that the students would have no experience with molecular drawings until later in the semester. Every professor who taught general chemistry II, organic, and computational chemistry was asked to assist us, and the classes that participated are listed in Table 3.1. The only class that did not participate in version III who participated in version I was the inorganic course, owing to the fact that none of these professors used webassign in their classes. All of the students who took versions II and III of the VSCS assessment tool were offered some extra credit by the instructor of their class. For example, the physical chemistry students were offered a percentage added to their homework total if they completed the assessment tool, while the general chemistry II classes were offered a set number of points added to their total end of the semester score. Table 3.1 is a list of the courses whose students took versions II and III of the VSCS assessment tool. The table is organized first by the version number, and then by the semester in which the tool was taken and finally by the chemistry course and number of students that participated.
### Table 3.1: Course title and the number of students who took versions II and III of the VSCS tool

<table>
<thead>
<tr>
<th>Version II</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2009</td>
<td>Organic (Org) I</td>
<td>347</td>
<td>Physical</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Summer 2009</td>
<td>Chemistry 201</td>
<td>95</td>
<td>Chemistry 101 (Two Summer sessions)</td>
<td>SSI - 78</td>
<td>SSII - 75</td>
</tr>
<tr>
<td>Fall 2009</td>
<td>Chemistry 201</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total number of students</td>
<td>653</td>
<td></td>
</tr>
<tr>
<td>Version III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring 2010</td>
<td>Chemistry 201</td>
<td>413</td>
<td>Intro Org</td>
<td>98</td>
<td>Org I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.3: Research questions

Three main research questions directed the analysis and organization of the data obtained from version III results of the VSCS assessment tool.

- Can the skills proposed from Rochford and Archer’s theoretical framework be tested and differentiated from each other using the VSCS tool?
- How do novice students solve and conceptualize questions that theoretically test the eight skills from Rochford and Archer’s framework?
- What kinds of processes or resources do novice students use to solve visual-spatial questions?
3.4: Factor analysis history

The earliest development of factor analysis involved the two-factor theory of human intelligence. This theory was first promoted in England by Spearman and colleagues, who theorized that everyone possessed a general intelligence factor, or the \( g \) factor.\(^9\) \(^10\) “Although his 1904 paper does not include an equation for a factor analysis model, his theory can be clearly interpreted to imply that a single general common factor accounts for the intercorrelations of the measured variables”.\(^11\) After sources of disagreement with his theory emerged,\(^12\) Spearman modified it to include a second factor which was a unique factor associated with a particular mental test to a subject.\(^13\) In the United States, however, Thurstone was developing mental ability tests, and stood in contrast to Spearman’s beliefs.\(^14\) Thurstone developed the notion of multi-factor analysis, and applied this analysis to a variety of psychometric problems. One of the solutions that Thurstone discovered with factor analysis is that although he had proposed a two factor model of visualization, one factor for seeing flat objects and the other for solid space, his analysis showed only one such factor. Even though the British made significant strides in the development of factor analysis, once the Thurstonians arrived on the scene in the 1930’s, the United States was the major center of factor analysis research until the 1970’s.\(^15\)

Spearman had started the conversation about factor analysis with matrices, which are ways to represent the linear transformations essential to factor analysis.\(^9\) In the 1950’s however, factor analysis took a different turn and researchers started to consider statistical models which are statements “about the distribution of a set of random variables”.\(^16\) This
move to a model-based approach was gradual, and was based on an idea that an observed test score comprises a specific part and a common part as in the previously mentioned two-factor theory. This model-based approach was explicitly stated in a later work by Spearman.\textsuperscript{13} Eventually it became clear that factor analysis was a powerful technique for categorical data, but it was also widely used on binary data as well. Ultimately, “[I]n factor analysis, we are asking whether the dependencies among a set of variables can be explained by their common dependence on one or more unobserved latent factors”.\textsuperscript{16}

Today factor analysis can be described as, “both an art and a science, where researchers follow a series of analytic steps involving judgments more reminiscent of qualitative inquiry, an interesting irony given the mathematical sophistication underlying EFA [Exploratory factor analysis] models”.\textsuperscript{17} This technique evolved from a solely psychological construct to a social science technique in the 1970’s. Today every major academic field has utilized factor analysis in some function. The change occurring over the last 100 years has been made possible by the advancement of computer technology and the rise of statistical software such as SAS and SPSS to analyze the data. Prior to the 1970’s and the rise of computer technology, practical approximations were utilized to help researchers solve these complex problems.\textsuperscript{11} The use of computers promoted principal components analysis which is based on a least squares and best fitting reduced rank matrix. Subsequently, many techniques have arisen that have taken factor analysis further, including those of Kaiser,\textsuperscript{18} and McDonald who introduced nonlinear factor analysis.\textsuperscript{19}
Factor analysis is concerned with the reduction of a set of observable variables in terms of a small number of latent (unobserved) factors. Two different types of factor analysis were considered: exploratory and confirmatory. Exploratory factor analysis is run when the number of variables or factors to keep is unknown and determining the number of factors is important to describe the data. This type of factor analysis was done on previous research about this assessment tool. A confirmatory factor analysis is used when the researcher wants to confirm the number of variables expected. A common example about differences between the two types of factor analysis is a math achievement test. If an exploratory factor analysis was conducted on math achievement scores and two factors were found, the result could correspond to math achievement (what was explicitly being tested) and reading ability (what was implicitly being tested). Even though reading ability was not directly tested by the math achievement test, it is reasonable to consider it was still important for the students to have this ability while taking this fictional assessment. A confirmatory factor analysis might follow in order to confirm the two-factor structure.

Since questions in version I were modified in the newest version of the VSCS assessment tool, the first confirmatory factor analysis was run with the eight factors that were proposed to be the eight visual-perceptual skills. Both exploratory and confirmatory factor analyses will give a list of factor loadings for each question and every important factor found. A factor loading is a measure of how much influence the specific factor has on one particular question. Using the math achievement example as a reference, one math question requiring a
particularly large amount of reading to solve should load highly on the reading ability factor. The square of the factor loading estimates the proportion of the variance in an item that is described by a factor. A factor loading of 0.30 is considered a generally accepted minimum factor loading because the square of 0.30 equals roughly 10%, and this indicates that approximately 10% of the variance has been explained by a factor for a corresponding variable. Also, factor analysis is based on a generalized linear model and all the latent variables (question scores) must be fit to a linear equation. A student’s true score equals an additive combination of the factor loadings multiplied by the factors themselves plus an error term.

Determining how many factors to keep from an exploratory factor analysis is a subjective process for a researcher, although different statistical tests exist on how to decide this. One way is the Kaiser criterion which keeps all factors that have eigenvalues, or a measure of the variance, above one. This method usually overestimates the number of factors to be kept. Another way to determine how many factors to keep is the preferred Cattell scree plot. This is a plot of eigenvalues versus factor number, and where the plot suddenly levels off as the factor number increases is the place to drop all further components. An example scree plot is included in Figure 3.2. This scree plot shows the subjective nature of these research methods, as researchers might be tempted to cut the numbers of factors after 3 or even after 5 factors.
In the previous work, four separate factors were found to be important to the data of version I of the VSCS assessment tool. The first factor loaded highly on all but a few of the questions, which means that this specific factor was an influencer on all the questions. The second, third, and fourth factors loaded highly on specific questions that were written to test specific skills. Four of the five discrimination questions loaded on one such factor, all five of the figure-ground questions loaded highly on another, and five of the ten orientation questions loaded highly on the third factor. Thus it appears that the students used these skills when solving these questions, and the remaining five skills were not discriminated adequately on version I of the VSCS tool.

There are many solutions for the factor analysis model; however, two rotation methods that commonly help interpret the results are Varimax and Promax. The Varimax is an orthogonal rotation, which represents a solution that maximizes the sum of the variances.
of the squared loadings, and seeks factors (skills) where the factor loadings are either high or close to zero. The reason that these two outcomes are desired is because it is best to find factors that either have a high influence on a question or no influence at all, a factor with an intermediate influence over a question is hard to interpret. Clarification is obtained because the questions are assumed to be uncorrelated with each other, which means that the different skills and questions are independent. For this reason, the Varimax is one of the preferable rotation methods. Different from an orthogonal rotation, the oblique rotation allows the axis to be in any place in space, which means that the axis is not restricted to be orthogonal to every other axis. The oblique rotation allows the factors to be correlated with each other, which is not allowed by the orthogonal rotation. Promax is an oblique rotation method and constitutes the second rotation method employed in this research.

3.6: Cronbach’s alpha:

A way to judge reliability of the assessment tool, or to measure internal consistency of a test, is to determine Cronbach’s alpha. Cronbach’s alpha measures the correlations between test questions, and indicates the degree to which a set of items will measure a single, unidimensional latent construct. A Cronbach’s alpha is more appropriate when the items measure different substantive areas within a single construct, which is the case with the VSCS tool measuring different skills in a visual-perceptual construct or framework. A Cronbach’s alpha above a 0.60 is considered to be an acceptable measure of reliability. A
Cronbach’s alpha that is over 0.90 needs to be closely evaluated as it may be considered to be a test with redundant questions.

3.7: Item Response Theory

Item response theory (IRT) is a statistical technique that is performed similarly to factor analysis, except that IRT is concerned with student and test question information. With IRT it is assumed that the visual-perceptual skills or latent factors are continuous variables. Instead of considering the students’ 0 and 1 data (0 = incorrect, 1 = correct), the percentage of students getting questions correct or incorrect is considered. The probability of students getting an answer correct is based on several parameters, the first is a random variable or the ability of a student, and two fixed variables including the difficulty and discrimination level of the questions. IRT is a set of models based on the fundamental premise that the interactions of test items with the students that take them can be represented by a mathematical expression containing the question parameters and student characteristics. The essential parameter included in all IRT models is one describing the characteristics of the student, or the ability of the student on the task at hand. The ability of the student is not a parameter that can definitely be measured; instead it is a latent trait of a student, or something that is statistically modeled to find an appropriate answer.

The first question parameter that can be measured with IRT is item difficulty. This parameter is fixed for each question and needs to be estimated from the data. This is done by
focusing the data to an equation $p_i(\theta) = \frac{1}{1 + e^{-(\theta - b_i)}}$ that corresponds to a theoretical curve, which is shown in Figure 3.2. In this equation, $b_i$ is the estimated difficulty level, and $\theta$ is the ability of the student which is assumed to be a normal random distribution. On the vertical axis lies the percentage of the students who answered the question correctly whereas on the horizontal axis is the ability level of the student. Each question is compared with others and the difficulty level is read from the curves.

![IRT 1 Parameter (Rasch Model)](image)

Figure 3.2: Theoretical curves of two questions that show their difficulty levels

For example, in Figure 3.2 question one (blue curve with smaller diamond) is an easier question than question two (red curve with bigger square) because if 50% of the students get each of the questions correct, this corresponds to a middle ability level ($t=0$) for question one, versus a higher ability level ($t=1.5$) for question two. For this reason, the parameter $b_i$ (difficulty level) is also called the location parameter, because it determines how much to the
right or left the question is with respect to an intermediate ability \((t=0)\). The further to the right of the intermediate IRT curve a question falls, the higher it’s difficulty. The further the question is located to the left, the easier the question is.

The second question parameter that IRT can measure for a tool is item discrimination, or how much an item discriminates between someone who did well on the assessment versus someone who did poorly. This is achieved by fitting the data to an equation

\[
p_i(\theta) = \frac{1}{1 + e^{-\alpha_i(\theta - \beta_i)}}
\]

that is used to generate the theoretical curves, which are shown in Figure 3.3. The axis labels are the same as before, but now an additional parameter \(\alpha_i\) controls the slope of the curve for each question. Questions with low discriminatory power have less steep curvature, where the probabilities of getting the question correct for low and high skilled students change more gradually. A very high discriminatory question will have a very steep curvature, which will make the probabilities very different between low and high skilled students.

![Figure 3.3: Discrimination theoretical curves of two questions](image)

Figure 3.3: Discrimination theoretical curves of two questions

65
When \( a_i = 1 \) for every question, then all questions have the same discriminatory power, and the equation is reverted back to the one parameter IRT model described before, item difficulty. In Figure 3.3, two questions with the same difficulty level but different discriminatory power are illustrated. Question two (the red curve with bigger squares) has less discriminatory power than question one (the blue curve with smaller diamonds). Question one is able to distinguish between low and high skilled students better than the second question, where the probabilities do not change as sharply as in question one.

### 3.8: Categorical responses

The third version of the VSCS assessment tool contains seven new categorical questions. These questions were incorporated to analyze if there would be a difference in characteristics among the students who took the assessment tool. The first question was the gender of the student since previous research indicates that males do better than females at visual-spatial tasks.\(^{22}\) Also important was a student’s major (Chemistry, Biology, Engineering, Math, or another discipline) because past research indicates that chemistry majors seem to do better on the VSCS assessment tool than other science majors.\(^8\) The remaining categorical questions surveyed ethnicity, age, academic year and number of chemistry courses taken. At the end of the assessment tool, the seventh question asked if the students had used a model kit to solve any of the assessment tool’s questions. All these questions were intended to collect data and form a database that might be used in the future to explore any differences in score for any of the separate categories of students.
The think aloud method was chosen to interview the students because it is a method that usually involves a minimum of verbalization errors, students are allowed to use whatever tools the researcher has deemed are appropriate and students have everything they need to solve the problem in front of them, which basically eliminates memory errors. In this technique the interviewer instructs the students to think aloud while solving a problem, and avoids interruption of the students’ thought processes. By staying silent, the interviewer has an opportunity to assess whether the students are comfortable during the interview and if not it has been suggested the interview should end. Interviews on the VSCS assessment tool were done with a randomly selected group of 12 females, and 8 males. The location of the interview was a neutral place as protocol recommends; a special interview room in Riddick Hall equipped with audio recording and a camera in the ceiling to record what the students did with their hands during the interviews. The emotions of the students were ignored unless a student spoke about their feelings during the interview, in which case this was transcribed. Furthermore, pilot interviews were conducted with six students so that the researchers could practice the interviewing process. Students also had different tools at hand so interviewers could observe how the students were solving the visual-spatial problems. For example, students were given a model kit, pieces of paper, a small box, and pencils and pens to draw and notate. This was a way to ease possible verbalization challenges as students had resources such as the physical objects at hand to solve the problems.
Some problems may occur with the think aloud method, but precautions were taken to avoid them. The first potential problem could arise if a student changes an answer while being asked to think aloud without any verbal cues about the changes. Although this did happen a few times during the think-aloud interviews, checking with the student on his or her final answer before moving on to the next question minimized this problem. Another problem arose if the student interpreted the directions incorrectly and then gave incorrect information regarding the cognitive processes. If students were to read a question incorrectly during the interviews, and solved the question incorrectly as a consequence, the students were asked to read the question again. Most students would correct their errors after re-reading the question. A third difficulty that did arise was that students frequently skipped steps in their verbalization. Students were told to take their time, and assured that they had plenty of time to do the interviews. Most interviews were scheduled for an hour of the students’ time, although the longest interview only took 45 minutes.

Discussion exists regarding the think aloud method over whether to use novice or expert subjects in the interviews. Expert subjects are generally discouraged for knowledge acquisition because experts usually perform tasks very fast, in a routine fashion and avoid verbalizing during the task performance. If experts were used and would not verbalize their thoughts during the think aloud interviews then important aspects of the problem-solving process could be missed. Therefore, for the VSCS assessment interviews, only novices were used since they tend to better verbalize their thoughts, and all possible spread of answers are studied, either correct or incorrect, to properly understand students’ reasoning in answering these questions. In addition, using students who had never seen the questions before
increased the richness of the data, since they would not have any preconceived notions of what the questions entail.

During the interview process, a model question unrelated to chemistry was utilized to make the students feel comfortable, and to illustrate the think aloud process. This model question demonstrated that either the student or the interviewer could ask questions, or clarify the nature of the questions. The visual-spatial questions chosen to interview the students included a mix of new questions from version III and some of the questions from version I that loaded high on factor 1 (from analysis of version I).\textsuperscript{8} Also questions were added halfway through the interviews to reinforce the data on certain skills. More information on the questions chosen, the think aloud method, and its analysis are included in Chapter 5.
3.10: REFERENCES


CHAPTER 4. Changes made to the Visual-Spatial Chemistry Specific (VSCS) Assessment Tool from Version I to Version III

Rochford and Archer postulate that engineering students need eight specific visual-perceptual skills featured in Table 4.1,¹ and these skills have been proposed to be important to chemistry students as well.² The VSCS assessment tool provides questions chosen specifically to assess these types of skills in multiple choice and fill-in-the-blank formats. This section of the dissertation will show the changes that have been made to the questions in each of the skill categories from version I to version III, in an effort to feature all eight skills. Version I of the VSCS tool contains 47 questions,² whereas the latest version (III) reduced the number of questions to 33. This decrease was made primarily because a test of 47 questions posed a lengthy assessment tool and also promoted the student’s use of analytic skills. It was also decided that four questions per skill provided a reasonable number of questions for a total of 33 questions. Five questions from the orientation skill set were asked as previous research suggests that rotating molecules in the X, Y, and Z axes are separate factors.³

Students use analytic skills when they look at a figure, and take it apart to find an answer. Conversely, students employ holistic skills when they view the whole figure in their attempt to answer the question. Some theorize that visual-spatial questions should truly test holistic skills.⁴ A way to reduce analytic skill use is to shorten the amount of time students have with a question, presumably to limit the amount of time that they can take the picture apart in order to solve the question. The VSCS assessment version III was time-restricted to
45 minutes in order to address this issue. A maximum of 45 minutes was chosen because this was the maximum time it took colleagues in the chemistry department to read and answer all the questions.

In this chapter, all eight skill categories will be highlighted with a definition of the skill, an “old” question from version I and a “new” question from version III (if applicable) followed by a description of the changes that were made. Explanations of the answers and how the question from version III tests the specific skill are also provided. Table 4.1 summarizes the number of the questions on the VSCS assessment tool version III that test the specific skill, question(s) discussed in this section, and what the students are asked to do in the specific questions addressed.1

<table>
<thead>
<tr>
<th>Question #s on VSCS tool</th>
<th>Question(s) discussed</th>
<th>Skills assessed</th>
<th>Students are asked to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>1</td>
<td>Visual memory</td>
<td>remember what a figure looks like</td>
</tr>
<tr>
<td>5-8</td>
<td>5</td>
<td>Visual discrimination</td>
<td>perceive dominant features in objects and to discriminate one object from another</td>
</tr>
<tr>
<td>9-12</td>
<td>9</td>
<td>Visual figure ground</td>
<td>recognize a figure and its background</td>
</tr>
<tr>
<td>13-17</td>
<td>13, 16, 17</td>
<td>Visual orientation</td>
<td>rotate and reflect diagrams of molecules in terms of the observer</td>
</tr>
<tr>
<td>18-21</td>
<td>21</td>
<td>Visual form perception</td>
<td>interpret 3-D representations of molecules in a 2-D manner</td>
</tr>
<tr>
<td>22-25</td>
<td>23, 25</td>
<td>Visual sequencing</td>
<td>see images in a certain order or sequence</td>
</tr>
<tr>
<td>26-29</td>
<td>26</td>
<td>Visual constancy</td>
<td>recognize if figures of molecules are the same size, shape or color</td>
</tr>
<tr>
<td>30-33</td>
<td>30-31</td>
<td>Visual association</td>
<td>relate concepts in diagrams and words</td>
</tr>
</tbody>
</table>
1. **Visual memory** is the ability to recollect the dominant features of a diagram or to recall the order of items presented visually. Students with difficulties in this area may have problems distinguishing geometric objects and symbols accurately.

**VSCS Example Question #31 from version I,\(^5\) and #1 from version III\(^6\):**

**Old question #31 on Version I**

*In the next question* four different diagrams of the given molecule are presented, suggesting how the molecule would appear when viewed from different angles. In each case, **three of the four diagrams are of the same molecule**, whereas **one of the four diagrams is incorrect** because it shows a mirror image of the molecule.

For example, and are mirror images.

**New question #1 on Version III**

Study the reference molecule, when you click the Next button the picture will be replaced by four possible choices. Select the choice that is a mirror image to the reference molecule. You can go back and view the reference molecule up to 2 times.

Select the molecule below that is the mirror image to the reference molecule

**Figure 4.1:** Examples of memory questions on version I and version III. In the memory question from version III, two different pages of a website are represented

**Changes made:** These questions were posted on a separate website to make them truly memory questions, and were placed on a black background to make the molecules easier to see. Instead of having all four pictures come up at the same time with the student choosing which one is the mirror image, now the single picture they need to memorize comes up first.
On the next screen the answer choices appear (Figure 4.1) and it can be seen that the choices are the same four choices that were in version I. The students are instructed to find the molecule which is the mirror image to the molecule on the first page. The students can go back and look at either page a maximum of two times before they must answer the question. The use of the separate website allows the testing of visual memory skills because the students have to remember what the first molecule looks like before they answer the question.

**Explanation:** The correct answer to the question from version III is the third choice (bottom left) since it is the only one that is a mirror image of the other molecules. The first choice is exactly the same structure as the reference image, but as this is a memory question the two molecular images never appear on the same screen. The second choice is the same as the reference structure, except that it is rotated 90 degrees counterclockwise and viewed from the central atom. The last choice is also the same as the reference image, just rotated 30 degrees clockwise. The third choice is a mirror image of the reference structure because the green and white atoms are coming out of the screen (shown by the overlap depth cue on the green atom) and the yellow and red atoms are going back (note the lack of overlap cues on these two atoms). Depth cues are used to give the appearance of depth in a 2-dimensional drawing of a molecule. If the reference image were turned so that the green atom was out as is shown in the third choice, to make it the same molecule the red and yellow atoms would need to be reversed. Since they are orientated in the direction shown, this must be the mirror image.

Geometric objects, such as the tetrahedral molecule shown in this sample question, could be difficult to recognize as these depend on depth cues. For instance, when looking at
the third choice it would be hard to tell that the two side atoms are going back behind the screen if one did not have a grasp of the overlap depth cue. The symbols involved are the atoms, the lines (bonds), the molecules and the depth cues. Both geometric objects and symbols are important in understanding a question of this type and answering it correctly.

2. **Visual discrimination skills** involve an ability to perceive dominant features in diagrams, and to discriminate one image from another. Students with difficulties in this area could experience problems with congruencies, equivalences, inversions, reversals, and transformations with subsequent misunderstanding of symbols or diagrams.

**VSCS Example Question #1 from version I, and #5 from version III:**

In this question, the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles.

Pick the number of the figure which is **unlike (different from) the reference object.**

![Reference object]

1.  
2.  
3.  
4. All of these could be observed

![Reference object]

1.  
2.  
3.  
4. All of these could be observed

Figure 4.2: Example questions from the visual discrimination skill set
Changes made: The number of questions on the assessment tool was reduced from forty-seven to thirty-three, and only four of the five original discrimination questions were retained. The question that was removed did not load highly on factor 1 of versions’ I factor analysis, which included every question except this one, or on factor 4, which was the specific factor that included four out of the five discrimination questions. The questions which are highlighted above are the one that was eliminated from version I (on the left side) and the question that had the highest factor loadings on factor 4 in the first factor analysis (on the right side). The question that was removed had the only figures that were not redrawn from the original assessment tool, so the wireframe objects had a much heavier line width.

Explanation: The question that is included in version III (on right side) tests discrimination skills since all the diagrams are comparable to the reference image, just viewed from different corners (response 1), different angles (response 2), and different sides (response 3). This question was picked to differentiate between inversions, transformations, equivalences, congruencies, and reversals by having all three possible diagrams analogous to the reference; therefore the correct answer is 4. In this question, students need to perceive dominant features, such as angles, triangular faces and rectangular faces, in order to discriminate one image from another. Response 1 entails inverting the reference diagram and looking at it from the top corner; inversions involve turning upside down or setting an object on end. Response 2 requires viewing the reference diagram by reversing or looking at the diagram in an opposite position or direction, since one needs to invert the image and view it from one of the rectangular faces. Response 3 necessitates viewing the reference diagram from a slightly different angle and recognizing that the triangular faces are equilateral triangles, which
illustrate the concept of equivalences or images that are equivalent and congruencies or images that are consistent. Transformations that are defined as a change in form or appearance can be observed in all the options, since all the diagrams are different in appearance from the reference image.

3. Visual figure-ground skills involve objects being distinguished from their background. Students with problems with this skill may experience difficulties recognizing patterns.

VSCS Example Question #10 on version I and #9 on version III:

The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are in the cube. For each question choose the one best response.

Figure 4.3: Version I and version III figure ground questions

**Changes made:** This skill involves students’ ability to recognize the background of this diagram. The question illustrated above was modified with respect to length and semantics.
In addition, the question from version I required students to visualize outside the cube. The skill dictates that the background of the question should be kept in the confines of the cube. The other three figure-ground questions retained were also slightly modified in response to the semantic analysis (wording).

**Explanation**: Atom K is on the outside back wall of the cube on the dotted line that cuts the cube in half. Atom U is in front of atom K in the middle of the front top right quadrant. Atom U is above atom K because it is in the middle of the top quadrant, and atom K is on the middle of the cube. This question was asked because it denotes the patterns that connect atoms that make up the cube. Another similar pattern in the same cube involves atoms N and Q. The most important patterns to note are the solid lines which denote the outside edge of the box, and the dotted lines which make up the inside of the box. There are two vertical planes perpendicular to each other, and two horizontal planes, in the middle and the bottom of the box. Identifying patterns is distinctive in this test question since all the lines provide the background reference that students need to distinguish the position of the carbon atoms that make the diamond structure.

4. **Visual orientation skills** involve being able to perceive the positions of objects in space in relation to other objects and the observer. Students with problems in this area have troubles with spatial relations.

   a. **Spatial orientation skills** involve what three-dimensional representations will look like from a different perspective (rotation skills).

**VSCS Example Question #13 on version III**: 

7.8
If the structure in diagram A were rotated about the Y-axis in the direction that the axes show, which diagram below would represent the structure as seen after a rotation of 180 degrees?

Turning around the X axis  
Turning around the Y axis  
Turning around the Z axis

Figure 4.4: Example question from the visual orientation (rotation) skill set

**Changes made:** The ten visual orientation questions on version I were reduced to five in version III. Seddon et al. showed that rotation around an X, Y, and Z axis can be considered to be three separate factors, therefore, three different rotation questions around each of the X,
Y, and Z axes were retained. The questions that were eliminated did not load highly on factor 3, the factor that specifically identified these orientation questions on version’s I factor analysis. The only modification to this category in version III was the updated, clearer diagram of the axes.

**Explanation**: This type of question tests visual orientation skills, as students must be able to perceive three-dimensional molecular representations and rotate or turn them around a central axis to a different perspective, or mentally move them according to an anchor which in this case is understood to be the central atom. In order to come up with the correct answer, one must compare the molecule in diagram A to the set of axis (the observer) and then compare this molecule to the four responses (other objects).

Students need spatial relations, which are defined as how an object is located in space in relation to some reference image, to solve this visual orientation question. These types of questions are the second listed in this chapter that utilize depth cues. These molecular representations are set on a black background with nothing in the individual representations to relate them to each other; thus they are considered as being in space.

b. **Spatial relation skills** involve reflection and inversion.

**VSCS Example Question #17 and #16 on version III**: Among the molecular representations 1-4 choose the one which you would get after reflecting molecule A in the mirror.
Changes made: The question illustrated above was only one of the two types of reflection questions that were asked on version I of the assessment tool. The questions that were eliminated did not load highly on factor 3 of the factor analysis run on version I, which was the factor that specifically included these orientation questions. The type of question highlighted above was the easier of the two, because the only demand is to perceive the position of the molecule in relation to the mirror. The other type of reflection question asked on the VSCS tool had an axes diagram similar to the orientation axes (Figure 4.4). It asked students to reflect the molecule in a specific plane of the axes, and was more difficult because the plane to reflect in was not as obvious as the mirror. In Figure 4.6 this question is shown. In version III of the assessment tool, one of each kind of reflection questions, along with the 3 rotation questions added to five questions in this category.
Look at the following example question.

If this structure were reflected in the YZ-plane, the answer would be:

Your question is:
Imagine you are standing in front of the structure in diagram 1. If the structure in diagram 1 were reflected in the XZ-plane which diagram below could represent the structure as seen after reflection?

Figure 4.6: Second type of reflection question asked
Explaination: Reflection is reversing the right and left of the image according to a fixed plane; the only option that does this with the red atom at the bottom of the molecule is 3 in Figure 4.5. The answer to the question in Figure 4.6 is d, because to rotate in the XZ-plane means just reflecting the molecule in the opposite direction. These molecular representations sit on a white or black background with nothing to relate them to any of the other images.

Spatial orientation skills and spatial relation skills are related but distinct terms. They both use the depth cues, and they both involve perceiving the positions of images in space in relation to other objects and the observer. They are distinct because the spatial orientation skills involve rotation of the molecular representations around a fixed point, in this case the central atom, while spatial relation skills reflect the molecular representation through a fixed plane, in this case the mirror.

5. Visual form perception skills involve three-dimensional objects being represented by two- or three-dimensional diagrams. Students with problems in this area will distort, deform and create disproportional representations.

VSCS Example Question # 25 on version I$^{5,8}$ and #21 on version III$^{5}$
**Changes made:** Most of the molecular representations for the questions in this category were placed on black backgrounds, because students had problems seeing the white atoms on a white computer screen. Similarly, the number of questions was reduced from five to four. The eliminated question appeared to be an easy conceptual question, similar to another question that referred to the same molecular line representation. The question highlighted here has had one of the molecular representations modified from a pure line drawing to a line, wedge, and dash drawing, in order to give students additional spatial cues.

**Explanation:** This test question utilizes depth cues requiring students to visualize the 3-dimensional nature of the object. When students distort or twist the picture from its original form, the location of the objects is misrepresented. When students deform or misshape the structure, they will perceive the atoms to be larger or smaller than they are which will lead to disproportionate representations. The correct answer is “1”.

Figure 4.7: Questions from the visual form perception skill set

The diagram below is a ball and stick representation of a molecule of isobutane.

The diagram below are representations of a molecule of isobutane.

The hydrog en atom which is farthest from the hydrogen atom labeled “H” is hydrogen atom number ______.

Which hydrogen atom is farthest from the hydrogen labeled “H”?  

a. 1  b. 2  c. 3  d. 4
6. **Visual sequencing skills** involve the ability to see images in a particular order. Students could have problems with omissions, insertions, or substitutions of symbols with deficiencies of this type of skill.

**VCS Example Question #27 on version I:**

The diagram below illustrates the regular crystal lattice structure of zinc sulfide. The positioned black dots represent ions of zinc and numbered white circles represent sulfide ions. There are 18 ions represented in this unit cell.

View the ion labeled 8. Is ion number two above or below ion eight?

![Figure 4.8: Example question from version I of the visual sequencing skill set](image)

**Changes made:** These questions were completely rewritten, because after further review of the figure above, it was determined that it did not test ordering or sequencing skills. The new questions in version III included: a) a question where students are asked to form a box from the sides shown (Figure 4.8), b) hole punch questions that were originally in the Ekstrom et al. test questions, and c) a question that represented glucose as a line drawing, and asked the
students to build the molecule from selected pieces. In these questions students had to actually order pieces of a picture in order to solve the questions, or in the case of the paper folding questions, had to sequence a process in order to choose the correct answer.

**VSCS Example Question #23 and 25** on version III:

Look at the following box:

If you ignore the top and bottom of the box, what is the order that you could build the sides sequentially from the following pieces?

1. 2. 3. 4. 5.

a. 5, 2, 4, 3, 1  
b. 5, 2, 3, 4, 1  
c. 1, 4, 3, 2, 5  
d. 5, 3, 4, 2, 1

Below are square pieces of paper that have been folded as shown by the dotted lines. (The dotted lines are where paper has been before the paper was folded.) A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded.

![Diagram of paper folding](image)

a. b. c. d. e.

**Figure 4.9:** Questions testing sequencing skills from version III of the VSCS assessment

**Explanation:** In order to build the box in three-dimensions, certain pieces must be next to each other. For example, pieces 1 and 2 can not be next to each other because piece 1 is on the left side of the box, and piece 2 is on the right side of the box. Pieces 3 and 4 are two halves to the front face of the box, and have to be next to each other. Coming from the right side to the front of the box, 4 has to be first, because it is represented as the piece that is in that space. The only answer that is correct is “a”, because if one starts with piece 5 at the back, one can to piece 2. From piece 2, one must go to side 4 and then 3 (order they are in
around the box) and finally side 1. This question fits the sequencing category because the order the pieces fit around the box is key to answer the question.

The hole punch question is from Ekstrom et al.'s cognitive tests from the Educational Testing Service, and have been shown to test sequencing skills. In order to solve this question correctly, answer “a”, students must see the correct order of the folding of the paper. Since there are two separate folds on the piece of paper, the solution should have 4 holes. If a student omitted a fold, then an answer with only two holes would be given. These questions test sequencing skills because the order of the paper folding, and the sequence of the hole punch are the keys for students to correctly answer these questions.

7. **Visual constancy skills** involve the ability to see diagrams of objects that are the same size, shape, or color from others that are not. Students with problems in this area misinterpret changes in size, shape, or color of objects.

**VSCS Example Question #35 on version I and #26 on version III:**
Two different types of models of organic molecules are illustrated below: SPACE FILLING models and BALL-AND-STICK models. Space filling models more closely resemble the actual shape of the molecule as the electron clouds are represented. Ball-and-stick representations with elongated bond lengths show more clearly how one atom is connected to the next. In the next question, you are provided with a ball-and-stick model of an organic molecule. Set out below it are four diagrams of space-filling models of organic molecules. The models may be rotated in any direction.

**Pick the space-filling model that matches the ball-and-stick model.**

![Space-filling models](image)

Figure 4.10: Development of a visual constancy question

**Change made:** Molecules were presented against a black background, to eliminate confusion in trying to see a white atom against the white computer screen. All the answer choices for these questions were redesigned to ensure that these questions only tested constancy skills or the ability to recognize diagrams of objects that are the same size, shape, or color from others that are not. The way the directions read in version I indicated that the answer choices could be rotated in any direction; this was also testing visual orientation skills. Thus the answer choices were redesigned so that the rotation was eliminated, and all the choices were presented in the same direction as the reference ball-and-stick object. The
four questions that were included in version III tested the different parts of this skill: one tested different sizes of molecules, two tested different shapes of molecules, and one tested different colors of atoms in the molecules.

**Explanation:** These questions test visual constancy skills since they require observations of different representations of molecules using depth cues to determine whether they differ in size (there are different constituents on each possible molecule), shape (different orientations of the same and different molecules), or color (different identities of the atoms in the molecules). The specific question highlighted here tested if there were different constituents on each possible molecule or different sizes of molecules. The correct answer to this question is 1, since it is the only one that has all four white atoms in the correct orientation and correct size around the central gray atom. Both 2 and 4 differ from the reference structure by the white atoms not being in the correct shape or size around the central atom. The reason that 3 is not the correct answer is that the white atoms are too big and they engulf the gray atom in the middle. All incorrect answers differ in size from the tetrahedral ball and stick reference structure.

8. **Visual association skills** involve the ability to relate concepts which are represented in pictures and written words. Students’ problems include being “unable to identify figures that are presented in fragments or unable to visualize the missing portion of a partially incomplete object or diagram”.

**VSCS Example Questions #30-31 on version III:**

Refer to the following diagrams that are associated with each question. These diagrams are pictures of three-dimensional unit cells that are represented by cubes.
How many cubes are needed to fill the hollow part (in the middle) of the structure? (Q30). Treating the hollow portion as one “square” block, how many square blocks make up this structure? (Q31).

Figure 4.11: Example questions from the visual association skill set

**Changes made:** For these two specific questions, various phases of semantic analysis were performed since students had the greatest trouble with this question. There were eight original association questions on version I of the assessment tool. The questions that were eliminated were not decided upon until after the analysis on version II was performed. This analysis included a different technique to run the factor analysis, a principal axis factoring (PAF) method. This technique uses a reduced correlation matrix for predicting theoretical factors and identifies the underlying constructs of a tool. PAF is used mostly by statisticians who are looking for orthogonal factors accounting for the maximum available covariance among the variables. This differs from Principal Components Analysis (PCA) in that PCA is used for psychometric purposes, and it will identify scales and subscales. PCA also examines the structure of scoring systems, and is used for more tangible purposes. The theoretical construct that PAF predicts is which questions have large correlations; then these questions
should be eliminated from the assessment because a large correlation indicates that the questions are redundant. The questions that were redundant on the association skill set were eliminated from the VSCS tool.

**Explanation**: To identify correctly that there are four missing cubes in question 30, students need to visualize the missing portion of the incomplete diagram and relate it to fragments or to the small detached portion of the lines that connect the other blocks. The association between the written text and the figure is necessary to correctly answer question 31 as 21. This question asks students to include the middle portion as one “square” block in the counting process, with 6 blocks on each side, 4 on the top and bottom of the middle unit, and with 1 as the middle unit itself.
4.1: REFERENCES


CHAPTER 5. Using think-aloud protocols to investigate college students’ answers to visual-spatial questions

5.1: Introduction

Visual-perceptual skills may be a key to success in chemistry courses.\textsuperscript{1-3} Carter’s study showed that there was a statistically significant and positive correlation between visual-perceptual skills and questions that assessed problem solving skills in chemistry classes.\textsuperscript{1} Rochford’s research demonstrated that students who have poor visual-perceptual skills are more likely to fail science classes,\textsuperscript{2} while Yang et al. utilized a virtual visualization intervention to show how such interventions improved students’ scores on chemistry tests.\textsuperscript{3} In the past, visual-perceptual skills have been identified in chemistry as the ability to rotate an object and compare it to other objects. The Purdue Rotation of Visualization test (ROT) that was used to test visual-perceptual skills in Carter’s and Yang’s work,\textsuperscript{1,3} for example, assesses only visual orientation skills which are defined as the ability to rotate or reflect an object in space.\textsuperscript{4}

This dissertation theorizes that there are additional skills other than just visual orientation that are important for chemistry students. In previous work, the visual-spatial chemistry specific (VSCS) assessment tool was developed and distributed to a large student population enrolled in general, organic, inorganic, and physical chemistry courses.\textsuperscript{5} A qualitative approach was implemented to complement previous work and it consisted of students’ interviews regarding their thought processes when answering visual-spatial
questions. Quantitative and qualitative data may illustrate different aspects of an assessment tool. For the VSCS assessment tool, the main purpose of the quantitative data was to determine reliability and validity of the tool.\textsuperscript{5} Qualitative data was the next step in determining the face validity of the tool, or if the questions appear like a reasonable way to measure visual-perceptual skills. These data were also used to improve the VSCS assessment tool with regards to wording, picture order, numbering, and representations. The qualitative mechanism to monitor students’ thoughts about the questions on the tool was the think aloud method.

The think aloud method has been shown to be an effective way to collect information about problem solving during students’ cognitive processes.\textsuperscript{6} Researchers have used think aloud techniques in chemistry education to look at problem solving processes in chemical equilibrium\textsuperscript{7} and molarity.\textsuperscript{8} However, no studies have been done using think aloud in relation to visual-spatial questions or visual-perceptual skills of students. This qualitative study used the think aloud method to try to answer the following two research questions.

1. How do novice students answer visual-spatial questions meant to test different visual-perceptual skills?
2. What kinds of processes or resources do novice students use to solve visual-spatial problems?
5.2: Design of the interview study

5.2.1: Participants and the context of the study

Sixteen of the twenty interviewees were recruited from the researcher’s Fall 2009 laboratory classes at North Carolina State University. Participants were offered extra credit worth up to 2.25% of their final grade. The other participants of the research study were students who had taken the VSCS assessment once before. They were not offered any extra credit for their participation. Twenty students were included in the final sample with twelve female and eight male students. In addition, six pilot interviews were also conducted with students who had taken the VSCS assessment multiple times. The interviews were conducted in a special interview facility located in a building about a block away from the main Chemistry building. The interview room is equipped with a video camera mounted in the ceiling which records the working area. Figure 5.1 includes pictures of the interview room and the ceiling mounted camera. Table 5.1 provides information about the twenty participants.
Table 5.1: List of participant labels, genders, majors, year in college, and familiarity with the VSCS tool

<table>
<thead>
<tr>
<th>Student</th>
<th>Gender</th>
<th>Major</th>
<th>Year in college</th>
<th>Had seen VSCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Female</td>
<td>Textile Technology</td>
<td>Sophomore</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Female</td>
<td>Biological Sciences</td>
<td>Freshman</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Female</td>
<td>Biological Sciences</td>
<td>Freshman</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>Biological Sciences</td>
<td>Junior</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Male</td>
<td>First year college</td>
<td>Freshman</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>Female</td>
<td>Zoology and International studies</td>
<td>Freshman</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Female</td>
<td>Animal Science</td>
<td>Freshman</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>Male</td>
<td>Agricultural and Environmental Technology</td>
<td>Junior</td>
<td>No</td>
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<tr>
<td>9</td>
<td>Male</td>
<td>Chemistry</td>
<td>Graduate</td>
<td>Yes</td>
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<td>10</td>
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<td>Economics</td>
<td>Junior</td>
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<tr>
<td>20</td>
<td>Female</td>
<td>Animal Science</td>
<td>Sophomore</td>
<td>No</td>
</tr>
</tbody>
</table>

5.2.2: Procedures for conducting the interviews

The 20 interviews were conducted between September and December 2009 and student participation was voluntary. Before the interviews started, the students were informed of the purpose of the interview and were assured that their participation would be kept anonymous. Each participant was asked to sign a release form, giving the researchers permission to transcribe and use excerpts in any written publications. None of the students
seemed to be uncomfortable at any time during the think aloud process, so all twenty interviews were completed. The participants were handed nine to twelve visual-spatial questions on different sheets of paper and asked to think aloud while they solved the questions. The only skills not tested were memory skills, because they would be difficult to test with a paper and pencil test and discrimination skills, a category previously described by a separate factor on version I of the VSCS assessment.5

The questions asked during the interview process had different purposes. Some of the questions were chosen because they had very high factor loading values on the first factor on version I. For example, the first constancy question had one of the highest loadings on factor I in version I of the VSCS assessment tool (0.90). Other questions were new questions on version II and III of the assessment tool, and it was desired to see how students would respond to these questions. All three of the sequencing questions were new questions on versions II and III. The third sequencing question was added halfway through the interview process in order to monitor incorrect as well as correct answers with these novice students. Other questions were chosen because a model kit was beneficial to solving them; such as the orientation question and the two form-perception questions. A couple of questions were asked because the specific students asked these questions had gotten them incorrect when taking the VSCS tool for the first time, such as the discrimination and figure ground questions. Table 5.2 lists the questions used in the interviews based on the skill they tested, the number of students who answered the question, and the version of the assessment tool the particular question appeared on.
Table 5.2: Information on questions used during the interviews

<table>
<thead>
<tr>
<th>Skill</th>
<th>Question interviewed</th>
<th># of students</th>
<th>Question appeared in Version:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrimination</td>
<td>Wireframe diagrams – Pick which figure is unlike the tent diagram.</td>
<td>4</td>
<td>I, II, and III</td>
</tr>
<tr>
<td>Figure-ground</td>
<td>Diamond diagram – Where is K in respect to U?</td>
<td>17</td>
<td>I, II, and III</td>
</tr>
<tr>
<td></td>
<td>Diamond diagram – Atom letter M lies in the same horizontal plane as 4 choices</td>
<td>2</td>
<td>I, II, and III</td>
</tr>
<tr>
<td>Orientation</td>
<td>Molecule of ethene – Rotate it around the Z-axis</td>
<td>20</td>
<td>I, II and III</td>
</tr>
<tr>
<td>Form Perception</td>
<td>Which atom is furthest from your eyes in the 2-D diagram of ethanol</td>
<td>20</td>
<td>I, II and III</td>
</tr>
<tr>
<td></td>
<td>Which atom is closest to your eyes in the 2-D representation of the 3-D structure of n-butane</td>
<td>20</td>
<td>II and III</td>
</tr>
<tr>
<td>Sequencing</td>
<td>Put in order the sides of the box</td>
<td>20</td>
<td>II and III</td>
</tr>
<tr>
<td></td>
<td>Easy paper folding question</td>
<td>20</td>
<td>II and III</td>
</tr>
<tr>
<td></td>
<td>Difficult paper folding question</td>
<td>13</td>
<td>II and III</td>
</tr>
<tr>
<td>Constancy</td>
<td>Match the space-filling methane molecule to the ball-and-stick reference structure</td>
<td>20</td>
<td>I, II and III</td>
</tr>
<tr>
<td></td>
<td>Match the space-filling face-centered structure to the ball-and-stick reference structure</td>
<td>20</td>
<td>II and III</td>
</tr>
<tr>
<td>Association</td>
<td>How many atoms were in the unit cell</td>
<td>20</td>
<td>I, II</td>
</tr>
<tr>
<td></td>
<td>How many atoms were touching a central atom</td>
<td>20</td>
<td>I, II and III</td>
</tr>
</tbody>
</table>
5.2.3: Data Analysis

All interviews were videotaped and fully transcribed. The length of the interviews ranged between 18 to 45 minutes with the average being about 25 minutes. The resulting transcripts and videotapes served as the main source of data for this study. The qualitative data was analyzed by the constant comparative method, which is a four stage process that includes (1) comparing incidents applicable to each category, (2) integrating categories and their properties, (3) delimiting the categories, and (4) finally writing it up. In the first step, transcripts are read and reread and a matrix is composed from the students’ answers and their manner of solving questions. The second stage involves developing theoretical categories or classifications, and noting the common and unique thinking processes about the questions. The third stage makes comparisons between the different types of questions and the different types of students. The writing stage, where all the ideas that have been generated are organized into one coherent piece, completes the fourth stage.

The questions highlighted in this section seek to answer the research question, “What kinds of processes or resources do novice students use to solve visual-spatial problems?” After transcribing and rereading the interviews, it became apparent that “processes or resources” identified from the data could fit into five categories:

- Pointing at diagrams or figures
- Drawing or writing
- Using other objects (hands)
- Verifying with questions
• Making or handling physical representations

All twenty students interviewed used at least one instance of one of the five categories during their interviews, although some students did it more than others. Only a selection of the students will be presented to highlight the use of these specific resources in answering visual-spatial questions. The categories of resources are listed from most to least used in the next section.

5.3: Interview excerpts

5.3.1: Pointing at diagrams

The first interviews’ excerpts are from two different students working on the same question. Both students only used pointing to solve the first question, which required thinking about objects in a 3-dimensional way. This question tested figure-ground skills or the skills needed to see the background of an image; in this question the background was an illustration of the structure of diamond. The question is shown in Figure 5.2. Pointing was the most popular resource of the five used by students roughly 640 times.
The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube.

View atom letter K. Where is atom U with respect to atom K?

a. above  

b. below  

c. same level  

d. can’t determine

Figure 5.2: First question asked and recorded from seventeen of the interviewees

Of the 17 students answering this question, 6 of them answered it correctly concluding that atom U is above atom K. Of the 11 who answered it incorrectly the most common incorrect answer were that the two atoms were on the same level (8 students gave this answer). The first excerpt is from a female’s interview (student number 2 in Table 5.1) that got the answer correct, while the second excerpt is from a male’s interview (student 14 from Table 5.1) who got the question incorrect.

2: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K [points at atom K]. And where is atom U with
respect to K? [points at atom U]. So, um, I'm going to say. [Points at atom K and U concurrently with both hands]

Christian: Keep speaking your thoughts please.

2: It looks kinda above, but it looks almost on the same level. I'm gonna say it's not on the line, so I'm going to say it's above.

Christian: And how'd you get above again?

2: Cause this, K is on the line, [points to the line K is on] and U doesn't look like it's on the line, [point to U to indicate that it is above the line] it looks like it's a little bit above it. So should I, do I circle it?

Christian: Circle it.

2: Okay.

In the second excerpt, the same type of pointing is utilized to solve the problem, but student 14 points to a line that is not there.

14: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K. Where is atom U with respect to atom K? Well, here's atom U [pointing to atom U]. And I feel like atom K [points to atom K] is on the same dotted line, but it almost looks like atom U is slightly above it with respect to [points to the line that atom K is on] the shape of the line. But I think it's meaning that they are on the same dotted line [points to a line that he thinks atom U is on] so I'm going to go with c.
Both of these students used the same type of process (pointing) to solve the question. In fact, they both pointed to the exact same features of the question (point to K, point to U, point to line that K is on). Student 2 recognized that atom U was above the line and pointed to it answering correctly, while student 14 thought atoms K and U were on the same line and “inserted” a line into the figure by pointing to it.

5.3.2: Drawing or writing

Drawing or writing either on or next to the figure was the second most utilized resource in the interviews about the VSCS assessment questions with approximately 320 instances of use. It also was associated with other resources. The first excerpt is from a female student (number 3 in Table 5.1). This specific excerpt is one where drawing and/or writing were the only resources used and it was answered incorrectly. The other instances of drawing and writing were usually complemented with another resource. The other excerpt is of the same question from a different female student that answered it correctly. The question answered is shown in Figure 5.3. This question tests sequencing skills, which are the skills necessary to see objects in a particular order. In this question students must order the pieces around the box so they can visualize the correct sequential arrangement of the pieces and answer correctly choice a.
Look at the following box.

If you ignore the top and bottom of the box, what is the order that you could build the sides sequentially from the following pieces?

![Diagram of a box with sides labeled 1, 2, 3, 4, 5.]

- a. 5, 2, 4, 3, 1
- b. 5, 2, 3, 4, 1
- c. 1, 4, 3, 2, 5
- d. 5, 3, 4, 2, 1

Figure 5.3: Sequencing question asked of the interviewees

3: Look at the following box. If you ignore the top and the bottom of the box, what is the order that you would have to build the sides from the following pieces? Hum, okay, if you ignore the top and the bottom of the box, [crosses out the top and bottom of the box] what is the order that you would, that you would build the sides from the following pieces. Um, well you would need to put, um, the order. Okay, so I would number this 1, [writes side 1 on the left side of the box] number this one 5, [writes side 5 on the back side of the box] number this one 2, [writes side 2 on the right side of the box] and, number one, this side 3, [fumbles a bit here and writes side 3 on the opposite side of the front side of the box] and this side 4 [writes side 4 on the opposite side on the box]. So there's the 1, 4, 3, 2, 5 [circling choice c].
The reason that student 3 answered this question incorrectly is because she switched the order of the two front sides of the box. She might have done this because instead of visualizing the box as a 3-dimensional shape, she probably laid the box down flat and assembled the sides. This possibility is illustrated in Figure 5.4. Piece 3 has the bottom of the triangle pointing to the left, which appears when laid out flat to be the piece next to piece 2 (Figure 5.4). However, when building the box in a 3-dimensional way piece 4 must be next to piece 2 because it is the piece that occupies the right front side of the box (Figure 5.3).

![Figure 5.4: Incorrect solution to first sequencing question (# 23)](image)

The next excerpt is from a female student (17 in Table 5.1) who got the answer correct. Along with drawing, she also pointed frequently while solving the question.

17: *Okay, look at the following box, if you ignore the top and bottom of the box, what is the order that you build the sides from the following pieces? Okay, ignore the top, and ignore the bottom* [crossing out the top and bottom]. *So, then you would need, what is the order that you could build the sides. Then you would need 1* [writes 1 below the question] *and then 2, um, flip those.* [points to sides 3 and 4]

Christian: *Keep speaking your thoughts.*

17: *Um, I would just be this side,* [points to side 1 and then to the place where side 1 is represented on the box] *and then 5 is this side,* [writing 5 on the back wall of the box]
and then 2 is this side, [writing 2 on the right side of the box] and then if you flip, [pointing to side 3] um, 3 or 4, no, never mind, they're good. Um, you could put 4, yes, put 4 and then 3. [writing the numbers 4 and 3 in their respective places on the box] So, 1, 5, no, if you started with 5, then 2, then 4, than 3, then 1, [pointing to the choices] So that would be 5 [circling side 5 on the box] which is good, 2, [circling side 2 on the box] and then 4, which is that, [pointing to side 4] and that would be good, 3, [circles 3 and 4 on the box] and then 1, so that would be a.

This student almost switches the order of sides 3 and 4, but realizes that “they are good” probably realizing that the 3-dimensional shape of the box is the key to answer the question correctly.

5.3.3: Using hands

This resource was first recognized in the rotation question when students would use their hands to indicate a rotation of the molecules. Then the process was noted in other questions as well, when the interviewees would rotate the paper to view the figure in a different way or use a pencil to track cognitive processes. This resource was the third most used during the interviewing sessions; students utilized it about 240 times. The first interview excerpt is from a male student (student 5 in Table 5.1). This question asks students to visualize a rotation of a molecule around a set of defined axes, and is featured in Figure 5.5. In the second interviewee’s excerpt (female student number 6 in Table 5.1) the student also points a few times to make her argument.
If the structure in diagram A were rotated around the **Z-axis** in the direction that the axes show, which structure below matches a rotation around the Z-axis?

5: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Okay, diagram A, so, in terms of the Z-axis, [uses one hand to show a rotation] okay, well, that'd be b, because it is the only one that's rotating that way.

Christian: I'm sorry, why did you pick b again?

D: Because like, well the X-axis is going horizontal, [uses pencil to indicate the x-axis] and Y-axis is going vertical, [uses pencil to show a straight up and down axis] and the Z-axis runs through both of those. [uses a pencil to indicate the z-axis] And a looks like, it
looks like it's been rotated across the Y and the X, [uses pencil to indicate a rotation around both axis] and b looks like it was just turned along the Z [pencil is turning, indicating a rotation around the z-axis] which would make it seem most obvious for the answer.

Student 5 correctly answers this question like thirteen of the other twenty students, in part because when rotating around the z-axis the depth cues of the molecule do not change. The only choice that does not change any angles, foreshortened lines, overlap cues or the relative size of the atoms is choice b. In the next excerpt from student 6, she answers the question incorrectly by trying to rotate the reference molecule around all three axes.

6: If the structure in diagram A were rotated around the Z-axis in the direction that the axis, axes show, which structure below matches a rotation around the Z-axis? So, okay, if the structure in diagram A was rotated around the Z-axis, was rotated around this way, [indicates a z-axis rotation with pencil] um, which match the rotation below, okay, so, let's see, okay. So first it's rotated this way, [uses pencil to indicate a x-axis rotation] and then this way, [uses pencil to show a y-axis rotation] um, I would say.

Christian: Keep speaking your thoughts, please.

6: Okay, oops, sorry, [laughs] okay so diagram A is, [points at diagram A with pencil] alright it's looking towards me, and so first you need to put it down, [points to choice c with pencil] so it look forward like this, [indicates a rotation of choice c with a pencil] and then you want to turn it this way to the left, and then down, so I'm just going to guess d.

Christian: Okay, and why did you pick d again, I'm sorry?
6: Um, because, alright, if I am reading this right, [pointing at the x-axes] um, it's going, the Z-axis is rotating this way, [indicates a z-axis rotation with pencil] so then it would, the two blue atoms [points to diagram A’s two blue atoms] would be facing up and down [indicating a rotation with one hand] and then the Z if it's turning that way, then I'm guessing, it's turning around, [indicating another rotation with pencil] so the two white ones would be facing me vertically and then it looks like it's saying that, um, the Z-axis is turning this way, so I'm guessing, it's going, looking at me horizontally now, [indicates two more different rotations with the pencil] so that was my thought process.

5.3.4: Verifying or clarifying aspects of the questions

Students who verified or asked the interviewer questions always used another resource (either by pointing, drawing, using hands, or handling a physical representation), and this resource was used a total of 90 times during the twenty interviewing sessions. The two interviews that are highlighted here are by students who used a minimum of other resources. Both of these interview excerpts were done with the same association figure, but two different questions about this figure, which is shown in Figure 5.6. Association skills involve the ability to relate concepts which are represented in pictures and written words. Students’ problems include being “unable to identify figures that are presented in fragments or unable to visualize the missing portion of a partially incomplete object or diagram”.11
This unit cell is represented by spheres.

Figure 5.6: Two association questions asked during interview process, but were on two separate pieces of paper

These two questions are classified as association questions because students need to visualize the back of the structure and identify how many spheres there are, even though the complete structure is not shown. Students also need to visualize how many spheres are surrounding one which is missing in the diagram. The first female student (number 2 in Table 5.1) got the first question correct by answering 36 spheres, along with nine of twenty students who also got this question correct. The excerpt of student 2’s answer to the association question #1 in Figure 5.6 follows.

2: *This unit cell is represented by spheres, how many spheres are in this structure? Is this talking about just the ones like I can, [points to the figure, and taps on several atoms] can tell are spheres or?*

Christian: *How many are there total in the structure.*

2: *Okay, so, there’s 4 [making marks on each of the spheres in the top row] and 3 [making marks on each of the spheres going back] and then 3 going down, [making marks on each of the spheres going down] so this means there's 12 in each row, and*
there's 3 rows, [points back at the figure and indicates a face of the cube, and the 3 faces going back] so 12, 36, yeah [counting with her fingers and mumbling 12, 24, 36].

The question this student asked indicated that she was confused with how many spheres she was seeing in the figure. Student 2 also points and writes on the figure to correctly answer the question.

The second excerpt is from a different female student (number 7 in Table 5.1) who answered the second question in Figure 5.6 incorrectly. The correct answer to this question is six spheres, and only six of the twenty students answered this question correctly.

7: Okay this unit cell is represented by spheres. Consider a sphere on the inside. How many other spheres will it touch? Just one sphere, I'm considering only one?

Christian: Um, hum.

7: Okay so if there's only one this is going to be the structure right here, [drawing a circle with 4 circles surrounding it] it's going to be touching 4 on this side and I can assume that the back side is going to look the same, so one sphere on the inside is touching 4, or it's going to be touching, sorry, 8 on the outside.

Student 7 answered this question incorrectly because she thought the question asked about atoms which did not exist but were represented by the dark coloring in the figure.

5.3.5: Building or handling physical representations of the objects

The two excerpts that illustrate the use of building or handling physical representations of objects highlight two different questions. The use of physical
representations only occurred in 20 instances but there were only limited questions where physical models could be used. The first excerpt shown here is one from a female student (number 13 in Table 5.1), where she is answering the question shown in Figure 5.7. Eleven of the thirteen students who were interviewed with this question answered it correctly as choice a, along with student number 13.

On the left are square pieces of paper that have been folded as shown by the dotted lines. (The dotted lines are where paper has been before the paper was folded.) A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded.

Figure 5.7: Third sequencing question asked of thirteen of the twenty interviewees

13: *Pick the figure that shows the positions of the hole when the paper is completely unfolded. Okay, so, wait.*

Christian: *It's folded the bottom in.*

13: *Does it matter if is not a square?* [tries folding up the bottom of the paper that the question is on]

Christian: *It doesn't matter, no.*

13: *So, that, Wait.*

Christian: [mumbling, hands interviewee another piece of paper] *a blank piece of paper,*
whatever you want.

13: *So it's been folded here,* [folds blank piece of paper down once] *so I have to do it here, right? Sorry I have to make it a square so I can see it.* [rips the bottom of the blank piece of paper off]

Christian: *It's alright.*

13: *So, that's my square, yeah, so now it's folded,* [rotates paper around] *so it can have, that,* [folds it 2nd time]. *So there's where it is in the original picture, then it has a hole here.* [puts a big hole through with pen]

Christian: *That's awesome.*

13: *That's a big hole, and then when I open it, well it was like this, so when I open it should be like this, and like this, which means there's 4, right there, it started like that, and it matches up with a.* And I didn't do it like that, or it would have matched up with e [rotate paper around] *cause I started off like that, so that gives me a.*

When this student finally gets the piece of paper folded correctly, and identifies the answer as a, she second-guesses herself by rotating the paper. If she had rotated the paper, the answer would have been e, but this student correctly comes to the correct solution at the end.

The second example comes from another female student that also made use of physical representations exclusively, except that she answered the question in Figure 5.8 incorrectly. Twelve of the twenty students answered this question correctly.
The diagram below is a representation of a molecule of n-butane.

If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes?

a. carbon a  
b. carbon b  
c. carbon c  
d. carbon d

Figure 5.8: Figure-ground question answered by interviewees

This particular student tried to build a model of the molecular figure, but had very limited experience with model kits. The correct answer to this question is carbon b, because it has the most wedged lines around it (which indicates something is coming out of the paper towards you), and these wedge lines are the longest (indicates that this atom is closer to you than the atoms with the shorter lines).

19: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom is, in the drawing is closest to your eyes? Which carbon atom? Okay, I can use these, right? [starts taking the atoms out of the model kit]

Christian: Sure

19: Okay, um.

Christian: Carbons are usually the black ones with four pegs on it, but you can use whatever color you want.
Christian: Yeah, for carbon, usually the black ones are for carbon.

Christian: Yeah, yeah, yeah, okay, [reaching for black atoms] and then have you have hydrogen here, [add a hydrogen to the carbon] and then you have another hydrogen here [adding another hydrogen] so that goes beyond the paper, [rotates molecule around] actually that's how it goes [adding hydrogens on while she is talking about it] so then you would have another hydrogen, and then, hold on, you would have a hydrogen sticking out on this side, and you would have two behind the paper, and then you would have another carbon atom, on this side, [adding second carbon] and then you would have two hydrogen atoms right here, [adding two more hydrogens to second carbon] and the one back here would be connected to an, a carbon atom. Okay so you have 2 sticking out like that, behind the paper, [uses hand to indicate an outward motion] you have this one, behind the paper, one in front of the paper like that, then you have these which are sticking out from the paper, and this one goes behind the paper, like that, [adding third carbon atom] and then this one, you have 2, these two behind the paper, two hydrogens, [adding hydrogens attached to the third carbon] and then you would have 2 hydrogens behind the paper, and then you would have carbon atom sticking out from, above the paper, [adding 4th carbon] and then you would have a hydrogen atom going back towards behind the paper, so it would be. You have one sticking out, two back, one sticking out from the paper, here you've got this one sticking out from the paper, these two sticking out, [referring to the molecule she just built] and this one behind the paper [referring to carbon c] and then you've got these two behind, this one sticking out, and then you've got
this one behind, and these two sticking out this is going to be the one back, [adding a
stick to carbon d] So the carbon atom that is furthest from sight is c [circles c].

Christian: Read the question again, I'm sorry.

19: If you visualize the model from left to right, which carbon atom in the drawing is
closest to your eyes? Closest, so, the one closest would be d [circling d].

Christian: Okay. [student taking model apart] I'll take it apart later.

This student built the molecule in an incorrect way, however she never asked what the
different lengths of the wedged and dashed lines meant. This student had only used the
model kit once, and that was in this researcher’s Chemistry 102 laboratory course. The use
of model kits is not required in Chemistry 102, so most of the teaching assistants do not use
them. In this student’s laboratory class they were used to illustrate the molecular geometry of
various molecules, but the most complicated molecule that was built by the students was
C₂H₂ and PF₃. The n-butane molecule shown in the question is substantially more difficult
than anything built previously by this student.

In conclusion, the resources that were most utilized by the students were actual
physical processes. Although pointing was the most used resource, it did not yield the most
correct answers. (See Chapter 6 for the number of times each resource was used
successfully.) This is a significant finding because visual-spatial questions must necessitate
the use of physical processes to answer them. The least utilized physical process used by the
students was building or handling physical representation, and this resource lead to the
highest percentage of correct answers. This finding will be discussed in Chapters 6 and 7.
5. 4: REFERENCES


CHAPTER 6: Results

6.1 Quantitative results

Factor analysis is a statistical technique used to describe variance among observed variables where the interdependencies between them can be used to reduce this set of variables into factors. In the case of the VSCS assessment the factors are presumably the visual-perceptual skills that are highlighted as important to chemistry students. Of the 978 students who took version III of the VSCS tool, 200 of them did not answer one or more questions. This is a considerable number and therefore demands some attention. The majority of missing answers was concentrated in the memory questions, and the effect is practically insignificant in the remaining questions. Figure 6.1 illustrates the effects of removing students with at least one missing question in comparison with imputing the students’ responses assuming they got the missing questions incorrect. Even though neither of these two approaches (removing missing or zero imputation) is totally appropriate, three strategies were adopted and compared in this analysis:

- Zero imputation
- Removing students with missing questions
- Pair-wise removal in which the tetrachoric correlation is calculated in a pairwise fashion; this strategy was utilized whenever observations were available for a specific pair of questions.1
Figure 6.1: Comparison of the proportion of correct answers per question under the approach of removing the missing responses or imputing the missing responses as a zero

All three approaches did not show significant changes in the analysis, so the second approach was taken. Thus, these 200 students’ data were cut from the final analysis, and only the data from the 778 students’ who completed the VSCS assessment is featured in the factor analysis and item response theory sections of the dissertation.

6.1.1: Confirmatory factor analysis

The first quantitative test that was run on the data from version III was a confirmatory factor analysis (CFA) due to the hypothesis that with the changes that were implemented on the VSCS tool (Chapter 4), the data should show eight distinct factors corresponding to the eight visual-perceptual skills. CFA depends on several statistical tests to verify the relationship between the observed data and underlying factors.
• **Chi-square test** shows the difference between the expected eight-factor structure and observed factor structure. A chi-square value close to zero would indicate that the eight-factor structure is valid. In addition, the probability level must be greater than 0.05 to indicate a valid factor structure.

• **Root Mean Square Error of Approximation (RMSEA)** is related to the residual in the model. It ranges from 0 to 1, and usually acceptable RMSEA values of 0.06 or less would indicate that the eight-factor structure is correct.2

• **The Comparative Fit Index (CFI)** is equal to the discrepancy function adjusted for sample size. It ranges from 0 to 1, and usually acceptable CFI values are 0.90 or greater.2

The results from the CFA are shown in Table 6.1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Observed value</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Square (df=467)</td>
<td>3948.2129</td>
<td>Close to 0</td>
</tr>
<tr>
<td>p-value &gt; Chi-Square</td>
<td>0.0001</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>RMSEA Estimate</td>
<td>0.1070</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Bentler’s CFI</td>
<td>0.5358</td>
<td>&gt;0.90</td>
</tr>
</tbody>
</table>

The results from the CFA show that the eight-factor solution is incorrect because the Chi-Square results were much greater than zero (with a p-value less than 0.05), the RMSEA values were greater than 0.06, and the CFI numbers were less than 0.90. The eight-factor solution was hypothesized to describe the eight separate skill categories but analysis showed the hypothesis to be invalid. The next step taken was to find out how many factors describe the data from version III of the VSCS assessment tool.
6.1.2: Exploratory Factor Analysis

An Exploratory Factor Analysis (EFA) was then run on the data from version III of the VSCS tool. This method, as the name implies, explores the data and tries to determine the best number of factors by not assuming any specific number. The Scree plot obtained by EFA using the 33 questions is presented in Figure 6.2. This is a popular method by which to determine the number of factors from an exploratory factor analysis.\(^3\) As evidenced in this graph, the elbow or break in the chart occurs after the second factor. This results supports looking at the results with a two-factor solution.

![Scree plot from the analysis of version III of the VSCS assessment tool](image)

Figure 6.2: Scree plot from the analysis of version III of the VSCS assessment tool

Another way to determine the number of factors from the data is to look at the number of factors that have eigenvalues above one as stipulated by the Kaiser criterion. Below is a table of eigenvalues and the proportion of variance each factor describes. The fourth column is the cumulative variance, or the variance from the above rows added together.
The Kaiser criterion retains all factors that have an eigenvalue above one, because they must extract the equivalent of one variable to be significant. The table above, however, indicates that the Kaiser criterion would retain 13 factors; which is not practically supported. Furthermore this table indicates that two factors contribute to explain only 22.1% of the cumulative variance. This could mean that the other 78% is error, or more likely that the two-factor solution does not describe all the data.

Factor analysis is based on a linear model and equation,

\[ x = \lambda_n \cdot f_n + e, \]
where \( x \) represents the student’s score on a particular question, \( \lambda_n \) are the factor loadings on \( n \) important factors, \( f_n \) are the factors on \( n \) important factors, and \( e \) is the error term. To find the student’s true score, a correlation matrix is needed and from the matrix the eigenvalues and eigenvectors can be determined. The coefficients of the factors are derived from the eigenvectors of the sample covariance matrix or the correlation matrix of the observed variables. These coefficients, \( \lambda \), are called factor loadings. A high loading for an observed variable on a particular factor indicates that this particular factor is greatly influencing the observed variable.

The factor analysis model may show several solutions. Therefore, two rotation methods were used to help interpret the results. The two rotation methods were Varimax and Promax. The two-factors solution with both Varimax and Promax rotations are shown in Figure 6.3. Both rotations provide very similar results, since an oblique rotation should reproduce an orthogonal solution. The first factor seems to be describing a general visual skill. The second factor is represented by questions that add a second layer of complexity by involving multiple viewpoints such as changing frames of reference. A multiple viewpoint complexity is defined as the possibility that a question could have multiple ways to view the diagram, and a complexity is defined as additional layers of information that are needed to solve the questions correctly (examples include multiple depth cues, rotation of molecules in addition to other processes, and three-dimensional environments that need to be visualized). Hence the two-factor exploratory factor analysis considered in this dissertation supports that two sets of skills are involved in the VSCS tool: one general visual skill and one multiple viewpoint complexity skill. (For additional information, see Chapter 7- Conclusions)
One measure frequently used in psychometric skills tests is a measure of the internal consistency or reliability of a test. A common measurement of reliability is the Cronbach’s alpha. Internal consistency/reliability is high when items are measuring the same construct.
As an example, the Cronbach’s alpha of the whole test (33 questions) was calculated and compared with the Cronbach’s alpha of the questions with high loadings in the first factor of the two factors version of the EFA. As can be seen in Table 6.3, the Cronbach’s alpha of 33 questions is very similar to the Cronbach’s α of the 18 questions, which could be interpreted as the reliability of the test is not apparently affected when reducing the number of questions from 33 to 18.

Table 6.3: Cronbach’s alpha values for the whole version III of the VSCS assessment, the questions that made up the first factor, and the questions that made up the second factor

<table>
<thead>
<tr>
<th>Whole test (33 Questions) Cronbach’s α</th>
<th>0.665</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Factor (18 Questions) Cronbach’s α</td>
<td>0.623</td>
</tr>
<tr>
<td>Second Factor (8 Questions) Cronbach’s α</td>
<td>0.258</td>
</tr>
</tbody>
</table>

6.1.3: Item Response Theory:

6.1.3.1: 1-Parameter Model

As described in Chapter 3, the 1-parameter model assumes only the difficulty level of each question. This model was fitted using Quasi-Newton method and the convergence criterion was achieved after 91 iterations of the data. The adjusted parameters are presented in Figure 6.4 for the 33 questions; the more positive the value, the greater the difficulty of the question. The value of zero as an intermediate difficulty level is an arbitrary value used in IRT analysis. It is important to notice that the assumption of the 1-parameter model can be
too strong (assume equal discrimination power) and for that reason the 2-parameter model was employed.

![Figure 6.4: Estimated difficulty levels for the 33 questions under the 1-parameter model from version III of the VSCS assessment](image)

6.1.3.2: 2-Parameter model

Due to the large number of parameters (2 per question = 66) and observations (n=778) the 2-parameter model took 250 hours of optimization until the convergence criterion was achieved. The additional parameter, the discrimination coefficient is estimated and presented in Figure 6.5. These results are sorted by the questions from smallest discriminatory power to the ones with more discriminatory power. As we can see, it seems that the equal discriminatory assumption under 1-parameter model is not true; otherwise this
figure would be a constant line at 1. However, the test statistic at the end of this section will either support or not support this first impression. Question 25 and 30 have very high discrimination power; however, questions 7 and 4 have the smallest discriminatory power.

![Power of Discrimination](image)

**Figure 6.5**: Estimated discriminatory coefficients for the 33 questions under the 2-parameter model for version III of the VSCS assessment

In this study the 1- and 2-parameters item response models were adjusted assuming the presence of only one general visual skill. By setting the parameter \( a_i = 1 \) in the equation that describes the 2-parameter model

\[
p_i(\theta) = \frac{1}{1 + e^{-a_i(\theta - b_i)}}
\]

for all questions, the exact formulation of 1-parameter model is reached again. This indicates that the 1-parameter model is a particular case of the 2-parameter model, and that model 1 is nested in model 2.

All the parameter estimates for the 33 questions are shown in Table 6.4 in order to facilitate analyzing both parameters (difficulty and discrimination) together. The results are
color-coded, where under the “Difficulty” column the more difficult questions are in red and orange shades, and the less difficult questions appear in yellow and green. Under the “Discrimination” column the highly discriminating questions are in red and orange. This table shows what we know from IRT that discrimination and difficulty are two separate and independent parameters. For example, it is possible to have an easy question that is highly discriminating (Question 17) and a hard question that does not discriminate at all (Question 2). Only two questions (Question 1 and 19) have high values for both parameters.

Table 6.4: Difficulty and discrimination coefficients for version III of the VSCS assessment

<table>
<thead>
<tr>
<th>Question</th>
<th>Difficulty coefficients</th>
<th>Discrimination coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>2.03</td>
<td>0.82</td>
</tr>
<tr>
<td>Q2</td>
<td>6.08</td>
<td>0.23</td>
</tr>
<tr>
<td>Q3</td>
<td>1.86</td>
<td>0.28</td>
</tr>
<tr>
<td>Q4</td>
<td>4.32</td>
<td>0.16</td>
</tr>
<tr>
<td>Q5</td>
<td>-1.1</td>
<td>0.42</td>
</tr>
<tr>
<td>Q6</td>
<td>-1.07</td>
<td>0.45</td>
</tr>
<tr>
<td>Q7</td>
<td>-12.91</td>
<td>0.13</td>
</tr>
<tr>
<td>Q8</td>
<td>-2.43</td>
<td>0.27</td>
</tr>
<tr>
<td>Q9</td>
<td>-1.65</td>
<td>0.59</td>
</tr>
<tr>
<td>Q10</td>
<td>-1.1</td>
<td>1.08</td>
</tr>
<tr>
<td>Q11</td>
<td>-0.76</td>
<td>0.92</td>
</tr>
<tr>
<td>Q12</td>
<td>0.61</td>
<td>0.84</td>
</tr>
<tr>
<td>Q13</td>
<td>-7.07</td>
<td>0.47</td>
</tr>
<tr>
<td>Q14</td>
<td>-1.23</td>
<td>0.93</td>
</tr>
<tr>
<td>Q15</td>
<td>-3.51</td>
<td>0.5</td>
</tr>
<tr>
<td>Q16</td>
<td>-0.92</td>
<td>0.69</td>
</tr>
<tr>
<td>Q17</td>
<td>-3.74</td>
<td>1.03</td>
</tr>
<tr>
<td>Q18</td>
<td>-1.27</td>
<td>1.1</td>
</tr>
<tr>
<td>Q19</td>
<td>2.45</td>
<td>0.24</td>
</tr>
<tr>
<td>Q20</td>
<td>-3.43</td>
<td>0.27</td>
</tr>
<tr>
<td>Q21</td>
<td>-0.07</td>
<td>0.74</td>
</tr>
<tr>
<td>Q22</td>
<td>-3.49</td>
<td>0.42</td>
</tr>
<tr>
<td>Q23</td>
<td>-1.54</td>
<td>0.81</td>
</tr>
<tr>
<td>Q24</td>
<td>-3.14</td>
<td>1.1</td>
</tr>
<tr>
<td>Q25</td>
<td>-1.76</td>
<td>1.44</td>
</tr>
<tr>
<td>Q26</td>
<td>-3.62</td>
<td>0.5</td>
</tr>
<tr>
<td>Q27</td>
<td>-0.85</td>
<td>0.34</td>
</tr>
<tr>
<td>Q28</td>
<td>-2.21</td>
<td>0.86</td>
</tr>
<tr>
<td>Q29</td>
<td>-1.63</td>
<td>0.55</td>
</tr>
<tr>
<td>Q30</td>
<td>-2.23</td>
<td>1.54</td>
</tr>
<tr>
<td>Q31</td>
<td>2.77</td>
<td>0.32</td>
</tr>
<tr>
<td>Q32</td>
<td>3.06</td>
<td>0.49</td>
</tr>
<tr>
<td>Q33</td>
<td>-2.09</td>
<td>1.29</td>
</tr>
</tbody>
</table>
There is evidence to reject the null hypothesis, which theorizes that the model with 1-parameter is not equivalent with the model with 2-parameters. In fact, the model with 2-parameters has been shown to be more suitable than the model with 1-parameter. This provides evidence that the assumption of all questions being equally discriminatory is violated. If the p-value of this test is 0.01 or below, this means we can reject the null hypothesis of the 2-parameter model being replaced by the 1-parameter model. In this test the p-value is <0.0001, therefore the 2-parameter model is required to describe the data. In other words, the difficulty and discrimination coefficients are important in interpret the data from the VSCS version III.

The Cronbach’s alpha was calculated for the questions with high discriminatory power for a total of 15 questions (highlighted in red and orange on the third column in Table 6.4). This model was performed with the assumption that there is one visual skill in place. Cronbach’s alpha is 0.652796, very similar to the Cronbach’s alpha for the complete test.

6.2: Categorical results:

A total of seven categorical questions were asked of students when they took the VSCS assessment tool. Only six of the questions have been highlighted in this dissertation because the seventh question, which asked students if they had used a model kit during the assignment, did not yield enough responses to analyze. For exact numbers and the frequency and percentages of all the categorical questions see Appendix IV. Of the remaining six questions, the only question with a significant difference in score as analyzed using ANOVA
was the gender question. In Table 6.5, the p-values are listed for the different categories of students using a 2-way ANOVA. The null hypothesis for this test is that the students who identified themselves in these categories have equal scores on the VSCS assessment tool and if a p-value is less than 0.01, the null hypothesis can be rejected. Roughly 50% of the students who took the assignment identified as female, and the other half as male. Gender of the students was the only category that was found to have a significant difference with a p-value of 0.0064. Therefore, there is a difference in the scores of females and males. The males scored higher than the females with a total score of 21 versus females 19.5.

Table 6.5: Categorical questions results from a 2-way ANOVA for the data from version III of the VSCS assessment

<table>
<thead>
<tr>
<th>Category</th>
<th>p-value</th>
<th>Significant differences</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>.0064</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Males</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Females</td>
<td>19.5</td>
</tr>
<tr>
<td>Ethnicity</td>
<td>.9047</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major</td>
<td>.4575</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>.5017</td>
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<td>.1982</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semesters of Chemistry</td>
<td>.4761</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.3: Qualitative results

Originally the research question dealt with cognitive resources or processes students might use when solving visual tasks. The question considered whether any significant patterns of mental cognition could be ascertained from the interviews. After analyzing
twenty interviews, it became clear that the data obtained could not show cognitive patterns, and only showed students’ use of physical processes in a very superficial fashion. However, these interviews were fully analyzed by transcribing, reading, rereading, and re-listening for missed clues. Several issues might have been responsible for why the interview data were not representative of cognitive resources. The visual-spatial questions were very specific and narrowed in what they ask students to do which may have reduced the process to a series of tasks that might not require forming a mental image of the objects. Another limitation was brought on by the experience of the interviewees, since they were all novice students with limited experience with these types of questions or the think aloud process. The data only show the students used basic physical resources or processes, and these processes were broken into five categories: students who point at specific aspects of the questions, students who use their hands, pencils, or the paper itself to indicate operations on the molecules, students who draw or wrote annotations, students who verify by asking the interviewer questions about the problems, and students who use physical representations to solve the problems. Figure 6.6 is the rubric used to determine when the instances of resource use happened in the interviews.
Pointing* –

1. Students need to point to a specific figure without lifting hand from paper. Need to point to a picture (not to directions or answer choices that have no figure).
2. If students point to two different aspects of a diagram that will count as two resource’s use – even if didn’t lift hand from paper.
3. Whenever they point to one aspect of a question – that will count as just one resource use – no matter how many times they point towards it.
4. Does not include pointing back and forth between the same features, or pointing at the same feature multiple times (with or without lifting hand from paper).

Hands/pen/paper –

1. Students need to be lifting hands off paper to indicate an aspect of the question’s directions or meaning to the student, such as a rotation.
2. Students need to be using pencil to denote an aspect of the question’s meaning.
3. Students need to be turning paper to indicate the meaning of the question to the student.
4. One instance will be counted for each aspect of the question the student is exploring.

Drew or wrote* –

1. Students need to be drawing an original figure related to the question.
2. Students need to be circling on a figure or writing on or next to a figure in order to answer the question.
3. This category does not include drawing or tracing or circling multiple times in one spot. This will be counted as one instance.
4. Does not include writing down the answer, or circling an answer from a multiple choice list.

* Sometimes it is hard to tell the difference between a point and a draw – wait for them to draw – and if they do, mark it as a draw, rather than a “pointing”.

Verifying –

1. Students need to be asking the interviewer a question, about the question at hand. Questions such as “Is this the right answer?” or “Can I use this?” do not count.

Physical representations –

1. Students must handle or build a physical representation of the question.

Figure 6.6: Rubric used to determine the number of instances of process use during the interviews
Table 6.6 presents the interview results of the three most used resources to solve the visual-spatial questions: pointing, using hands/pen/paper, and drawing/writing. The first column gives the student identification number, and the second column indicates how many questions the students attempted during the interviews. Each resource comprises three columns. The first column is the average number of times a student used a resource per question. This is found by dividing the number of times the student had used the particular process by the number of questions on which the resource was used. The second column indicates how successful the student was at solving the question. Listed first is the number of questions a student successfully answered by using the technique over how many total questions a student attempted to solve by using the specific process. The third column under each resource use is the ratio of number of questions successfully answered by total number of questions a student attempted to solve turned into a percentage. At the bottom of the table are the successful average percentages of the resource use by all twenty students. Pointing, using hands, pens, or paper, and drawing and writing had about the same average percentages at 63, 70, and 67, respectively. There is no trend with these results because students who used these tools more had the same chance of getting the questions correct as students who used the tools less frequently.

Table 6.7 highlights the last two processes: students who verified or asked the interviewer questions, and students who handled physical representations. The first two columns are again student identification number, and the number of questions attempted by each student.
Table 6.6: Results from the three most used resources by students to solve the visual-spatial questions, column notation is in the text

<table>
<thead>
<tr>
<th>Student #</th>
<th># questions attempt</th>
<th>Pointing</th>
<th></th>
<th></th>
<th></th>
<th>Hands / Pen/ Paper</th>
<th></th>
<th></th>
<th>Drawing / Writing</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average use per Q</td>
<td># correct / # attempt</td>
<td>% Success</td>
<td>Average use per Q</td>
<td># correct / # attempt</td>
<td>% Success</td>
<td>Average use per Q</td>
<td># correct / # attempt</td>
<td>% Success</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>2.1</td>
<td>6 / 10</td>
<td>60</td>
<td>1.7</td>
<td>5 / 6</td>
<td>83</td>
<td>1.6</td>
<td>5 / 7</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>4.9</td>
<td>9 / 11</td>
<td>82</td>
<td>2.2</td>
<td>5 / 6</td>
<td>83</td>
<td>2</td>
<td>2 / 2</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>2.2</td>
<td>6 / 9</td>
<td>67</td>
<td>1.3</td>
<td>1 / 4</td>
<td>25</td>
<td>5.6</td>
<td>7 / 11</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>3.8</td>
<td>5 / 11</td>
<td>45</td>
<td>1.4</td>
<td>2 / 8</td>
<td>25</td>
<td>5.6</td>
<td>7 / 11</td>
<td>64</td>
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<tr>
<td>5</td>
<td>11</td>
<td>2.8</td>
<td>7 / 8</td>
<td>88</td>
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<td>7 / 7</td>
<td>100</td>
<td>0</td>
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<td></td>
<td></td>
</tr>
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<td>6</td>
<td>10</td>
<td>4.6</td>
<td>7 / 9</td>
<td>78</td>
<td>3.3</td>
<td>5 / 6</td>
<td>83</td>
<td>2.8</td>
<td>4 / 5</td>
<td>80</td>
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</tr>
<tr>
<td>7</td>
<td>11</td>
<td>3.5</td>
<td>5 / 10</td>
<td>50</td>
<td>1.3</td>
<td>3 / 6</td>
<td>50</td>
<td>2.8</td>
<td>4 / 5</td>
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</tr>
<tr>
<td>8</td>
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<td>2 / 4</td>
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<td>0</td>
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</tr>
<tr>
<td>9</td>
<td>10</td>
<td>3.8</td>
<td>7 / 11</td>
<td>64</td>
<td>1.8</td>
<td>2 / 4</td>
<td>50</td>
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<td>1 / 1</td>
<td>100</td>
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<td>10</td>
<td>13</td>
<td>3.5</td>
<td>7 / 11</td>
<td>64</td>
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<td>100</td>
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<td>0 / 1</td>
<td>0</td>
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<tr>
<td>11</td>
<td>9</td>
<td>2.7</td>
<td>7 / 8</td>
<td>88</td>
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<td>4 / 5</td>
<td>80</td>
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<td>8 / 9</td>
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<td>10</td>
<td>3.8</td>
<td>9 / 11</td>
<td>82</td>
<td>5.8</td>
<td>5 / 6</td>
<td>83</td>
<td>2.6</td>
<td>3 / 3</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>11</td>
<td>5.1</td>
<td>8 / 10</td>
<td>80</td>
<td>3.3</td>
<td>4 / 4</td>
<td>100</td>
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<td>8 / 10</td>
<td>80</td>
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</tr>
<tr>
<td>14</td>
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<td>2 / 3</td>
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<td>17</td>
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<td>9 / 12</td>
<td>75</td>
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<td>6 / 8</td>
<td>75</td>
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<td>8 / 11</td>
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<td>5 / 11</td>
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<td>1 / 3</td>
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<td>19</td>
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<td>20</td>
<td>11</td>
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<td>Average #’s</td>
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<td>70</td>
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<td>67</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
In these cases, an average process use per question number would be misleading, especially for the physical representations where students only made one physical representation per question when they attempted to use this resource. The two columns highlighted are a ratio of the number of questions a student successfully answered by using the process over the number of total questions a student attempted to solve by using the specific resource. The subsequent column has this ratio converted into a percentage. Under this column at the bottom of the table are the successful average percentages of the resources use.

Table 6.7: Results from the last two processes used to solve visual-spatial questions

<table>
<thead>
<tr>
<th>Student #</th>
<th># Questions Attempt</th>
<th>Verifying</th>
<th>Physical Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td># Correct / # Attempt</td>
<td>% Success</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>0 / 1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2 / 2</td>
<td>100</td>
</tr>
<tr>
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<td>3 / 4</td>
<td>75</td>
</tr>
<tr>
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<td>11</td>
<td>0 / 1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>1 / 1</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
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</tr>
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<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>13</td>
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<td>0</td>
</tr>
<tr>
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<tr>
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<td>0</td>
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Verifying had the lowest success rate, as just under half of the times it was used yielded a successful result (47%). The method that continually helped the most frequently was building or handling a physical representation of an object (88%). All but three of the instances this technique was used (20 times) resulted in a correct answer. Two of these incorrect instances occurred with students building a molecular model that had very limited experience using the model kits.
6.4: REFERENCES


CHAPTER 7: Conclusions

7.1: Quantitative data

Factor analysis and item response theory (IRT) are both statistical models that require continuous data. Factor analysis’s continuous data must be derived from a correlation matrix because of the need for absolute values, while item response theory uses proportions of correct answers. While factor analysis examines variance in the data by reducing the number of influencing factors, IRT explores the difficulty and discrimination levels of individual questions. Although a 2-factor model was shown to be the best fit for the data from factor analysis, the IRT analysis was run assuming a 1-factor model due to the difficulty to run a multidimensional IRT analysis. Both analyses resulted in very similar outcomes. Figure 7.1 shows a side-by-side comparison of the results from both IRT and factor analysis.

A significant finding is that all of the questions that are highly discriminating on the assessment tool load high on either factor 1 (Q10, 11, 14, 16, 17, 18, 21, 23, 24, 25, 28, 30, 33) or factor 2 (Q 1 and 12). Finding that they all load highly on either of the two identified factors heightens their importance. Most of the highly difficult questions load high on factor 2 (Q1, 2, 4, 12, 19, 32). However, the highly difficult questions were not considered to be as notable as the discriminating questions, because a discriminating question means that this question can differentiate a high ability from a low ability student. The difficulty levels identified in IRT as high range from 0 and above, whereas the discriminating values range from 0.6 and above. Only three questions (9, 13, and 26) load highly on factor 1 and are not
identified as difficult or discriminating. There are two questions (8 and 29) on factor 2 that are not identified as difficult or discriminating (same levels as before). Even though there are these exceptions, most of the difficult and discriminating questions load highly on either of the two factors and most of the questions that load highly on the two factors are difficult and discriminating. This finding suggests that the similarities in the techniques correspond to a similar question pattern, because a relationship exists between item response theory and factor analysis.¹

![Figure 7.1: Results from both Item Response Theory and Factor analysis](image)

Figure 7.1: Results from both Item Response Theory and Factor analysis
Factor 1 seems to be a general visual-spatial skill and includes 18 of the 33 questions from six of the eight categories of questions. All of the questions that are represented by factor 2 are different and all involve multiple viewpoints complexities. For example, questions 9-12 are categorized under figure-ground skills but questions 9-11 load highly on Factor 1, while question 12 loads highly on Factor 2. In Figure 7.2, all 4 questions are illustrated.

The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube.

9. View atom letter K. Where is atom U with respect to atom K?
   a. above b. below c. same level d. can't determine
10. Atom letter S lies on the same outside vertical plane as atom letter E, Q, R or T?
11. Atom letter M lies on the same horizontal plane as atom letter Q, R, S, or U?
12. Atom letter Q lies on the same vertical plane as atom letter H, P, R, or T?

Figure 7.2: An illustration of questions 9-12, and Question 12 requires two viewpoints to visualize the diagram

Questions 10 through 12 all have the same semantic pattern (as can be evidenced from the underlined sections). The difference between questions 10, 11, and 12 is that question 12 involves two different viewpoints. Question 10 asks students to view atom S from the
outside vertical plane and there is only one outside vertical plane on which atom S lies. Question 11 asks students to view atom M on its horizontal axis. Again, there is only one horizontal axis on which atom M lies. Question 12, however, asks students to view atom letter Q on its vertical plane. As evidenced by the two red boxes in the diagram, there are two vertical planes on which atom letter Q could be. Although only one possibly correct answer is listed (atom T), a multiple viewpoint complexity is possible that could increase the level of complexity for discerning which plane the answer assesses. When students view this diagram from the correct viewpoint, the question will be simplified; if they do not students must erase their frame of reference and reconsider a different viewpoint.

An additional example of the multiple viewpoint complexity skill occurs with the figures from the form perception questions (Q 18, 19 and 21). Questions 18 and 21 load highly on factor 1, and question 19 loads highly on factor 2. Figure 7.3 depicts the figures from the questions with the factor 1 and factor 2 questions notated.

![Factor 1 and Factor 2](image)

Figure 7.3: Figures from the form perception skill questions
The first figure (shown under factor 1) asks students which atoms are furthest from their eyes, after it tells them the differences between the dashed and wedge line notation. This question is asked on a computer screen so students are viewing the molecule straight on. All that is needed to answer this question is to anchor the figure with the straight lines and recognize that the atoms with the dashed wedges lie behind the paper, and are therefore the furthest from the students’ eyes. The second set of figures under factor 1 asks students which atom is furthest from the atom marked “H”. Since two figures are given here, and both of them have one straight line (meaning it is in the plane of the paper), it is easier to view this straight line as the anchor point of the question in order to figure out that the answer is atom 1. However, under factor 2 there are two ways to view this figure. One way is to look at the figure straight on, while a second viewpoint is brought on by the question itself, which reads “If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes?” This presents the opportunity to look at the diagram from the side or end of the molecule. This molecular picture has no straight lines, and students have no anchor line from which to view the figure. The multiple viewpoint complexities in this question is brought on by the fact that students have no pre-determined frame of reference to view the figure from (no straight lines) giving rise to two different ways to view the diagram as well.

A third example of the differences between factor 1 and factor 2 is found in questions 26 and 29, both of which test constancy skills and are featured in Figure 7.4. Question 29 loads highly on factor 2 and involves rotation along with deciding about differences in color to see what the different atoms are. The correct answer to question 29 is molecule 2, because it is the only one that shows the correct color of atoms in the correct positions. Question 26
involves visualization of different sizes of atoms but with no rotation involved. In this case
the multiple viewpoint complexity skill consists of extra layers of complexity by involving
rotation elements in addition to constancy skills.

Figure 7.4: Two different constancy questions show difference between factor 1 and 2

The fourth and final example of differences between factors 1 and 2 is illustrated by
two questions on the association skill set, questions 30 and 32, which are featured in Figure
7.5. In question 30, which loads highly on factor 1, students can visualize both the back and
the front of the structure in order to identify that four cubes would be able to fit into the spot
mentioned. Question 32 requires students to mentally image inside the structure in order to
answer correctly that there are six atomic spheres that will touch one in the center. The
limited representation asks viewers to imagine atoms they cannot directly observe. The possible approaches to determine spheres on the inside are not restricted nor defined. Therefore, the potential for viewing this three-dimensional environment in multiple ways requires a multiple viewpoint complexity skill.

Figure 7.5: Two different association questions show difference between factor 1 and 2

Question number 1, the first memory question, loads high on Factor 2 and is highlighted in Figure 7.6. The molecular answer choices are rotated from the reference molecule and depict a tetrahedral molecule. In the tetrahedral molecule the five atoms are always depicted by depth cues, such as overlap cue, foreshortened line cue, or relative angles depth cue. Molecules represented in the other memory skill set questions (3) do not involve as many depth cues as these tetrahedral molecules. These tetrahedral molecules introduce multiple viewpoint complexities by requiring viewers to decipher different types of depth cues in order to answer correctly. Students need to comprehend these additional layers of information, which suggests the requirement of a multiple viewpoint complexity skill to solve them.
Cronbach’s alpha data was presented in Table 6.4. The reliability and internal consistency measured for the whole test (0.66) was almost the same as for the 18 questions that loaded significantly on the first factor (0.62). This could mean that another version of the VSCS assessment tool could consist of just these 18 questions, and that this version would show the same reliability as the whole tool. Cronbach’s alpha also can be interpreted in terms of redundancy of the questions; a low cronbach’s alpha (< 0.60) may indicate that the questions are not at all redundant, whereas a high cronbach’s alpha (> 0.90) may be interpreted as all the questions measuring the same skill. Although factor 2 cronbach’s alpha is less than the 0.60 cut off for redundancy (0.26) the eight questions that make up factor 2 may measure different skills and are thus not redundant. These factor 2 questions do have a common variable, however, in that they all contain multiple viewpoint complexities that consisted of questions that could represent multiple ways to view the diagram and additional layers of information. Although the hypothesis of the dissertation was that the factors would
separate according to skill category, this does not seem to be the case. Instead, the questions seem to separate on something much more fundamental, multiple viewpoint complexities in viewing the figures associated with each question.

7.2: Categorical data

The finding that males who took the VSCS assessment tool did better than the females who took it has some precedent. In the 1970’s Maccoby and Jackin showed that males have better spatial skills than females do.² The educational testing service data also highlight that males score higher than females on assessments that measure visual-spatial ability.³ In chemistry there are data that show a significant difference between males and females scores on assessment tools that measure just one visual-perceptual ability, visual orientation skills.⁴ However, there are also other chemistry research studies that have found that there is no significant difference in visual-perceptual score among college aged chemistry students.⁵ Nevertheless, for the VSCS assessment tool, it has been shown that males do outperform females significantly.
7.3: Qualitative data

The findings have a precedent that students who built or handled physical representations during the interviews were the most successful at answering the questions correctly. Work done in various fields has shown that students who handle physical representations do better at visual-spatial tasks.\textsuperscript{6, 7, 8} Talley’s study showed that general chemistry students who handled molecular models during class time, outperformed students who learned by a didactic, lecture-type style, outperforming them both in the final exam and on the questions that tested their higher order thinking skills.\textsuperscript{6} The control group scored higher on the knowledge type questions, and both scored equally on the comprehension style questions. The researchers interpreted this to mean that working with molecular models promotes higher order thinking skills. Students who worked with the molecular models in the interviews answered the visual-spatial questions correctly more often than students who did not handle the molecular models. This could be interpreted to mean that these students might be operating on a higher cognitive level as compared to the students who did not handle the representations.

Another study showed that biology students who handled blocks and imagined cross-sections of them, scored higher on several visual-spatial assessment tools.\textsuperscript{7} The first assessment tool was one that directly tested the activity “the Planes of Reference” test, which required students to draw what the plane of a solid figure would look like when cut in a certain way. The other assessment tools were more general and included the cube comparisons test,\textsuperscript{3} the embedded figures assessment (disembedding ability test),\textsuperscript{9} and a
surface development test. The specific assessment that did not show an increase in score for the experimental students was the disembedding ability test. The researchers found this to indicate that handling blocks would raise scores on related assessment tools, but that it would not raise scores on unrelated assessments – such as the disembedding ability test. Lord’s paper shows that working with physical representations of objects is a way to enhance visual motor skills, which is what happened when the students build or handed physical representations of the questions during the interviews.

In yet another study, psychology students took pre-tests of common general visual-spatial assessment tools, and then were split in an experimental group of tables of four students comprising two low scoring students and two high scoring students. These four students worked together during three one-hour sessions where they would first re-take the test, and then handle physical representations of the test figures. One of the representations employed paper cut-outs of a surface development test, a second used overhead transparencies of embedded figures, and a third hour was dedicated to Styrofoam molds of the Shepard-Metzler test questions. After the experience of working with the physical representations, the experimental group outperformed the control group on all three tests in which physical representations were handled, as well as on a fourth visual-spatial test which had no models. This paper shows that building and handling physical representations of visual-spatial questions can improve students’ scores on visual-spatial assessments.
This dissertation expands on previous work by the same researcher, and emphasizes several different points. The Visual-Spatial Chemistry Specific (VSCS) assessment tool was revised, and rewritten in its current version III. Factor analysis on the newest version of the VSCS assessment tool revealed that there were not eight distinct factors as previously speculated, but instead only 2 important factors. One of these is labeled as a general visual-spatial skills factor and is present in 18 questions from six of the eight categories of skills. The second factor invokes a multiple viewpoint complexity skill, which consisted of questions that could have multiple ways to view the diagram through additional layers of information.

IRT data showed which questions were considered difficult and which were discriminating among the 778 students who completed the VSCS tool. All the questions that were discriminating and all but two of the most difficult questions were represented on factors 1 and 2, showing the convergence between factor analysis and IRT. The research question “Can the skills proposed from Rochford and Archer’s theoretical framework be tested and differentiated from each other using the VSCS tool?” can now be answered. Although the eight skills cannot be differentiated from each other using the VSCS tool, a different distinction is made with the two-factor solution. This work supports the interpretation that one factor describes a general visual-spatial skill while a second factor describes a multiple viewpoint complexity skill. The second factor present in 8 questions
appears when multiple layers of visual complexity may be required for students to visualize different aspects of a diagram.

A second important aspect of the research in this dissertation is the inclusion of the interview data, where 20 students were interviewed about the way they solved selected questions on the VSCS assessment tool. Although the original research question considered cognitive resources that would be found from the interview data, issues with the students having insufficient experience with the think aloud method and the questions being very specific limited the observations to physical processes. The novice students used physical resources to solve the questions on the VSCS assessment. These physical processes included: pointing at a specific object or diagram; using hands to represent an object; drawing or writing on or next to a figure; verifying or asking questions of the interviewer; and building or handling a physical representation of an object. The interview data showed that students who build or handled a physical representation of the object were the most successful in attaining the correct answers. The deliberate incorporation of physical representations of objects in chemical construction should benefit students because the use of a physical tool yielded the highest percentage of correct answers during the interviews.
7.5: REFERENCES


APPENDIX I: Version II of the Visual Spatial Chemistry Specific assessment tool (paper copy)
Visual-Spatial Chemistry Specific (VSCS) Assessment

This assessment tool is meant to measure seven visual-perceptual skills that are theorized to be important for chemistry students. Your thoughtful answers will help determine its validity. If a model kit is available, you may use it.

The first seven questions are category questions, please answer them honestly. If the questions have diagrams as possible answers, the letter choices are placed before the pictures. Do your best!

1. I affirm that I am the person whose name is on the scantron sheet. I give my permission for these scores to be used without my name attached to them for research purposes only. If so, mark a.

2. What is your gender?
   a – Male
   b – Female

3. What is your ethnic background?
   a – African American / Black
   b – Asian American / Asian
   c – Native American / Alaskan Native / Pacific Islander
   d – Latino American / Hispanic
   e – European American / Caucasian / White
   If Other, leave blank

4. What is your major?
   a – Chemistry
   b – Engineering
   c – Biology and Biological fields
   d – Math / Statistics
   e – Other

5. How old are you?
   a – Under 18
   b – 18 – 20
   c – 21 – 25
   d – Over 25

6. What year are you in your academic institution?
   a – First year
   b – Second year
   c – Third year
   d – Fourth year
   e – Past fourth year

7. How many semesters of chemistry have you taken?
   a – This is my first
   b – 1-2
   c – 3-5
   d – Greater than 8
   e – 6-8
8. In the next four questions, the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles.

Pick the number of the figure which is **unlike** (different from) the reference object.

Reference object:

![Reference Object](image)

- a.
- b.
- c.
- d. All of these could be observed

9. Pick the number of the figure which is **unlike** (different from) the reference object.

Reference object:

![Reference Object](image)

- a.
- b.
- c.
- d. All of these could be observed
10. Pick the number of the figure which is **unlike (different from) the reference object.**

Reference object:

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<td><img src="image1" alt="Reference Object" /></td>
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<td><img src="image1" alt="Image 4" /></td>
<td><img src="image1" alt="Image 5" /></td>
</tr>
<tr>
<td>a.</td>
<td>b.</td>
</tr>
<tr>
<td>c.</td>
<td>d. All of these could be observed</td>
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11. Pick the number of the figure which is **unlike (different from) the reference object.**

Reference object:

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<td><img src="image2" alt="Image 3" /></td>
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<tr>
<td><img src="image2" alt="Image 4" /></td>
<td><img src="image2" alt="Image 5" /></td>
</tr>
<tr>
<td>a.</td>
<td>b.</td>
</tr>
<tr>
<td>c.</td>
<td>d. All of these could be observed</td>
</tr>
</tbody>
</table>
The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response.

12. View atom letter K. Where is atom U with respect to atom K?
   a. above   b. below   c. same level   d. can’t determine

13. Atom letter S lies on the same outside vertical plane as atom letter
    a. E   b. Q   c. R   d. U

14. Atom letter M lies on the same horizontal plane as atom letter
    a. Q   b. R   c. S   d. U

15. Atom letter Q lies on the same vertical plane as atom letter
    a. H   b. P   c. R   d. T
16. If the structure in diagram A were rotated around the **Y-axis** in the direction that the axes show, which diagram below would represent the structure as seen after a rotation of 180 degrees?

![Diagram A](image1)

Options:

- a.
- b.
- c.
- d.

17. If the structure in diagram A were rotated around the **X-axis** in the direction that the above axes show, which structure below matches a rotation around the X-axis?

![Diagram A](image2)

Options:

- a.
- b.
- c.
- d.
18. If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis?

Turning around the X axis  
Turning around the Y axis  
Turning around the Z axis

Diagram A

a.  
b.  
c.  
d.

19. Among the molecular representations choose the one which you would get after reflecting molecule A in the mirror.

Molecule A  
Mirror

a.  
b.  
c.  
d.
20.

Note: The X- and Y- axes are drawn in the plane of the paper. Imagine the Z-axis as being perpendicular to them, coming out of the paper.

Look at the following example question.

If this structure were reflected in the YZ-plane, the answer would be:

Your question is:
Imagine you are standing in front of the structure in diagram 1. If the structure in diagram 1 were reflected in the XZ-plane which diagram below could represent the structure as seen after reflection?

Diagram 1

a. b. c. d.
21. The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram \( \overrightarrow{\text{below}} \) indicates that a bond projects behind the screen, and \( \overrightarrow{\text{out}} \) indicates that a bond projects out of the screen towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper.

Which atom(s) is (are) furthest from your eyes?

a. 8 b. 3 c. 5, 7 d. 1, 2 e. 5, 8

22. The diagram below is a representation of a molecule of n-butane.

If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes?

a. carbon a b. carbon b c. carbon c d. carbon d

23. The diagram below is a ball and stick representation of a molecule of n-butane.

Which hydrogen atom in the drawing is furthest back from your eyes?

a. hydrogen 1 b. hydrogen 2 c. hydrogen 3 d. hydrogen 4
24. The diagrams below are representations of a molecule of isobutane.

Which hydrogen atom is farthest from the hydrogen labeled “H”?

a. 1    b. 2   c. 3   d. 4

25. Glucose is a primary metabolite in living things, here is one of its structures.

How would you build this molecule from the top down using the following pieces?

a. 9, 6, 4, 7    b. 2, 4, 6, 4, 7    c. 9, 1, 6, 4, 7    d. 2, 4, 5, 6, 4, 7
26. Look at the following box.

If you ignore the top and bottom of the box, what is the order that you could build it from the following pieces?

\[ \begin{align*}
1 & \quad 2 & \quad 3 & \quad 4 & \quad 5 \\
\end{align*} \]

a. 5, 2, 4, 3, 1  
  b. 5, 2, 3, 4, 1  
  c. 1, 4, 3, 2, 5  
  d. 5, 3, 4, 2, 1

On the left are square pieces of paper that have been folded as shown by the dotted lines. (The dotted lines are where paper has been before the paper was folded.) A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded.

28. Pick the figure that shows the positions of the holes when the paper is completely unfolded.

\[ \begin{align*}
& \quad a. \quad b. \quad c. \quad d. \quad e. \\
\end{align*} \]
29. Two different types of models are illustrated below: SPACE FILLING models and BALL-AND-STICK models. In the next four questions, you are provided with a ball-and-stick model of an organic molecule. Set out below it are four diagrams of space-filling models.
Pick the space-filling model that matches the ball-and-stick model in questions 29-32.

![Ball-and-stick model](image)

![Space-filling models](diagrams)

30. Pick the space-filling model that matches the ball-and-stick model in questions 29-32.

![Ball-and-stick model](image)

![Space-filling models](diagrams)
31.

32.
Refer to the following diagrams for questions 33 and 34. These diagrams are pictures of three-dimensional unit cells that are represented by cubes.

33. How many cubes are needed to fill the hollow part (in the middle) of the structure with the cubic blocks?
   a. 1  b. 2  c. 4  d. 12

34. Treating the hollow portion as one block, how many blocks make up this structure?
   a. 5  b. 6  c. 21  d. 24

For questions 35 and 36 refer to the following diagram. The unit cell is represented by spheres.

35. How many spheres are in this structure?
   a. 12  b. 30  c. 36  d. 48

36. Consider a sphere on the inside, how many other spheres will touch it?
   a. 4  b. 6  c. 10  d. 12

37. If you used a model kit for this assessment tool, mark a.
Appendix II: Memory questions printed from website (Questions 1-4 of version III)
Enter your full name in the box below then click Continue.

Continue
Study the reference molecule above, when you click the Next button the picture will be replaced by four possible choices. Select the choice that is a mirror image to the reference molecule. You can go back and view the reference model up to two times.
Select the molecule below that is the mirror image to the reference image.
Question 2

Study the reference molecule above, when you click the Next button the picture will be replaced by four possible choices. Select the choice that is a mirror image to the reference molecule. You can go back and view the reference model up to two times.
Question 2’s answer choices
Study the reference molecule above, when you click the Next button the picture will be replaced by four possible choices. Select the choice that is a mirror image to the reference molecule. You can go back and view the reference model up to two times.
Question 3’s answer choices
Study the reference molecule above, when you click the Next button the picture will be replaced by four possible choices. Select the choice that is a mirror image to the reference molecule. You can go back and view the reference model up to two times.
Question 4’s answer choices

Select the molecule below that is the mirror image to the reference image.

[Images of four molecular structures]
Thank you for taking this memory quiz. Close this window to continue with the WebAssign assignment.
Appendix III: Version III of the Visual-Spatial Chemistry Specific Assessment Tool
Visualspatialassessmet4 (1118633)

Current Score: 0/39

Description
An assessment tool meant to gauge eight different visual-spatial skills.

Instructions
The first two questions are category questions, answer these questions honestly. Answer each question only if you can see a picture associated with it. This assessment is meant to evaluate your visual-spatial skills. If a model kit is available, you may use it. Thank you very much for your help.

If you have any questions about this assessment please e-mail Caroline at cmchrist@ncsu.edu

1. 0/1 points[Required] [1332937]
   I affirm that I am cmchrist@ncsu. I give permission for my test scores to be used without my name attached to them, for research purposes only.
   
   [ ] I agree

2. 0/1 points[Required] [1332938]
   What is your gender?
   
   [ ] male
   [ ] female

   What is your ethnic background?
   
   [ ] African American/Black
   [ ] Asian American/Asian
   [ ] European American/Caucasian/White
   [ ] Latino American/Hispanic
   [ ] Native American/Alaskan Native/Pacific Islander
   [ ] Other

   What is your major?
   
   [ ] Chemistry
   [ ] All Engineering fields
   [ ] Biology and Biological fields
   [ ] Architecture
   [ ] Math / Statistics
   [ ] Other

   How old are you?
   
   [ ] Under 18
   [ ] 18-20
   [ ] 21-25
   [ ] Over 25

   What year are you in at NC State?
   
   [ ] First
   [ ] Second
   [ ] Third
   [ ] Fourth
   [ ] Past Fourth
   [ ] Graduate student

   How many semesters of chemistry have you taken?

http://www.webassign.net/v4cgcmchrist/ncsu/control.pl

Page 1 of 15
3. 0/1 points [Discrimination] {13329442}
In the next four questions, the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles.

Pick the number of the figure which is **unlike (different from) the reference object**. If all figures are like the reference object, choose 4.

- 1
- 2
- 3
- 4 All of these could be observed

4. 0/1 points [Discrimination] {13329451}
Pick the figure which is **unlike (different from) the reference object**. If all figures are like the reference object, choose 4.

- 1
- 2
5. 0/1 points Discrimination 132945
Pick the figure which is unlike (different from) the reference object.
If all figures are like the reference object, choose 4.

6. 0/1 points Discrimination 132946
Pick the figure which is unlike (different from) the reference object.
If all figures are like the reference object, choose 4.
7. 0/4 points Figureground [1332948]
The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are in the cube.

View atom letter K. Where is atom U in respect to atom K?
- [ ] above
- [ ] same level
- [ ] can't determine
- [ ] below

Atom letter S lies on the same outside vertical plane as atom letter E, Q, R, or T? [ ]
Atom letter M lies in the same horizontal plane as atom letter Q, R, S, or U? [ ]
Atom letter Q lies in the same vertical plane as atom letter H, P, R, or T? [ ]

8. 0/1 points orientation1 [1332950]
Use these axes for questions 8-10.

If the structure in diagram 1 were turned around the Y-axis in the direction that the axes show, which structure below matches after a rotation of 180 degrees?

Diagram 1

9. 0/1 points Orientation2 [1332952]

If the structure in diagram 1 were turned around the X-axis in the direction that the axes show, which structure below matches a rotation around the X-axis?

Diagram 1
10. If the structure in diagram 1 were turned **around the Z-axis** in the direction that the axes show, which structure below matches a rotation around the Z-axis?

![Diagram 1](http://www.acifhs.com)

11. Note: The X- and Y- axes are drawn in the plane of the paper. Imagine the Z-axis as being perpendicular to them, coming out of the screen.

Look at the following example question.
If this structure were reflected in the YZ-plane, the answer would be

Your question is:
Imagine you are standing in front of the structure in diagram 1. If the structure in diagram 1 were reflected in the YZ-plane which diagram below could represent the structure as seen after reflection?

Diagram 1

12. 0/1 point orientation.png [1332954]
Among the molecular representations below, choose the one you would get after reflecting molecule 1 in the mirror.

http://www.webassign.net/v4cgicmchrist@ncsu/control.pl
13. 0/1 pointsformperception1 [1332965]

The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram indicates that a bond projects behind the screen, and indicates that a bond projects out of the screen towards you. Atoms that are connected with straight lines indicate that the bond is on the plane of the screen.

Which atom number(s) is (are) furthest from your eyes?

14. 0/1 pointsformperception2 [1332968]

The diagram below is a representation of a molecule of n-butane.

The carbon atoms are labeled 1, 2, 3, 4. If you visualize the molecule from left to right which carbon atom number is closest to your eyes?

15. 0/1 pointsformperception3 [1333025]
The hydrogen atoms are labeled 1 thru 4. The hydrogen atom which is **furthest back from your eyes** is hydrogen atom number

16. 0/1 points[perception][1332970]
The diagrams below are representations of a molecule of isobutane.

Which hydrogen atom is **furthest from the hydrogen atom labeled "H"**?

17. 0/1 points[sequencing][1332971]
Glucose is a primary metabolite in living things, here is one of its structures.

How would you build this molecule from the top down using the following pieces?

- 2, 4, 5, 6, 4, 7
- 9, 1, 6, 4, 7
- 9, 6, 4, 7
- [2, 4, 6, 4, 7]

18. 0/1 points[sequencing][1332982]
Look at the following box.
19. 0/1 points (sequencing) [132988]
On the left are square pieces of paper that have been folded as shown by the dotted lines. (The dotted lines are where paper has been before the paper was folded.) A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the hole(s) when the paper is completely unfolded.

http://www.webassign.net/v4cgicmchrist@ncsu/control.pl
20. 0/1 points

Pick the figure that shows the position of the holes when the paper is completely unfolded.

![Diagram of a paper folding sequence with options A, B, C, D, and E.]

21. 0/1 points

Two different types of organic molecules are illustrated below: SPACE FILLING molecules and BALL-AND-STICK molecules. Space filling models more closely resemble the actual shape of the molecule as the electron clouds are represented. Ball-and-stick representations with elongated bond lengths show more clearly how one atom is connected to the next.

In the next four questions, you are provided with a ball-and-stick molecule. Set out below it are four diagrams of space-filling molecules. Pick the space-filling molecule that matches the ball-and-stick molecule.
22. 0/1 points constant [13330055]
Pick the space-filling molecule that matches the ball and stick molecule.

23. 0/1 points constant [1333007]
Pick the space-filling model that matches the ball-and-stick model.
24. 0/1 pointsconstant4 [1333008]
Pick the space-filling molecule that matches the ball-and-stick molecule.

http://www.webassign.net/v4cgcmchrist@ecsu/control.pl
26. 0/1 pointsassociation3 [1333011]
Consider a white sphere on the inside of this unit cell, how many other spheres will touch it? 6

27. 0/1 pointsassociation4 [1333014]
Use the following unit cell for this question.

How many cubes are inside and have no face visible on the outer surface? 1

28. 0/1 pointsonmemory question [1333018]
Directions: In the external site below, there will be memory questions where a reference image of a molecule will be shown. Study this reference image, because it will go away and four choices will come on the screen. The choices suggest how the molecule would appear when viewed from different angles. In each case, three of the four diagrams are of the same reference image, whereas one of the four diagrams is incorrect because it gives a mirror image of the reference image. Pick the one choice that is a mirror image to the reference molecule.
For example, and are mirror images. When you understand these directions - go to this external site to answer these questions. Please enter your name as it appears in webassign on the first page. Enter in the number of questions you answered: 4

29. 0/1 points model [1333019]
Did you use a model kit for this assessment?
  □ yes
  □ no

30. 0/1 points Opinion question [1333020]
Do you have any comments or concerns about this assessment?

Key: Answer

Assignment Details
Name: VisualSpatiaiassessmei (1191633)
Submissions Allowed: 2
Category: Extra credit
Code: locked: Yes
Author: christian TA, caroline
Last Saved: Feb 27, 2010 01:28 PM EST
Permission: Protected
Randomization: Person
Which graded: Last

Feedback Settings
Before due date: Question Score, Assignment Score, Publish Essay Scores, Question Part Score, Mark
After due date: Question Score, Assignment Score, Publish Essay Scores, Key, Question Part Score, HelpHints, Response, Save Work, Response

http://www.webassign.net/v4cgicmchrist@ncsu/control.pl
Appendix IV: Categorical data used to obtain p-values
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Appendix V: Directions for the think aloud study, which were read to the interviewees, and
the confidentiality agreement they were asked to sign
Hello

The purpose of this interview is to help me to better understand your thought process as you answer these questions. I don’t care whether you get the right answer or not. Do you understand?

Your performance on the assessment is not going to be discussed at all today, and if we do use your interview in a future research study you will not be identified by name. We are videotaping the interview today, but we do not have the camera pointed at your face. All we are interested in is your words and your hand motions when you are describing your thought processes. Do you understand this?

(Then will you sign this confidentiality agreement? This says that we will not use your name when we identify the data, and it also gives us permission to audio and/or video tape this session.)

I am going to give you a few questions. Read each item aloud as if you were taking the test for the first time, and talk aloud to yourself as you think about the problem. Please keep talking aloud while solving them until you produce an answer, as if I were not here. Feel free to use a pencil and paper or the white boards but please speak your thoughts, plans, purposes, anything to help me understand how you interpret the question and how you get to your answer. I care only about your thinking process and your methods. (Here are the directions to follow while doing the interview that I just explained.) Are you ready to begin?

If you want some water, here is a bottle just for you, and here are some implements to solve these problems, you can use whatever you like. Holly is here to control the camera, and to help me with an example problem. I am going to model with her, what I would like you to do.

As you can see, she asked me questions – which are perfectly legit, she also was confused at times, and I can ask her questions. But really my purpose here is to make sure that you keep on speaking your thoughts.

<table>
<thead>
<tr>
<th>The more you can verbalize your thoughts, the better for us.</th>
<th>Will you please verbalize what you are doing?</th>
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</thead>
<tbody>
<tr>
<td>Can you clarify your thoughts there?</td>
<td>What do you mean by ____?</td>
</tr>
<tr>
<td>Please keep speaking your thoughts</td>
<td>What are you thinking now?</td>
</tr>
</tbody>
</table>
Confidentiality agreement

I, [insert name], give permission to the researchers at North Carolina State University to audiotape and/or videotape record me while solving problems. I understand that the interviews may be transcribed and may have excerpts used in various publications and presentations; however, I also understand that I will not be identified by the researchers in the case of any public display or discussion of this data.

Printed name: __________________________________________________________

Signed: ________________________________________________________________
Date: ______________________
Appendix VI: All 20 interview transcripts listed in order by student number
Interview with student 1

1: The diagram below is an illustration of the structure of a diamond. Each lettered black, black dot represents an atom of carbon and all are within the cube. For each question, choose the one best response. View atom letter K. Where is atom letter U with respect to atom K? Um, I think there on the same, [pointing at atom U] they look like they're on the same, like, uh, horizontal line, so I think they're on the same level.

Christian: So why do you say same level again, I'm sorry?

1: What?

Christian: So why do you say same level again, I'm sorry, why do you say same level?

1: Same level, [points to the line inbetween them] because they're on the same horizontal line, so.

Christian: Okay, thank you.

1: Next one?

Christian: Okay.

1: Okay, if the structure in diagram A were rotated around Z-axis in the direction that the axis, axes show, which structure below matches a rotation around the Z-axis? Oh, diagram A, [points at diagram A] so then you're turning it sorta diagonally so.

Christian: So do you see which one is the Z-axis in my diagrams?

1: Yes, it, it's the, [points to the Z-axis picture] it's not, yeah, I can't think of the right word for it, so I think it would be b, [pointing to b] because it's not going, it's not rotating up or down, [holds pencil up and swings it back and forth] it's rotating kinda sidewayish, [holds pencil sideways and swings it back and forth] and diagonally, so.

Christian: Okay.

1: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects beyond, behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. The atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms is the, which atoms is are furthest from your eyes? Um, I think the hydrogen, ur, hydrogen 8 and hydrogen 5 [circling hydrogen 5 and 8] are the furthest because they're supposed to be going back, [uses pencil to indicate behind or away from her] so, yes, I think those are, those should be in the, um, behind the paper, so.

1: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eye? I think that, um, carbon atom.

Christian: Keep speaking your thoughts please.

1: I think that carbon atom would, the carbon atom closest would be d [pointing at d] because it, um, has 3 lines coming towards me, [uses pencil and swings it towards her] no, no, no, no I think it would be c, [points at c] because all, almost all of the lines are going back, [points pencil away from her, indicating back] so compared to the other ones it would
be forward. [points pencil towards her, indicating forward]

1: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? So, 1, 2, 3, 4, and 5 [pointing at the pieces], um, you'd use 5, 1, 3, 4, and 2 [writing the numbers as she said them] Or I guess 5, 2, 4, 3, and 1 would be the closest, [points to the correct spots on the box where the pieces go] because you're going clockwise, [swings pencil in a clockwise direction] and I went counterclockwise, [swings pencil in a counterclockwise direction] so, I think a.

1: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the, before, before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, it's on the dotted line, [pointing to the first reference paper fold] and that was where, okay so that was where, so the holes would be [pointing to where the hole was punched in diagram A] diagonal to each other [drawing a square with two circles where the holes should be] because it was folded at the corner. So it would be d.

1: Pick the figure that shows the positions of the holes when the paper is completely unfolded. So they folded it 1, 2, so they folded it 3 times [pointed to the different reference folds] and then punched it, so you'd have one right there, one where it starts, one on the other side, [drawing square with 2 circles at first at the place where it was punched, and then eventually the 4 holes get drawn in] and then, I think 2 more because, yes, because it, they folded it 3 times [uses hand to show a folding motion] so there would be 4 layers of the paper when they punched it so it would be a.

1: Two different types of models are illustrated below: Space-filling models and ball-and-stick models. In the next two questions, you are provided with ball and stick, with a ball and stick model of, of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space-filling model that matches the ball and stick model. So, it has 4 bonds, [pointing to the reference ball-and-stick structure] so they're like 5 different molecules, [uses hand to indicate 5] I believe it would be a because it just looks like it more, all the molecules look the same, or all the atoms look like their in the same part of the molecule, so I'd go with a.

1: Two different types of models are illustrated below: Space-filling models and ball-and-stick models. Pick the space filling model that matches the ball and stick model. Um, so, there are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, [pointing to and counting the atoms] 14 um, [writing 14] 14 atoms in the molecule, so and most of them are on this side, [points to the left side of the ball-and-stick reference structure] so I, or, hum it's either a [points at a] because it has the most or it's either d because it has them in the right spot. [points at d, and traces the molecules] So, I'm going to go with d, because it looks like they're in the right spot, because I can't tell with a, so.
1: This unit cell is represented by spheres. How many spheres are in this structure? Do I need to tell in all, [points to top of structure] or the ones I can see?  
Christian: Well, all of them.
1: Okay, so, 1, 2, 3, 4, on that side, 1, 2, 3, on that side. [draws lines above the atoms on the top back row and right side] [sneezes]  
Christian: Bless you
1: Thank you, so they're be 12 on each face, [writes 12] and there are 1, 2, 3, 4, 5, 6 faces, [points to each side] so there'll be 72 spheres, [writes 72] except than they'll in the middle, so I believe there are 2 in the middle, so I think it would be 74 [writes 74] spheres in all, yes, I think that's it.

Christian: Last question, I want you to read through this list of skills silently to yourself, I'm going to give you a couple questions back, and I want you to match the skills you think you used to solve the questions with.
1: Okay.
Christian: Okay, so let me give you a couple of these questions back [pause while reading]  
1: So I need to  
Christian: What I want you to do, is here are a couple of the questions back, and I want you to write on the question any skills you think you used to solve the question with.
1: Okay  
Christian: Okay  
1: So, and do you want me to say it out loud?  
Christian: Yea, and explain the reasoning about why you think you used the skill to solve the question as well.

1: [Looking at the diamond question] Okay. I think this first one would be figure ground first of all, because, um, [writing off camera] you have to look at the, where they are and distinguish it from the background, [pointing to the diamond structure] and the picture. So I think it would be figure ground, and form perception, [writing off camera] because you're looking at a 2-D representation of a molecule or, a, diamond. So I think it would be form perception, and discrimination, because you're having to look at the picture, [writing off camera] and then, um, figure out which one, or how they are the same, so I think that's all for the first one.

1: [Box question] This one, I think it is um, sequencing, [writing off camera] because you're
having to, um, put the pieces together in a particular order, um, and, form perception, [writing off camera] so.

Christian: Why form perception again, I'm sorry?
1: Um, form perception, oh, yeah, form perception because you're looking at a 2-D representation of a box, and having to put it together with the pieces [pointing at the box and the pieces] that they give you, so.

1: [1st Unit cell question] And then this one, I think is, um, form perception, [writes form perception] and then, discrimination [writes discrimination] because you're counting how many they are. And I think it's form perception, because you're looking at a 2-D model of a 3-D object.
Interview with student 2

2: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K [points at atom K]. And where is atom U with respect to K? [points at atom U]. So, um, I'm going to say. [points to atom U and k at the same time]

Christian: Keep speaking your thoughts please.

2: It looks kinda above, but it looks almost on the same level. I'm gonna say it's not on the line, so I'm going to say it's above.

Christian: And how'd you get above again?

2: Cause this, K is on the line, [pointing to the line K is on] and U doesn't look like it's on the line, [points to U and the lines around U] it looks like it's a little bit above it. So should I do I circle it?

Christian: Circle it.

2: Okay.

2: If the structure in diagram A were rotated around the Z-axis in the direction that the axes shows, which structure below matches a rotation around the Z-axis?

Turning around the Z-axis, [points to the words "Turning around the Z-axis, and also pointing to choice a] Oh, so, [points to the diagram A], it would be turned on it's

Christian: Keep speaking your thoughts please.

2: Oh, I don't know [uses hands to indicate the position of the molecule], to rotate it diagonally. [points to the z-axis rotation diagram and also diagram A again] I think it would be on it's side, [points to choice b, and uses hands to indicate on the paper a rotation around the z-axis] so I'm going to say b.

Christian: Why do you say b again?

2: Cause, [points again at the z-axis rotation diagram] it's not being rotated, [points to choice d, and then back to diagram A] it's not being flipped up [points to choice c], and it's not being turned [points to choice d], so I think it's being, [uses hands to indicate a rotation as shown in choice b] yeah, that's my guess.

Christian: I'm sorry, you think it's being what?

2: I think it just turning, [uses hands to indicate a rotation] it's not gonna like, make a complete like 90 degree, [uses hands on paper to indicate a 90 degree turn] or go up or down, [uses hands to indicate going up or down] it's going, [again uses hands to indicate a rotation as shown in choice b] turn on it's side.

Christian: Thank you.

2: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the place of the paper. Which atoms, which atom is furthest from your eyes? Well, I don't think it's the bold [points to the two bold atoms] because that's pointing out towards you, and I think it has to be one of these, [points to the two hashed
atoms] one of the hashed, because that's supposed to be behind it, and [points to atom 8] this H is farthest away so 8, wait, yep, can I just circle?
Christian: Sure. [circles the number 8]

2: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? [pause]
Christian: Keep speaking your thoughts.
2: Okay, from left to right, [mumbling under breath].
Christian: Keep speaking your thoughts.
2: They all seem the, like the.
Christian: So the notation of this question, is the same as the notation of the last question.
2: Oh, okay
Christian: The hashed wedge is
2: Oh, the hashed wedge is away from you, and the bold.
Christian: And the bold are behind the paper, um, hum, um hum.
2: Um, then I'm going to say d because it has the most bold, which would be the most toward you, [uses hand and waves it towards herself] cause it has three, [points to choice d] and this one has 2 [points to choice c], and well that one has 3 too [points to choice b without lifting hand] Never mind I'm going to say b.
Christian: Why b?
2: Because it's a, I don't know, the bigger bond, [points to the bond between a and b] I don't know, it's longer, and this one's shorter, [points to the bonds between c and d, and a and b at the same time] so b.

2: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides, what is the order that you could build the sides from the following piece. If you ignore the top and bottom, [pause]
Christian: Keep speaking your thoughts.
2: Is, is this the top and bottom? [points to top and bottom of the box]
Christian: Yeah.
2: Like these two? [points again to the top and bottom of the box]
Christian: Yes, yes, of the box.
2: Oh, I was seeing it wrong, so [points to side 5]
Christian: So what do you mean you were seeing it wrong?
2: I'm just keep seeing it different ways, the box, like, it's confusing me [laughs], um, 5 is the back, [points to side 5 again] and then, 2, 3, and 4 are the front, [points to sides 3 and 4] so, [mumbling] 5, [points to side 5 again] 2, [points to side 2] 4, [points to side 4] 3, [points to side 3 again] 1, [points to side 1] so 5, 2, 4, 3, 1, so a.
Christian: How did you get a again?
2: Um, I started at the back with 5, [points to the back of the box] and then worked around [uses hands to indicate a circle - around the box] so, wait, yeah.

2: On the left are square pieces of paper that have been folded as shown by the dotted lines.
The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. So there'd be one here and here [pointing to the picture A folding diagram and drawing on picture A another hole in the lower left hand corner], when the paper unfolded, so d.

Christian: How, how'd you know that?

2: Cause if you fold it back down, [using hands to indicate a fold] it's going to be in the corner [points at picture A again] where it was cause you're going through both, [using fingers to indicate a punch] so.

2: Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, so, here's the, [points to the paper folding diagrams] I'm just gonna like, there's going to be one here, [draws on picture A a hole on the bottom of the fold] cause that comes from that fold, and then you fold it back over, [points to the first paper folding diagram, and uses hands to indicate a fold] it's going be on both in the same spot [draws on picture A the other two holes on the top and left of the fold], so yeah, so a.

Christian: How you'd get a?

2: Cause when you fold, when you fold this one back over, there's going to be one here, [points to the third paper folding diagram] and then and when you fold the whole thing over, [uses finger to indicate the same fold] it's going to be in the same spots as the other two, yeah, yeah.

2: Two black or two different types of molecules are illustrated below: space-filling molecules and ball-and-stick molecules. In the next two questions you are provided with a ball and stick molecule. Set out below it are four diagrams of space-filling molecules. Pick the space-filling molecule that matches the ball and stick molecule. So, there's one on top, and three on the sides, [points to the outer atoms on the reference ball-and-stick molecule] so it's not b, [points at choice b] because that doesn't match this, [points at reference structure] and it's not d, [points at choice d] cause they're not, so c or a, [points to choice a] and I think it's a, because this one looks like it has like a space, [points to the top of choice c] over here, when they should be equally spaced around the, around the middle, [points to the top of choice a] so a.

2: Two different types of models are illustrated below: space-filling models and ball-and-stick models. Pick the space filling model that matches the ball and stick model. Whoa [laughs]

Christian: You'll get it.

2: This ones hard, um, okay, ah, so there's four up top, and 4 on the bottom with one in the middle, [points at the different aspects of the reference structure and points at choice d] and then there's 2, 1 on each of the outside, [pointing and counting the outside atoms on the reference structure] that's not right [pointing to choice a], and that one doesn't have enough [pointing to choice b], and this one doesn't have the ones on the outside of the box, [pointing to choice c] like these [pointing to the ones on the outside of the reference structure again], so
I would say d.
Christian: Why did you say d again?
2: Cause it has 4 on the corners [points to choice d's top] on top and bottom, [points and counts the top and bottom of the references structure's atoms] then it has one in the center on each of the sides, [pointing to the ones on the outside of the reference structure again] which is what this one shows [pointing to choice d], I think, yeah.

2: This unit cell is represented by spheres, how many spheres are in this structure? Is this talking about just the ones like I can, [pointing to the figure] can tell are spheres or?
Christian: How many are there total in the structure.
2: Okay, so, there's 4 and 3 and then 3 going down, [drawing marks in the top front row, the side right row, and in the right column] so this means there's 12 in each row, [points at the front face] and there's 3 rows, [points at the 3 rows going back] so 12, 36, yeah [mumbling 12, 24, 36] yeah.

2: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will it touch? Um, so, this, [pointing to the middle of the structure] it would be touching this one to the left and right, [pointing to two spheres on either side of the dark spot] up and down, [pointing to the ones on top and bottom] so 4, then it would have 4 more on the other side of it, [using hands to indicate different layers] there's another layer in front of this, [pointing at the diagram, indicating in front of the front face] so 8.

Christian: So the last question, I have, there is a 8 list of skills there, I want you to read through the skills, and ah, to yourself, and then I want you to identify the skills that you think you used to when you solved the questions, okay.
2: Oh these ones? [pointing to the list of skills].
Christian: Yeah.
2: Okay.
Christian: Read these to yourself, and I'm going to give you a couple of the questions back. [pause while reading skills]
2: Am I supposed to just read them?
Christian: So what I want you to do is write on the question, any skill you think you used to solve the question with.
2: Okay.
Christian: Write on the questions themselves.
2: Out of these, what I used?
Christian: Right, what you used to solve it with.
2: Okay. Um, [looking at the space-filling with methane] so, so it's discrimination, and orientation kind of I guess.
Christian: Can you explain why you picked the skills you did for the question.
2: Discrimination because I look at all of them, and I pick out which one I don't think it could be, based on how I think it should look.
Christian: Can you write on the questions, the skills you think.
2: You want me to write?
Christian: Ah, hum. [writes off screen]
2: Do you want me to write why?
Christian: No, that's okay, you also said orientation, why did you say orientation as well?
2: Oh, Orientation? [writing off screen] Because I turn them around to see if they look the way they should to me, like this one I didn't think, because if you turned it around there would be a missing space, [using hands to indicate a rotation] and I think that's it.

2: And this one [the box question], orientation, cause that was confusing me [laughs and writes orientation]
Christian: So how to rotate the box, or how to see the box?
2: Yeah, I kept seeing it in different ways, so, and then, and then figure ground, because I had to find where the back was, where I had to, I don't know, that might not be the same thing I'm thinking, [mumbling] seeing the background.
Christian: What were you thinking?
2: I just didn't know, like, trying to figure out which was the back, and then trying to see which, where the sides, based on which part I thought the back was on it, so. [writing off screen] And seeing things in a particular order, because I had to see the sides, [writing off screen] and so sequencing.

Christian: Okay, last question.
2: And this one [orientation question] I had to rotate, so, I had to put it up in the axis so orientation, [writing off camera] and um, then I had to interpret it because it's a figure so form perception, [writing off camera] I guess.
Interview with student 3

3: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the best response. So each lettered black dot represents an atom of carbon. View atom letter K. Where is atom U with respect to atom K? Okay, so within the cube, K looks like it is on a corner. Okay so R is on the face. So, L, U, R, and S are faces. Hum, I want to say it is um, it's above.

Christian: okay.
3: Do I go on to the next one?
Christian: That's fine

3: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? So, Z.
3: Okay, hum, and can I build it and everything?
Christian: To build this one, see the one with the yellow, with the gold rod, right there?
3: This one?
Christian: No, the one with the yellow balls,
3: Oh, okay
Christian: yeah, that one.
3: Okay, so, [holding the model in her hand upright],
Christian: Keep speaking your thoughts.
3: Hum, okay, I was just trying to think. If it started, like this was the, the Y-axis, and so, if it was rotated over the Y-axis [drawing a coordinate system showing the X and Y-axes] Which quadrant does it matter in? Does it matter?
Christian: It doesn't really matter I guess, I don't really know
3: Okay, well, I'm going to say it's b, just because, like, the Z-axis is a tilt. [draws the z-axis line into her coordinate system] And that is the only one here, that I see is tilted, or that's tilted.
Christian: Okay.

3: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that, the bond, that a bond protects behind the paper, and bold wedge indicates that the bond protects, projects excuse me, out of the paper towards you. Atoms connected with the straight line indicate that the bond is in the plane of the
paper. Okay, which atoms are furthest from your eyes? So if these are going, [circling the atoms and bonds with the hashed wedges] um, away from you, behind the paper, [waves hands to indicate away from her] then they are going to be the furthest away from my eyes. So the Carbon to hydrogen bonds [writes C-H] are going to be the furthest away, so, and these are all in the planes, [draws lines through the straight lines] and these are coming towards me, [drawing lines through the bold wedges] so these are definitely out, so it'd be 2 to 5 and then 1 and 8 [writing them, while saying them].

3: The diagram below is a representation of a module, of a molecule of n-butane.
Christian: n-butane.
3: Oh, okay, butane, [laughs] If you visualize the molecule from left to right, [draws an arrow from left to right] which carbon atom in the drawing is closest to your eyes? So if dashed is behind the plane, and bold is, um, towards you, [writes "dashed behind the plane", and "bold towards"] and then there are no straight lines, so. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? So, okay, so, we're focusing on the carbon atoms. [circles the 4 carbon atoms] So on this one the hydrogens, [points to carbon a] the carbon is going to be, [tries to use hands to indicate a raise in height] I wanna say it'd be raised up, since, um. If its, um, if the wider side of the, um, [circles the wide side of the bold wedge connecting carbon atom a to the hydrogen on the left of it] of like the triangle, [draws a triangle] whatever, is towards the hydrogen, does that mean the hydrogen is farther up? [waves fingers to indicate going up]
Christian: Yes [mumbling] The broader side is raised up.
3: Okay, the broader side is raised up, okay so, so that means that b is a possibility, [crosses out a] and [pause].
Christian: Keep speaking your thoughts.
3: Oh, okay [laughs] um, I'm trying to think, because all of them have um, a dashed line and a broad line connected to them. [points at the lines connected carbons b, c, and d and the hydrogens below them] With the, well it looks like the more narrow edge is with c. [crosses c out] And, um, so this, this carbon is going to be raised up, [points to carbon b] but the hydrogens are going to be above that, this carbon is raised up as well, [points to carbon d] and these hydrogens are going to be above that, but this one has just this hydrogen below it, [uses hand to indicate below] I don't know if it would matter too much, so I'm going to pick b.

3: Look at the following box. If you ignore the top and the bottom of the box, what is the order that you would have to build the sides from the following pieces? Hum, okay, if you ignore the top and the bottom of the box [crosses out the top and bottom of the box], what is the order that you would, that you would build the sides from the following pieces. Um, well you would need to put, um, the order. Okay, so I would number this 1, [writes 1 on the right side] number this one 5, [writes 5 on the back wall] number this one 2, [writes 2 on the left side] and, um, number this one, this side 3, and this side 4 [writes 3 on the left front of the side of the box, and traces this pattern on the box and writes 4 on the left front side]. So there's the 1, 4, 3, 2, 5.
3: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where the paper has been before, the dotted lines are where the paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, on the left are square pieces of paper that have been folded as shown by the dotted lines. A hole has been punched in the paper as indicated in picture A, [circles picture A] for each question. Pick the figure that shows the positions of the holes, so that means there's more than one, so c is out [crosses c out, because it only has one hole], when the paper is completely unfolded. So it was only folded once, [points and draws another hole on picture A] a hole was punched there, and then when you fold it back, it's going to be at the corner, [circles choice d, and points again to picture A] and I guess kinda mid center [circled holes on choice d].

3: Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, it was here, [points at the first paper folding figure] and it was folded over, [draws a line through the fold] hum, over that X- or Z-axis or whatever that weird.


Christian: Yeah, they'll come in handy big time.

3: Okay, so it was folded over once, [draws a line through the fold on the second hole punch figure] and can I like, can I fold these piece of paper.

Christian: Sure, that's fine.

3: So it was folded over once, it looks like [starts folding the piece of paper that the question is on] and then.

Christian: [mumbling - hands the interviewee another piece of paper].

3: Can I just go ahead and tear it.

Christian: Sure.

3: [starts tracing the box on the piece of paper, and then starts tearing it to make it a square]. Okay, so it was folded over the, and then it was folded again, and then a hole was punched, so the hole would go all the way through. So there are 4 holes at each of the folding points right there, [tracing the lines of the paper and notating the holes on the physical model] so it would be a.

3: Two different types of, of models are illustrated below: space-filling models and ball and stick models. In the next two questions, you are provided with a ball-and-stick model of a molecule. Set out below are the four diagrams of face, of face-filling models of that molecule, okay. Pick the space-filling model that matches the ball and stick model. Okay, so are, so the gray is the, [drawing on the gray space in choice b] is the space?

Christian: Ah, hum.

3: Okay, so you have 1, 2, 3, 4. [drawing on the four atoms of the reference ball-and-stick
molecule] and then this one is projected at me, and there's 3 in the background [points at the 4 atoms on the reference ball-and-stick molecule] so this doesn't look like it would be one, nor does this [crosses out b and d]. And I guess if you were to take and look at this gray portion, [draws on central atom on the reference ball-and-stick structure] and just kinda blow it up, [uses hands to indicate the atom getting bigger] um, it would look like a, well a and c look similar, it's just, you can't [points and draws on the top atom of choice c] it's like the, um, the molecules in a are, [points and draws on the top atom of choice a] um, are consumed more by like, the space. Okay, In the next two questions, you are provided with a ball-and-stick model of a molecule. Set out are four diagrams of space-filling molecules that pick that. So really I guess, like all the space you need is right here, [drawing on the ball and stick reference object] so I guess you would expect, the, um, these molecules to stick out more than those. [pointing at choice c] and that has the one coming out, and the 3 in the background so I'm going to say c.

Christian: Okay.

3: Two different types of models are illustrated below: space-filling models and ball and stick models. Place pick the space-filling model that matches the ball and stick model. Hum, okay, okay, so, this, is, it has corners, [circles on corner atom on the reference ball-and-stick structure, and writes corners at the bottom] faces, [writes faces at the bottom] it has no center, it has, it has all the corners, and all the faces, [points at the reference structure] but no center so, so b is out [crosses out choice b and circles it's center atom] because it has a center right there, and c is out because it has a center [crosses out choice c] Um, this one it has the corners, [drawing on choice d] and then the one behind it, one face behind it, 2, 3, 4, 5, 6, faces, so the 6 faces [writes the faces as numbers on choice d without lifting hand from paper]. Um, this one here, [points to choice a] I not quite sure what this is, this, this looks a lot more complex than the ball-and-stick model that there were, that's up here. [points back at the reference structure] So I'm going to go with d.

3: This unit cell is represented by spheres. How many spheres are in the structure? Okay, so there are 1, 2, 3, 4, [draws on some of the atoms] oops, 1, 2, 3, 4, 5, 7, 8, [counts the atoms by pointing to them] okay, so there are 8 corners. [writes 8 corners below the question]
Christian: I actually meant how many whole spheres were in the structure.
3: Oh, so, not ownership.
Christian: Not ownership, I meant how many whole spheres are in the picture, I guess I should say.
3: So just count the spheres?
Christian: Count the spheres, yeah.
3: Okay, 1, 2, 3, 4, [counts some silently] 9, 10, 11, 12, [points and counts the spheres on the top of the structure and writes 12] 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24. [continues counting, and writes 24] Are there, just how many you can see, or?
Christian: No, [mumbles].
3: Oh how many are in the structure, I get it, okay, so if there are 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12. [counts the top atoms again] if there 12 on each plane and there are 3 planes [draws a
line through one of the planes] 12 times 3, [writes 12 x 3] 12, 24, 36, so 36 spheres.

3: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? Okay, so a sphere on the inside, so that means that none of these are going to touch it, [crosses out the ones on the top], and wow, um, okay, so, these are definitely not going to touch them, [crosses out the atoms on the sides and top] and these are definitely not going to touch the spheres, [crosses out the atoms on the bottom sides] hum, and so it might just be the two at the top, [points to and draws on the top face of the structure] and the two at the bottom, so just 4, so I'd just guess 4.

Christian: Okay, so for the last question, I have a list of skills, 8 skills, read them to yourself, and I'm going to give you a couple of the questions back, and I want you to match the skills to the questions I'm going to give you.

3: Okay.

Christian: But you can read them to yourself, though. [pause while reading] 3: Okay.

Christian: So write on the question, any skill, any skills you think you used to solve the questions with, so write on the question itself 3: Okay.

Christian: Make sense?

3: Yeah, um, hum distinguishing objects from their background, interpret 2-dimensionals, okay, so form perception [writes form perception on the space-filling with the methane molecule], um, relate concepts which are shown in pictures and written words, [writes association], perceive dominant features, distinguish objects from their backgrounds, [points to the choices again] so this is their background [writes figure ground]

3: So this one again was form perception [writes form perception on the n-butane question], um, order, probably sequencing, because you have to determine that. [writes sequencing]

3: Hum, that's again form [writing form perception on the diamond question], figure-ground, [writes figure ground] okay.
Interview with student 4

4: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose one best response. View atom letter K. Where is atom U with respect to atom K? I would say atom U is on the like the same level. Do I need to say why?
Christian: Why?
4: It just looks like it, I mean it's like, like common sense. You got this line right here [pointing to the line that atom K is on], three-dimensional shape, [uses hands to indicate a cube] it just looks on the same level.
Christian: Okay
4: So do I circle c?
Christian: Circle c, yeah.

4: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? [pause, points to picture A]
Christian: Keep speaking your thoughts.
4: Well this one is turning around like the Y-axis [pointing to the Y-axis rotation picture] so it wouldn't be that one, this one's the X-axis [pointing to X-axis picture], and that ones the Z-axis [pointing to Z-axis picture].
Christian: You got that right.
4: So,
Christian: Do you understand which one is diagram A?
4: This is diagram A [points to diagram A]
Christian: Uh, hum. [points to all the choices]
4: I would say b, cause
Christian: Why would you say b?
4: It just looks like an educated guess kinda, cause it's sitting like this, [uses pen to point away from himself] that looks like it's going to be the, [waves pen back and forth] ah, a looks like it's going to be the X-axis, [points to choice a and then the x-axis] d looks kinda the same as a, [points to choice d] b looks really good, and then c looks like, um, it's rotating around the Y-axis, so I would say b.
Christian: Okay, thank you [hands me question]

4: The diagram below is a stoich, stoichiometrical, big word there.
Christian: stereochemical
4: stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atom is are furthest from your eyes? Well, um, it's not going to be number 4, [points to atom 4] cause that's like pointing towards me on the paper, [uses pen to indicate pointing towards himself] 3's on the paper, [points at 3] so it's not going to be
that one, [crosses out 4 and 3] so is 2, [crosses out 2] 5 is a good choice [points at 5] but 8 would be further away, so it'd be either 8 or 6.

Christian: Okay
4: And I would just, probably 6, because it just looks further, cause you have to go to 7 [points to atom 7] to get to 6, and that would be further in my opinion.

Christian: Okay
4: So just circle 6.
Christian: Okay.

4: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? Which carbon atom, so, from left to right, well that ones on the paper [points to carbon a], that ones in front of me [uses hands to indicate above the paper], that one puts it back [points to some of the other atoms], which is that one would be on back on the paper I guess? No, that one would be behind the paper? And then d would be in front of me, so I would say c, carbon c.

Christian: Why did you say c again?
4: Cause, I don't know, a, if a is on the paper, [points at a again] and then you have c carbon which is coming out of the paper at you, [uses hands to indicate coming out of the paper] it's going to be right here, and then b if that's on the back, [uses hands to indicate behind the paper] then wouldn't that be on the paper? I don't know, I'd just say c, just kind of like, more of a guess.

4: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? What? Um...

Christian: Here is a little box [handing him the small box]
4: Oh the box, okay, I guess 5 is going to be that. [points to side 5 and then to the back of the box] Oh I see what it is asking.

Christian: What did you think it was asking you before?
4: I didn't understand at all, I wasn't paying attention to that. [points at the box] If you ignore the top and bottom of the box what is the order that you could build the sides from the following pieces. Well I mean you could take like, 5. 1. I do, like, 5, [points at side 5] 2, [points at side 2] 1, [points to side 1] that's 5, [points to the back of the box] and that's 2, [points to the right side of the box] 4, 3, 1. [points to pieces 4, 3, and 1 while saying them] 5, 2, 4, 3, 1 so it'd be a. Cause, I started in the back, [points at the back of the box] worked that way, [points at the right side of the box] which is 2, [points at side 2] than 4's [points at side 4] right there, [points to the side that 4 occupies on the box] then 3 [points to side 3] is right here, [points to the side that 3 occupies on the box] and then 1's [points to side 1] right there [pointing to the left side of the box].

4: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been
punched in the paper as indicated in picture A for each question. Pick the figure that shows the position of the holes when the paper is completely folded.

Christian: Unfolded
4: Completely unfolded?
Christian: Uh, hum. [pause] [points at the first hole punch figure] Keep speaking your thoughts.

4: Well that was where it was before it was folded, [points again at the first hole punch figure] a hole has been punched in the paper as indicated in picture A, [points at picture A] pick the figure that shows the positions of the holes, okay, so it'd be d.

Christian: Why would it be d?

4: Well, if you punched a hole, [points at picture A again] a hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper. Well if punch it, in A it's going to go through, [indicates with hands a hole being punched] through it, [pointing back at picture A] and then when you unfold it you're going to have a hole where a is here, [points at choice d] and then where it's unfolded like right there, [points at picture A again and draws the other hole in picture A] so it'd be d.

Christian: Okay.
4: Pretty tricky questions, Caroline

4: Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, [points to the first hole punch picture] this is that line of the paper, [points to the second hole punch figure] you fold it there, [points and traces the second and third hole punch figures lines] punch the hole, and then you're going to unfold that there, so there's going to be a hole here, and then when you unfold it there's going to be a hole here and here, [drawing on figure A the positions of the other holes] so it's going to be a.

4: Two different types of models are illustrated below: space-filling models and ball-and-stick models. In the next two questions, you are provided with a ball and stick model for a molecule. Set out below are four diagrams of space-filling models of that molecule. Pick the space-filling model that matches the ball and stick model. Do I have to use these? [indicating the model kit]

Christian: You can use whatever.
4: Okay, um, well, it's kinda, it's not going to be this one, it's not going to be b, [crosses out b] just because b is not right, it's not going to be d, [crosses out d] so it's either a or c. I would pick c because a [pointing to choice a and then to the reference ball-and-stick object] just the middle one is like, [indicating with hands a triangle] not the same shape as a circle. C looks like it's possible.

4: Two different types of models are illustrated below: space-filling models and ball-and-stick models. Pick the space-filling model that matches the ball-and-stick model. So up here, you have to have 5, [pointing to the top of the ball-and-stick reference object] because you have like 1, 2, 3, 4, 5 at the top. [counts the top atoms and points to them] And
that's four, so that's not going to be it [crossing out choice b] and then that ones' just really weird, so it's not going to be it [crossing out choice c]. So it's between a and d right now, and a, [points back at the reference object again] a looks really deformed, [crosses out choice a] and d is right, it has 5, and there's the ones on the side, and on the bottoms. [points to both the reference and choice d to show that they match each other] So it's d.

4: 10, This unit cell is represented by spheres. How many spheres are in this structure? Um, are in the structure so it's talking about the black ones? Christian: The white ones are the spheres. 4: Okay, are in the structure, so how many are in it, and not on the edge? Edges don't count? Um, it just going to be 1, 2, 3, just gonna be, I have no idea. This is a tough one, 3, 4, 5, 6, I'd say 12, just cause it looks like they can fit one in each hole [points to a top dimple] and there's 1, 2, 3, 4, 5, 6 [counting the top dimples in the structure] on the top, and 6 on the bottom. 6 and 6 is 12.

4: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? Well if you have a sphere on the inside, if there's like one under here, [point to a top dimple] that's like 1, 2, 3, 4, [counting the ones below it] and then there's going to be 4 on the bottom [uses fingers to indicate 4] and that be it right, just 8.

Christian: The last question, is a list of skills, there are 8 skills there, read them to yourself, and I'm going to give you a couple of questions back and I want you to match the skills you think match the question. Okay? 4: So like association? Christian: You don't have to read them, you can read them to yourself. 4: Okay, [pause while reading] Okay. Christian: So basically, here are the questions, and I want you to write on these questions, any skills you think you used to solve the questions. So just write, does that make sense? 4: So I would write association, just write it. Christian: Yes, yes. Whatever you think you used to solve the question with. 4: [writes association on the hole punch question and then writes orientation]. Christian: So why association? 4: Association is says relate concepts which are shown in pictures and written words, well this is just a picture, like I can associate, and just like, orientation, since there was a hole there, [points at picture A] I knew there was going to be, like, a hole there and there, so, go to the next one? Christian: Sure.

4: Um, [the box question], I would say like association, because there was a picture, and um just, I could relate the concepts. like once I figured out there was a box there, [points at the box] um, constancy because I mean 3 and 4, 3 is obviously that, and 4 is, so it had to be, [points at sides 3 and 4] like next to each other. Um, and orientation cause I mean you had to build the box a certain way, I guess.
4: And, um, [the n-butane question], definitely figure-ground, because I mean the question before that was saying that some are sticking out of the paper, [uses pen to indicate sticking out and behind the paper] and some are behind it. [writes figure-ground] Um, and form perception, [writes form perception] because it is a 2-dimensional thing trying to represent a 3-dimensional object, and I guess orientation, because you know you had a central carbon atom, [uses hands to indicate a central atom and then waves hands around in indicate the other constituents] and then you had all this stuff coming off of it. [writes orientation]
5: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon are all are within the cube. For each question choose the one, the one best response. View atom letter K. Where is atom U with respect to atom K? Above, below, same level or can't determine. Um, well they look there in the same cube, [points to the outside of the cube] they look like their on the face of that cube, but there, [points at atom K] K looks like it is slightly below U, so below.

5: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Okay, diagram A, so, in terms of the Z-axis, [uses one hand to indicate a rotation] okay, well, that'd be b, because it is the only one that's rotating that way. Christian: I'm sorry, why did you pick b again?
5: Because like, well the X-axis is going horizontal, [uses pencil to show this axis] and Y-axis is going vertical, [uses pencil to show a straight up and down y-axis] and the Z-axis runs through both of those. [uses pencil to show the z-axis] And a looks like, it looks like it's been rotated across the Y and the X, [waves pencil to show a rotation around both axes] and b looks like it was just turned along the Z [uses pencil to show a z-axis rotation] which would make it seem most obvious for the answer.

5: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram the hashed wedge indicates that a bond projects behind the paper, and the bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atom or atoms are the furthest from your eye? Okay, um, atoms connected with straight lines are on the paper, well then if the hashed wedge indicates that its behind the paper, [uses one hand to indicate behind the paper] and the bold one says it's toward you, [waves hand to indicate towards himself] then, the bold ones would obviously be closer, and the hashed ones would be farther away. So, then it would be obvious that the two hashed ones would be the right answer, [writes 5, 8] because if they are behind the paper, they are the farthest from you, cause the straight lines are on the paper.

5: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom is in the drawing is the closest to your eyes? Um, if you visualize it from, from left to right, [uses pencil to indicate a left to right direction] closest to your eyes, that would be a, because if you're going from left to right, then or, do the same, do the same rules apply as the hashed? [points to the structure] Christian: Um hum. 5: Oh, okay well then.. Christian: [mumbling] 5: Okay, well then it would be b then, because they are all, they're all bolded so they'd all be in front.
Christian: I'm sorry, what do you mean by they'd all be in front, I'm sorry?

5: Like when it said that the bolded slash were uh, well that one said it was through the paper, which would make it closer to you, [uses hand to indicate closer to himself] and the hashed would be farther away, [uses hand to indicate farther away] and the b atom has three bolded and only one slash, [points to the b atom in the structure] and if you are going from left to right, b is the second letter, and it has the most bolded, so it would be the one closest to you.

5: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Okay, um, if you go 1, wait, in order, [pointing to side 5] so you could go 5, 2, [points to side 3 without lifting hand] and then, 4, 3, 1, [points to sides 4, 3, and 1] so a, because if you built em like out of that order, then the walls wouldn't be able to stand because they wouldn't have anything to touch.

5: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes where the, when the paper is completely unfolded. Okay, well the bottom corner was folded up, [uses pencil and moves it from horizontal to straight up to indicate a fold up] and then the hole was punched, closer to the middle, so, once it's unfolded [moves pencil down to indicate a unfold] it punched through both pieces of paper, so it would be closer to the middle and in the bottom corner that was folded [circles d].

5: Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, it was folded diagonally in half, [twists pencil to indicate a fold] and then in half again [turns hand over to indicate another fold] to make a small triangle, and punched [taps pencil to paper to indicate a hole punch] closest to the middle, so since it was folded twice, that would be four equal pieces times one hole [taps pencil a few more times to indicate 4 holes] would be four holes, and since it was located, like in the middle of the one of the sides, [twists hand again] but more towards like the middle of the actual square, [points at diagram A] then it'd be a when it was unfolded.

5: Two different types of models are illustrated below: space-filling models and ball and stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set it out, no, set out below it are four diagrams of space filling molecules of that molecule. Pick the space filling molecule that matches the ball and stick molecule. Um, well, I'm guessing that basically the space filling is the same molecule, just without the sticks, and there's one, there's a darker central one, [points to the central atom] with four, like outer atoms, [points to the four outer atoms in the ball-and-stick reference structure] I guess, in the molecule, [spreads fingers apart wide, to indicate a spread apart molecule] so it would be a. Christian: I'm sorry, why did you pick a again?

5: Because like, um, I figure with the space filling molecules and the ball and stick molecules are basically the same, just minus the stick, [points and waves pencil at the sticks
in the ball-and-stick reference object] like the space ones would just be the actual like, atoms touching, [draws fingers together to indicate atoms touching] instead of being separated by the stick, [points and waves pencil at the stick again] and there was a darker one in the center, [points to the central atom] with, hum, interesting. 2 of these could be the same, I guess, but then it had four outer atoms, [points at 4 outer atoms on the ball-and-stick reference structure] three towards the side, and 1 directly on top of it. [uses hand to indicate a spread out molecule] But two of these look like they could be it, [points to a and c] like in the same position, so I just picked a because it looked like it's closer and in the same formation as the model.

5: Two different types of models are illustrated below: space filling models and ball and stick models. Please, pick the space filling model that matches the ball and stick model. Oh, Lord, um, this one, it looks like one of the ah, I forgot what it's called, where it's, it's like the face of the cube is taken up, [points to the front face of the ball-and-stick reference structure] so, it's got, on each face of the cube it's got five, [pointing to the outer atoms on the ball-and-stick outer face] ah, little atoms, four in each corner and one in the middle. So the one that looks most like it would be d because without all the lines it's still has four on each corner [points to the 4 corners on choice d] and the one on the middle on each face.

5: This unit cell is represented by spheres. How many spheres are in this structure? And, the first, front face of the sphere [pointing to the front face of the structure] is 4 by 3, [I stopped recording here, and came back on soon after that] and the, on that face, [uses pencil to indicate the front face of the structure] and then it's depth is 3 spheres, so you could just do the twelve times the three and find the volume of it, and that would equal 36 spheres.

5: Okay, this unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it. And it's the same dimensions as that, so there would be 36 total spheres but one on the inside, would be, [pointing to a sphere on the front face] it would have, um, a sphere touching it on all four sides, [pointing to indicate 4 spheres around the central sphere on the front face] and then in front and in back, so that would be 6 spheres coming in contact with it. Unless, it doesn't look like the space in between the spheres, [points to the black sections] is ah, close enough for the ones on the inside to touch, [uses hands to indicate a touching of spheres] to the ones diagonal of them, [pointing at the front face] so I'm just going to say it's touching 6 spheres.

Christian: For the next question, I want you to read through these list of skills, you can read through them silently to yourself, I'm going to give you a couple of the questions back, and what I want you to do is indicate which skills you used to solve the question.

5: Okay [pause while he reads the skills]

Christian: Here are the questions. If you could just write on the questions any skills you think you used to solve the question with.

5: Okay, do you want me to talk this through too?

Christian: Yea, talk through why you used the skill.
5: Okay well this one was asking from the left to the right, which of the molecules would stick out the most [n-butane question], and I had to use memory [writes memory] from the previous question to remember that the bold hashed marks were on, like, closer to you, [uses hand to indicate closer to him] and the slashed ones were farther away, [uses hand to indicate further away] and, ah, I had to use orientation [writes orientation] because I had to look at it from left to right, as opposed to any other direction, and, ah, hum, form perception, because it's a 2-dimensional object, and it wants you to look at it, like, [spreads hand out again] like it wants you to look at it as a molecule, which would be 3-dimensional. [writes form perception] Okay, and sequencing because it tells you a order you have to look in, [writes sequencing] so, and well association because it's a picture, and you have to associate the picture with what it's telling you, so, [writes association] what it's telling you to do in the question, and I think that's about it for that one.

5: Okay, the first one that sticks out would be the form perception because, it's a 2-dimensional figure that can easily be shown by like if you were [uses hands to indicate a hole punch] actually folding a piece of paper. [Hole punch question] So form perception [writing this down]. Okay, um, orientation, [writes orientation] because, um, basically like the hole is kinda rotated along the square once it's folded, because after it is folded the four times, once you unfold it, [using hands to indicate a folding and then unfolding] instead of there being one hole, there's four holes. [pointing at diagram A] Um, sequencing [writes sequencing] because you had to look at it in the order that it was folded so you can find the location of each hole, and, hum, I think that's about it for that one.

5: Okay this last one, [unit cell question] it was, um, you had to figure out the, how many spheres were touching an inside sphere, and memory was the first thing I used, [writes memory] because I saw that it had the same dimensions as the, the ah, the spheres in the first, in the first problem like this, um, association, [writes association] because, because I had to get the words to look at the picture, and then I had to look into the picture to see like the inside spheres [points at the front face] and figure out how many it was touching. And by looking into the picture that has to do with the form perception. [writes form perception] And, hum, let's see, uh, discrimination, [writes discrimination] because I'm not, I don't really have to pay attention to the outside spheres, only the ones that are touching the inside spheres. [again points at the front face] So, um, I think that's it for that one.
Interview with student 6

6: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K [points to atom K]. Where is atom U with respect to atom K? [points to atom U] So atom U, Okay so alright, atom U is closer to me, [circles atom U] and atom K is in the back, [circles atom K] um, so, atom K looks like it's at the same, no wait, okay, if R is directly there [drawing a line between R and K], than U is up, [drawing a line between R and U] it's probably above wait, with atom U, yeah [rereading the question], atom U is above, okay.

6: If the structure in diagram A were rotated around the Z-axis in the direction that the axis, axes show, which structure below matches a rotation around the Z-axis? So, okay, if the structure in diagram A [points to diagram A] was rotated around the Z-axis, was rotated around this way [uses pencil to indicate a z-axis rotation], um, which match the rotation below, okay, so, let's see, okay. So first it's rotated this way [uses pencil to indicate a rotation and points at choice a], and then this way [uses pencil to indicate another rotation], um, I would say

Christian: Keep speaking your thoughts, please.

6: Okay, oops, sorry [laughs], okay so diagram A is, alright it's looking towards me, and so first you need to put it down, so it look forward like this, [pointing at choice c] and then you want to turn it this way to the left, [uses pencil to indicate turning choice c] and then down, so I'm just going to guess d.

Christian: Okay, and why did you pick d again, I'm sorry?

6: Um, because, alright, if I am reading these right [pointing at the x-axes], um, it's going, the Z-axis is rotating this way, [uses pencil to indicate a z-axis rotation] so then it would, the two blue atoms [points to the 2 blue atoms in the reference structure] would be facing up and down [waves hand to indicate up and down] and then the Z [points at the y-axis] if it's turning that way, [uses pencil to indicate a rotation] then I'm guessing, it's turning around, so the two white ones would be facing me vertically [points again at the reference structure] and then it looks like it's saying that, um, the Z-axis is turning this way, [indicating another rotation with pencil] so I'm guessing, it's going, looking at me horizontally now, [points at choice d] so that was my thought process.

6: Okay, the diagram below is a stereochemical representation of a molecule of ethanol. In this diagram the hashed wedge indicates that a bond projects behind the paper, and a bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms, um, are furthest from your eyes? Okay, so, furthest from your eyes, which would be behind the paper, [uses pencil to indicate behind the paper] so that would be, um H8 and then H5, um, yeah, those would be the furthest because they're behind the carbon, which is, ah, facing me, so it's behind that, [uses hand to indicate further from her] and then the hydrogens with the dark bonds would be facing me, so that would be closest to me. [uses hand to indicate closer
to her] So furthest from my eyes would be H8 and H5.

6: The diagram below is a representation of a molecule of n-butane. Okay, if you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? Okay, ah, which carbon atom is closest to my eyes. [points to whole structure] Okay, so, carbon a, [points to just carbon a] let's see, no, well, there's two hydrogens behind it, and there's a hydrogen in front of it. [points to carbon a's hydrogens] so I wouldn't say carbon a, cause there's something in front of it. Um. carbon b there's two hydrogen's in front of it, [points to carbon b's hydrogens] and a carbon in front of it, um, so that means it would be behind that one, so, um, or no that carbon would be in front of this carbon, [points to carbon b and carbon a] alright I'll just keep that one. And ah, carbon c is going to be behind carbon b, and then carbon cd [points to carbon d] would be in front of carbon c. Um, I'm going to go with carbon b, because it's in front of carbon a, [points to carbon b and a again] so I think it would have dominance over, ah, carbon d.

6: Look at the following box. Okay, if you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Okay, so it has a face, um, alright, if you ignore the top and bottom, so just stick with the top and bottom, what is the order that could build the sides from the following processes. Okay, um, alright, alright, well, okay, [points to side 5] I'm guessing 5 is going to go first, [points to the back of the box] okay, and then you'd want to go to your right, [points to the right side of the box] so that would be then 2, so c and d are automatically out, and then, then next would come 4, [points to side 4] because you'd have to attach, [points to the right front side of the box] um, that's the only way that 2 would attach, so 2 to 4, um, and then 3 [points to side 3] and then 1 so then a, yes.

6: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A [points to choice a] for each question. Um, pick the figure that shows the positions of the hole when the paper is completely unfolded. Okay, so on the left are square pieces of paper, okay, [points to the first paper folding diagram] that have been folded as shown by the dotted lines, okay. So, the dotted lines are where the paper has been folded before. A hole has been punched in the paper as indicated oh this right here. [points to figure A] Okay pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay well's there's just one dot, um, but since it's punched when it's folded, [uses hand to indicate a hole punch] that means when it's unfolded there's going to be two dots, so therefore it would be d.

Christian: I'm sorry why you'd say d again?

6: Oh, um, because in picture A [pointed at picture A again] the corner is folded, um, and it has been punched, [uses hand to indicate a hole punch again] a hole has been punched there, so when you bring, um, that corner down [points to choice d] there's going to be the hole where you punched it in the corner, [circles the hole on figure A] and it's going to be down there at that corner [points to the bottom hole of choice d] and then the original hole, [points
to the top hole of choice d] um, that has been punched through in, um, that area.

6: The two, there's two different types of models are illustrated below, space-filling models and ball-and-stick models. In the next two questions, you are provided with a ball-and-stick model of a molecule. Set out below, set out below it are four diagrams of space-filling models of that molecule. Pick the space-filling molecule that matches the ball and stick model. Okay, so, here we have a tetrahedral, um, figure, and there is a central atom and then, um, with some surrounding it, um, so let's see a shows a tetrahedral molecule, [points at choice a] well I guess they all do just at different, um, angles. Um, it most likely will not be b, because, um, the ball and stick model only shows one atom on the top, [uses hand to indicate a circular atom] and then three surrounding it, [waves pencil to indicate 3 surrounding it] so it can't be b, because there's showing one atom on the top and one on the bottom, [points to choice b's top and bottom atoms] um, let's see, and it just most likely, and it can't be d because once again, it shows one on the top and one on the bottom, [points to choice d's top and bottom atoms] it just doesn't make sense. Um, let's see, okay, a and c are really similar, um, I'm going to say, since in the ball and stick model it has, [circles one of the sticks in the ball-and-stick reference molecule] um, the bonds that are connecting it is has like half the darker color and then, half the, ah, lighter color, um, I'm guessing it would correlate more with a, so I'm going to choose a.

6: Two different types of models are illustrated below: Space-filling models and ball and stick models. Pick the space-filling model that matches the ball and stick model. Okay, so we have a, ah, faces, there's faces and then there's corners, [points at the reference ball-and-stick structures faces and corners] so all the faces are occupied, and all the corners are occupied um, the ball and stick model. So it's, um, let's see, it's not b [points at choice b] because that's, ah, body centered because there's one in the center, [uses hands to indicate a round atom] um, and then c just doesn't look, that's in the, it looks like it's in the corners and the center again, [points at choice c] and that just doesn't look it makes sense. And then, let's see um, a looks like there edges occupied, [points at choice a] but there's no edges occupied in the ball and stick model, so therefore it would be d because there's the corners, and then it looks like there's the 4 faces [points at choice d's corners and faces] occupied so d.

6: This unit cell is represented by spheres. How many spheres are in this structure? Okay, so, let's see, um, 1, 2, 3, [points and counts down the row] okay, so, um you have 3 going down, [writes 3 below question] and then 1, 2, 3, 4, 4 going across, [points and counts across the top row] um, [writes 4 next to the 3] so that means you're going to have 12 on one face, [writes =12] and then you have 6 faces, right so 1, 2, 3, 4, 5, 6, [points and counts all the faces of the structure] times that by 6 [writes x 6 below the 12] so, um, 72 spheres.

6: Okay, this unit cell is represented by spheres. Consider a sphere on the inside, um, how many other spheres will touch it. So, we're looking for the coordination number, [writes CN] um, and alright, so if there's, if you're just looking at one single one, [colors in an outside atom] I don't want this one, I want this one [colors in one of the inner atoms], because that
just makes more sense, um, that means you have, [points at the reference structure] if there's one in front of it, [uses pencil to indicate in front] there's going to be one behind it, [uses pencil to indicate in back] and if there's one above it, [uses pencil to indicate above] there's going to be one below it, [uses pencil to indicate below] so, um, if you're looking at this one, [pointing back at the atom she had colored in] there's 1, 2, 3, 4, [counting the atoms that are around the colored one] that we can see, [writes 4] and then there's one touching it behind it, [writes +1 next to the 4] and then that mean there'd be one touching in front of it, [uses hand to indicate in front of it] so that's another one, [writes another +1] so 4, 5, 6. So that means 6 other spheres would be touching it.

Christian: I want you to read through this list of skills right here,
6: Okay.
Christian: And what I really want you to do, I really want you to, um, read them to yourself, and then indicate which skills you think match the question I'm going to give you again.
6: Okay.
Christian: Um, write on the questions any skills you think you used to solve the question.
6: Okay.
Christian: I'm going to give you a couple questions back, so let me see here.
6: Okay so I read through them then. [Pause while reading skills] Okay.
Christian: Here are the questions, just, just whatever skills you think you used to solve the question, and actually write them on the skill, write them on the question.

6: Write them on this? Okay. Okay, so for this, [Box question] um, I would definitely say sequencing because it's asking you to put it together in a specific order, so sequencing, [writes sequencing] um, let's see, um, I'm going to say, and probably orientation cause it's a 3-dimensional figure. [writes orientation] Okay.

6: Alright, um, this one is definitely like a 3-dimensional figure so form perception I would say [n-butane question], because you're, um, interpreting this 2-dimensional representation, um, [uses hands to indicate the long molecule] and trying to think of it 3-dimensionally. So form perception, [writes this] and um, let's see, and probably orientation again, because you're kinda thinking of, ah, the positions of the atoms, so orientation. [writes orientation] Okay.

6: Okay, and this one, ah let's see, um, you're distinguishing objects from their background, [diamond question] um, I guess, yeah, that would probably be a good one figure ground. [writes figure ground] And, um, let's see [mumbling under breath] and form perception again, cause you're once again looking at, ah, [points at the whole structure with whole hand] something that's on a piece of paper, and, um, trying to think of it in 3-dimensional form. [writes form perception] And yes, I think that's it.
Interview with student 7

7: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K. [points to atom K] Where is atom U in respect to atom K? Oh god, okay well this looks like its going forward, [pointing to the line between atom K and atom M] and I guess the darker lines mean that it's going, oh it's levels. Christian: The darker lines mean the atoms are connected to each other. 7: Okay, so the dotted lines mean that they're below it, right? [gestures with hands off camera] Christian: Um hum, right. 7: Okay, so I would assume. [points to atom U] Christian: So the dotted lines are like where the cube is, like where the cube, it's kinda like the cube's interworkings. Does that make sense? 7: Right, cause it's on the inside which means. Christian: Right, the inside. 7: Okay, [points back at atom K] so then, where is atom U in respect to atom K? Is this dot [points to atom U] on this dotted line right here. [points to the dotted line that K is on] Christian: Ah, it is not. 7: It is not, so that'd be inside, it's on the same level or can't be determined, um, oh god I'm so scared I'm going to get it wrong. Christian: That's okay, don't worry about it, I only want how you think about it. 7: Okay, so these are same level, [points to K and R with the same hand] so I'm going to assume it's on the same level. Flip? Christian: It's okay, can you actually circle your answer on the sheet, that'd be great. 7: Now flip? Christian: Now flip, flip, [mumbling]. 7: Okay

7: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Which structure below matches a rotation around the Z-axis, [points at the z-axis rotation] um, turning around the X-axis, were rotated around the Z-axis in the direction that the axes show. Turning around the, if diagram A were rotated around the Z-axis, turning around the Z-axis. [uses finger to indicate a turn] So it's asking me which picture would be showing that? [points at all the choices] Christian: Right, right. 7: That would be turning around the [pointing at choice c]. Christian: Keep speaking your thoughts please. 7: Sorry, that would be turning around the X or Y axis [choice c], I feel that would be turning around the X or Y [pointing to choice a]. I would assume that there'd be, [pointing to diagram A] if it was rotating this way, [uses both index fingers to indicate a z-axis rotation] that it would be b.
Christian: Why would it be b again?
7: Because if it starts off, [points at diagram A] this is how it's starting right?
Christian: Um hum, um hum.
7: So if it's starting off like that, then you're rotating it over the origin? [points back at the z-diagram axis]
Christian: Um hum
7: So, if it's facing this way, and you're rotating over the origin, [using hands to indicate a rotation] then it wouldn't be this one, or would it? Can I draw?
Christian: Sure, sure, sure draw, build, whatever you want to.
7: [drawing the x- and y- axes] So if it's facing this way, and then it rotates over. I'm sorry I don't mean to mess up your experiment.
Christian: [mumbling] It's okay.
7: [drawing circles on the axis to represent atoms] Does it matter where it starts?
Christian: No, it doesn't matter.
7: Okay, so if it's rotating over the Z, then it's going to be going, [draws another circle] it's rotating this way? [draws a circular arrow in the direction of the z-axis] It's rotating, so then it's going to flip, [drawing two more spheres in] facing, yeah I'm going to go with b, because it just seems like it would be [drawing circles that match b on the axis].
Christian: Okay.
7: Do you know which ones are the right answers.
Christian: Yeah, of course I do.
7: Oh god. It makes me nervous.
Christian: I really don't care about your answers, all I really care about is how you think about them.

7: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with the straight line indicate that the bond is in the plane of the paper. Which atoms is the furthest from your eyes? Furthest from my eyes, which means that 9 and 4 are closest to me, [circles atoms 9 and 4] and then this is on the plane of the paper, plane of the paper, plane of the paper, plane of the paper. [tracing over the lines that connect to atoms 6, 3, 7, 1 and 2] Am I, so I'm looking at this from above?
Christian: Um hum from above, right.
7: So this is going backwards, and this is going backwards [circles atoms 5 and 8] out the other end of the paper. [uses pencil to indicate a backwards motion] So I'd assume that if I'm looking at it from above. So I'm not looking at it from like this way?
Christian: No, no.
7: So, if it's on the plane, if I'm looking at it from above then 5 and 8 would be going backwards, [draws 2 lines] which means that they would be furthest from me. Now it's only an option of whether I'm going to be closer to 5 or 8. [pointing to atoms 5 and 8] And none of them can like be in a tie or whatever?
Christian: Read the question again?
7: Indicates atoms are connected with straight lines are indicated.
Christian: Right here [points to the question]
7: Which atoms, oh so it's which ones are the furthest from me?
Christian: Um hum.
7: It's going to be 8 and 5.
Christian: Can you keep your paper above the tape line, that's where the camera stops.
7: Oh sorry
Christian: It's okay, sorry if I didn't mention it before.
7: It's going to be 8 and 5.
Christian: Okay.

7: The diagram below is a representation of molecules of n-butane. If you visualize the molecules from left to right, which carbon atom in the drawing is closest to your eyes? From left to right, okay, so this is on the same plane, [traced hydrogen to carbon A bold wedge] these are further back, these are further back, [pointed to two hydrogen to carbon A hashed wedges] this is on the same plane as this, [pointed to the bold wedge connecting carbon a and carbon b and compared it to one of the hydrogen - carbon b bold wedges] this is further back, [points to the hashed wedge connecting carbon atoms b and c] which means this is connected so these are not an option because they are both farther back [crosses out c and d]. So it's a or b. [points to carbon's a and b] I'm assuming. And then, can I draw?
Christian: Sure, sure.
7: [drawing the hydrogen and carbon bonds]. And we're just talking about the carbons?
Christian: Just the carbons, um hum you got it.
7: From left to right, which carbon atom in the drawing is closest to your eyes. From left to right, so I'm going to go with a.
Christian: Why a again?
7: Because if you're doing left to right, if you're saying its closest to my eyes, [uses pencil and points it toward herself] is that from me starting from.
Christian: That H, right [circling the left most H].
7: So this carbon, since these two are behind [circling carbon's c and d] they're further away from me, [drawing an arrow from the structure] and this one's connected to the one that's already behind. d's connected to c which is already behind me, [points to carbon's d and c] and I'm going to go with a because it's left to right, and these two carbons are on the same plane [pointing to carbon's a and b].
Christian: Okay.

7: If you ignore the top and bottom of the box, in what order, wait, what is the order that you could build the sides from the following pieces?
Christian: Read the top sentence again there Look at the following box.
7: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? So I'm ignoring this right here, and this [crossing out the top and bottom]
Christian: Yeah, yeah.
7: And it's saying, so, what is the order that I could build the from the following. So this is the back of the box [pointing to piece 5], so this is the back. [writes back below piece 5] Let's see, this is, let's say this is the left side, this is the right side [writing L and R by the box]. This is the left side, no this is the right side of the box [writing R below piece 2], I think, oh, this is the left side [writing L below piece 1], and then this is the front, [pointing to pieces 3 and 4] both of these are the front [writing F below pieces 3 and 4]. So what is the order that you could build the sides from the following pieces. I just get to choose any order that I want?

Christian: Yeah.
7: Oh, okay well I'd do 5, I'd do the back first so 5 would be first, and then I'd do 5, and then I'd do the right side, so 2, and then the left, no, I'd do 5, 2, [points to the back and right side of the box] 5, 2, 3, 4, 1. So it'd be b.
Christian: Okay.

7: Okay, 6 on the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes, when the paper is completely unfolded. Okay, so this is where the hole was punched? [circles the hole on picture A]

Christian: Um hum, um hum.
7: Okay, so positions of the holes when the paper was completely unfolded. So this was folded into 4's, what was this folded into? [points to picture A] Is this just a regular sheet of paper? [draws a square]

Christian: Regular sheet of paper, um hum.
7: Okay so you've only folded the corner, [draws a line indicating a corner fold on box she drew] so then it would be d, because as soon as you unfold the corner, [uses hand to indicate a unfold] this would be the corner, [draws line to indicate corner fold on choice d] and so this would reflect onto that. [points at choice d] So it'd be, I'd pick d.

7: Pick the figure that shows the positions of the hole when the paper is completely unfolded. Okay, so you fold it in half sideways, [points at first hole punch figure] wait, so the hole would be, [draws a dot on the first hole punch figure] the hole was there, which means the hole would be here. [drawing another hole on the first hole punch figure] Which means the hole would also be here, which means it would also be here and here [drawing on the first figure 2 more holes]. Am I allowed to fold this?

Christian: It's fine.
7: So if this was a square, [folding piece of paper] can I rip it?

Christian: Sure.
7: [ripping a small square out of the bottom of the question paper] Okay, so we have, then we folded it like this and put a hole here, which means that the hole would also be here, and here, and it would come through here [folding and drawing the holes on the paper]. So it would be this one, it would be a.
Two different types of models are illustrated below, space filling models and ball and stick models. In the next two questions, you are provided with a ball and stick models of molecules. Set out below, wait, set out below it are four diagrams of space filling models of that molecule. Pick the space-filling model that matches the ball and stick model. Oh my gosh, does that just mean that the lines just go away? [points to the lines on the ball-and-stick reference structure]

Christian: The lines go away, yeah.

7: Oh, okay [starts building the molecule with the model kit] So this is the model that it is? Christian: Um hum, um hum.

7: Okay so then you just take away the sticks. [pulls one stick off the model] Which would be, from the way I'm looking at it would be. Okay I'm deciding between a and c [points to both a and c with one hand] because they both look around the same, but this one [pointing at the top atom of choice c] the balls seem to not be morphing with this [drawing on the gray part of a], like this one goes inside. And I don't know if because of this line,[circling another line on the ball-and-stick model] you see how there two separate colors, I don't know if it that has any impact on it, and because its the same color, I'm going to assume that it does, so I'm going to go with c.

Christian: And how did you rule out b and d in this case?

7: They're on, um, they just look like different shapes from the way that I'm looking at it. This ball is a full,[pointing to the top atom in the ball-and-stick reference structure] this ball takes, um, up this half [drawing on the top the gray ball in the center of the ball and stick model] so if it were to come down on top of it it would cover that. [using hands to indicate a cover] And this one, it seems like [pointing to choice d] also these two balls, these two molecules, seem like their kinda going out this way [drawing on the two side atoms on the ball and stick], and so on, ah, d [points back at choice d] it seems like these molecules are coming before this one, [drawing again on outer atom of ball-and-stick] and the same for b. [pointing at choice b]

Christian: Okay

7: Was that okay?

Christian: Yeah.
7: Okay, this unit cell is represented by spheres. How many spheres are in this structure? Okay, I'm going to assume that it's a 1, 2, 3, 1, 2, 3 [counts the first row, and back row of the structure] the first or the one, okay it's gonna have 1, there's going to be a layer in between here 3, 4, layer between there are 5. [writes layer numbers next to the structure] So I'm going to assume that layer 1, layer 3 and layer 5 are all the same, so it's going to be a 1, 2, 3, [counts 3 again going back] 3 by 4 which is 12, [writes $12 \times 3$] and 12 times 3 is 36, [writes 36] and then the layers between which is 2 and 4, so this is 1, 3, and 5 added together. [writes $1, 3, and 5$ above calculation] 2 and 4 are going to be filling the spaces in between, [pointing to a dark space in between] and so for every four up here, there's going to be one filling the space, [drawing a circle in a top dimple] and so there's going to be 1, 2, 3, 4, 5, 6 in between [drawing circles on all the dimples on the top] so 2 and 4 are going to be, that's gonna be 2 layers times 6 [writes $6 \times 2$] which equals another 12,[writes $=12$ without lifting hand] which is going to be 48. So how many spheres are in this structure 48.

Christian: Um, hum
7: Okay so if there's just one this is going to be the structure right here, it's going to be touching those, it's going to be touching 4 on this side [drawing a circle with 4 circles surrounding it], and I can assume that the back side is going to look the same? [uses pencil to indicate a back side]

Christian: Um hum.
7: So one sphere on the inside is touching 4, [writes $1 \times 4$] or it's going to be touching, sorry, 8 on the outside.

Christian: The last question, what I want you to do in this case I want you to read through these list of skills, read through them to yourself and I want you to go back and match the skills to the questions I'm going to give you.
7: Okay, read them out loud?
Christian: No, read them to yourself.
7: [pause while reading] Okay.
Christian: Okay here are the questions back. And I want you to write on the questions, any skills you think you used to solve the question.
7: Okay, [looking at the ball and still face centered cubic question] so on the back?
Christian: No, on the front.
7: [writes association] Okay, [mumbling] Do I have to think outloud to this.
Christian: Yes [mumbling], and tell me the reasons why you think that.
7: Okay, association because its giving me, um, specific directions, and I have to turn the directions, relate concepts which are shown in pictures and written words, I have to, um, take the directions and use them for the pictures.
Christian: Okay.
7: See diagrams of objects that are the same size, shape, or color, I would assume I'm using constancy, [writes constancy] because it says see diagrams of objects that are the same size, shape, or color, although they're not the same size, they are representing the same shape and they're the same color.

Christian: Okay.

7: Perceive dominant features in objects, and to discriminate one object from, I don't think I'm using discrimination.

Christian: Okay.

7: Figure-ground distinguish objects from their background, um, I don't think there's background to this, [uses pen to wave at the whole picture] so I don't think figure ground. Form perception, interpret 2-dimensional representation of 2 or 3-dimensional, um, objects, does that mean like in my head, I'm changing it into a 3-dimensional?

Christian: Um hum.

7: Okay, well I changed this into a 3-dimensional and I referenced it to what we did in chemistry 102 so I would say form perception. [writes form perception] Okay, memory, recollect the dominant features of a diagram. Does that mean memory from like what I've done in the past, or just memory from this.

Christian: Just from the question.

7: Okay for just the question. I don't think I, unless I'm remembering like what this looks like, but I think I was more comparing then remembering I guess, so I don't think memory. Orientation, rotate or reflect the positions of objects in space in relation to other objects and the observer. Well I'm moving them closer together, but I'm not reflecting or rotating them, so I don't think I'm using that. See objects in a particular order, sequencing, well they are in a specific order, so I would assume that, no I don't think I would do sequencing because they are in a specific order, but I'm not changing the order or anything like that, so I don't think it's in a particular, yeah, so just those three.

Christian: Okay.

7: Alright, the diagram below representations of models, um, lets see [n-butane question] okay, again I have to change the words into an idea and, um, so association, [writes association] okay. Consistency if the diagrams of the objects are the same size, um, I don't think that I did anything with size or color, I did, um, I was thinking about the shape, but I don't think that's what constancy is talking about as far as that goes. See diagrams of objects that are the same size, shape, or color, I think this is more so when you are comparing two, and I don't think, we're not comparing them, so discrimination to perceive dominant features in objects and to discriminate one another. Um, by dominant features do you mean the ones that, I guess I could assume that the dominant feature would be the one that closest to me? Is that what you mean?

Christian: Whatever you take it to mean?

7: Okay, I'm going to assume that the dominant feature is whatever is closest to me so, I'm gonna say, and this question was talking about which, um, carbon atom is closest to my eyes, [uses pen to indicate and points it to herself] so I'm gonna say discrimination. [writes discrimination] Okay, figure ground, disquemish, ah sorry, disquemish, [laughing]
distinguish objects from their background. I'm not really, there's no background to this, so I don't think I'm using that. Interpret 2-dimensional representations of yea this is, I had to change this into a, um sorry I'm spacing out,[writes form perception] I had do this in my head, so I had to make this 3-D, and I kinda somewhat drew it 3-D to me in my head, so form perception. Memory, recollect dominant features of the diagram. Um, again, it's all about how I interpret the word dominant features, but I don't really, I wasn't really recollecting anything, so, orientation, rotate or reflect the positions of objects in space in relation to other objects and the observer. Okay, it was talking, it says in relation, um, in this particular question, it's saying in relation to my eyes from left to right, so I think that was part of it. [writes orientation] Okay, and sequencing, see objects in a particular order, well if I'm going left to right, I'd definitely would put them in that order, which means there would have been a sequencing order. [writes sequencing]

7: Okay, and 5 [the box question] let's see, relate concepts that are shown in pictures and written words. Okay, um, I don't think this was association, although it did give me directions, that I had to turn into a picture in my head, I don't, I wouldn't consider it association, um, see diagrams of objects that are the same size, shape, right, because so I was dealing with the same shape, just subtracting two sides of it, I would assume that con, constancy was part of it. [writes constancy] Okay, discrimination, to perceive dominant features in objects, and to discriminate one object from another. For this one I would assume that dominant features would be which one I choose first, um, and so I would assume that I was, um, discriminating them. [writes discrimination] Okay, figure ground, distinguish objects from their background, I don't think there's any particular background unless [coughing] I'm sorry. Christian: It's okay.

7: I'm about to die in the middle of your presentation.
Christian: [mumbling] Don't worry about it.
7: Unless the, um, which one am I on, unless the, um, background was the top and bottom, but I'm not going to assume that. Form perception, um, interpret 2-dimensional representation, well they're both, everything on here is 2-dimensional, I mean it was, no, I'm going to go ahead and say that form perception was part of it, because, um,[writes form perception] again I have to picture it in my head as a 3-dimensional shape, and how I would put it together. I don't think memory is part of it. Orientation, rotate and reflect the positions of the objects in space in relation to other objects, um, I wasn't rotating or reflecting so I don't think orientation, and then sequencing, seeing objects in a particular order. Well I was deciding what order to put them together, so I think sequencing would be part of that. [writes sequencing]
Christian: Okay.
Interview with student 8

8: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question, choose one best response. View atom letter K. Where is atom U with respect to atom K? Alright, here's U, K, points to atoms U and K when he says the names] anything I would say below, looks like.

Christian: Okay, why would you say below?
8: Um, just cause, wait, I mean above, I was thinking about K, sorry. Cause it looks like, I mean it just looks like, points to line behind K since the cube is going this way, ur, yeah it looks like it's going down that way a little bit, points with his finger in a downward fashion so it looks like it would be higher.

8: Alright, if the structure in diagram A were rotated around the Z-axis in the direction that the axes shown, which structure below matches a rotation around the Z-axis? points at figure A] Ah, which structure below matches a rotation around the Z, well. [points to all 3 axes without lifting up hand] Talking about this is the Z-axis? [drawing a line on the Y-axis]
Christian: This is the Z-axis right here.
8: Okay,
Christian: Around the Z-axis right here.
8: Ah, um, which atom in the structure?
Christian: Keep speaking your thoughts.
8: Um, it looks like maybe a, points to choice a] cause maybe it's going, [indicates with pen a circular rotation] I'm not really sure, if anything I would say a.
Christian: Why would you say a again?
8: Because it looks like it's horizontal and flipping side over side. [indicates a rotation with pen]
Christian: Okay
8: I guess. Do I get to see if I got these right or not?
Christian: No, I won't tell you that.
8: Okay, [laughs]

8: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atom is furthest from your eyes? Okay, so it's talking about, I would have to say the hydrogen, hydrogen atom with the hashed wedge on the very back, number 8, I guess, looks the farthest away.
Christian: So why did you say 8 again?
8: Because it's behind the, points to the structure] it's behind the C, lower, like it goes straight up, points to the line that connects carbon 6 to the rest of the molecule] so, I guess 8.
Christian: Okay.
8: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom is in the drawing, in the drawing is closest to your eyes? From left to right, so the bold bonds are sticking out towards me, and the hashed wedge is going away, um, I would have to say carbon d, or b or d.
Christian: Why do you think those two?
8: Because they have three hashed wedges, or bold wedges attached to them. So I would have to say maybe b.
Christian: So why does that make them closest to your eyes?
8: Um, because it makes them move out towards me, [uses pen to indicate moving toward him] with the bold, I guess, I guess, I don't know.

8: Alright, look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Hum, build the sides from the following pieces. You could do, um, start with 5, [points at side 5] uh, and 5 and then 2.
Christian: Keep speaking your thoughts.
8: Um, 5 because it's solid, it looks like it should go first, 2, or actually yeah, I would say 5 and then 1, but that is not on here, so, 5, 2, and then 4, because it is attached to the 2, and then 3, and then 1 [circles choice b].
Christian: Okay.

8: On the left are square pieces of paper that have been folded as shown by dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper, to indicate, as indicated in picture A for each question. Pick the figure that shows the positions of the holes where the paper is completely unfolded. Alright, paper is completely unfolded. Well that one would be folded in half [pointing at choice e].
Christian: This is figure A right here, you get that?
8: Right, okay, or wait I'm supposed to, which one of these is figure A, [points at figure A and the rest of the choices] is that what I am figuring out?
Christian: No, in this case what they are saying is that, so basically they fold the piece of paper like this, and they punch a hole through there [folding paper over on the question], and then they unfold it.
8: Right, right, so then it would be d.
Christian: So why is it d?
8: Because there would be two holes right there in the corner if it was folded over and punched. [using my fold of the paper to answer]

8: Two different types of models are illustrated below, space-filling models and ball and stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below, set out below it are four diagrams space-filling models of that molecule. Pick the space-filling model that matches the ball and stick model. Um, well it's tetrahedral, so I would have to go with a. [points at choice a]
Christian: Why do you say a?
8: Um, I could be wrong, but I think that's a tetrahedral [pointing to the reference structure],
and that has the 3-base, the base pyramid [pointing to choice a, and tracing the top atom] and the molecule on top.

Christian: Okay
8: And the central atom.

8: Alright, two different types of models are illustrated below: space-filling models and ball-and-stick models. Place the space-filling model that matches the ball-and-stick model. That's a tough one. Um, probably, probably not c, [points at choice c] because there's 5 on each side, so not b or c, [points to choice c and b] um, a or d, hum, I'm going to go with a, or, actually d.
Christian: Why d?
8: Um, I think that a has too many molecules in it.
Christian: So why did you pick d again?
8: It just looks like it has the right amount from looking at it, it looks like it has 5 on each side, [pointing to the atoms in choice d] and it doesn't have any extra ones.

8: This unit cell is represented by spheres, spheres. How many spheres are in this structure? Alright, well, there's 4 across, 12 on that side, and then, let's see 6, 18, uh, 24, 28, 32, I'm guessing.
Christian: I'm sorry, how did you get that number?
8: Um, well I counted these as 12, [points to the front face of the structure] and then it looks like it is 2 deep. [points to the left bottom of the structure without lifting hand] so than there's 6 on back row, [points at the back top of the structure] 6 on that side, [points at the right side of the structure without lifting hand] and then there's 4 right there, [points at the back of the structure] and the same for, [points at the bottom of the structure] I didn't even think about the back side, there's 12 more there, is 12, 42, [writes 42] 44, and then plus 2, [writes 44 and crosses out 42] so 44 yeah, no 46. That's what it is, I forgot about the bottom. 46, I guess.

8: Alright, consider a sphere on the inside, how many spheres will touch it. Do they mean one big sphere on the inside, or are there lots of them?
Christian: Just one of the ones that you see on the outside.
8: How many will touch it, just one on the inside, zero?
Christian: Why do you say zero?
8: Because if it's the same size as the ones on the outside, there's just one on the inside, I mean, or is it, I mean is it floating around or is it just sitting there? [waving pen around off camera]
Christian: This is the complete structure.
8: I mean, zero or three? I guess it would take 3 to, I guess 3. [writes 3]
Christian: Why do you say 3?
8: Um, well actually 4, [crosses 3 out] because it is sitting down in there, then it's gotta have 4 to support it. Probably sitting on 4
Christian: Can you draw me what you mean on the figure up there?
8: Like, um if it's sitting on top right here, it's touching that one, that one, that one, and that
Christian: Here is a list of eight skills. I want you to read through the list of skills, and I'm going to give you a couple of the questions back, and I want you to write on the questions, any of the skills you used to solve the question. You can read them to yourself, you don't have to read them out loud.

8: Okay, [pause while reading] okay.
d8: Alright, um, let's see, [writing figure ground on the space-filling with the face centered cubic question, then writing form perception]. I guess that's it.
Christian: So why did you pick these two skills, I'm sorry?
8: Um, well, figure ground, because, you have to distinguish the objects from the background, [points at the reference object] and form perception, because if you look at it 2-dimensionally [points at the atoms on the reference object] right have you see that there are 5 on there, and 5 on that side, [points at some of the atoms of choice a] I guess.

8: Alright, um, [wrote on the unit cell question sequencing and figure-ground]
Christian: Why did you say these two skills?
8: Sequencing, cause I know they are in the same order on the bottom as on the sides you can't see. [points to the structure] And figure ground because I still have to distinguish it from it's background, how many are back there.

8: Okay, ah, hum [writing sequencing, discrimination, and figure ground on the box question]. Um, sequencing, cause obviously it matters what order you put it in. Um, discrimination, cause you have to figure out which ones take precedence over the others, um figure ground, because you are still dealing with the 3-dimensional object with a background.
Interview with student 9

9: Okay, in the next question, the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles. Pick the number of the figure which is unlike (different from) the reference object. If all the, if all figures are like the reference object, choose d.

Let's see here, um, it's hard to say for a, [points at choice a] ah, [points at choice b] b looks like it might be a longer object, I'm going go with, let's see though, c looks like it could be, but it looks a little too narrow. Let's see, I'm picking the one that is unlike, or different from, hum.

Christian: Keep speaking your thoughts.
9: Hum, I'm just thinking now, that, ah, only one of them looks like it to me, so if I had to guess, I don't know it would be a random guess, but I'd say a so.

Christian: You can circle them, circle them.
9: Circle them? Alright.

9: Alright, the diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question, choose the one best response. Let's see, view atom letter K, where is atom U with respect to atom K. Let's see here's K, [points to K], here's U [points to U]. Is it above yes, it appears to be above, it's not below, it's not on the same level above.

Christian: I'm sorry, why did you say above?
9: It just appears to be above, K's here [points to K], U's there [points to U], If I'm looking at the paper, it appears to be slightly above it, [uses both hands to indicate one above the other] that's why I say above.

9: If the structure in diagram A were rotated around the Z-axis in the direction that the axes shows, which structure below matches a rotation around the Z-axis? Turning around the X-axis, okay, let's see, that's okay X-axis is this one, [pointing to the x-axis rotation] Y-axis, [pointing to the y-axis] Z-axis runs this way, [pointing to the z-axis] okay so we are taking this and we are rotating it in that direction [uses one hand to show rotation around the axis] hum, supposed if I look at this one from the side, that might match it [pointing at option a]. Maybe that one too, but it doesn't say how far it's being rotated so that's kinda hard to say. [pointing at option b]. Wait, let's see, did I read this right? Well I'm wondering it doesn't really specify what angle you are viewing it from.

Christian: No, it doesn't.
9: Hum, c. [pointing at choice c]

Christian: Why don't you read the question again.
9: Alright, if the structure in diagram A were rotated around the Z-axis in the direction that the axes shows, which structure below matches a rotation around the Z-axis? Okay, well let me see if I leave this where it is [pointing to diagram A with one hand] and rotate it around the Z-axis, [uses hand to indicate a rotation] which seems to be [holds pencil against the molecule in the direction that the Z-axis is represented on the paper] at an angle to it, then
what would that look like? I don't really see it looking like any of these in my mind. Because I will picture these two staying in place, [pointing to the white atoms on opposite corners of the molecule] and these two moving to the vertical position, [pointing to the two blue atoms] I don't really see that matching any of these. Unless, I don't know, I would have to guess at random on that. I can't figure out, one versus another. I guess I would go with a. Christian: Okay.

9: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the screen, and bold wedge indicates that a bond projects out of the screen towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. What atom is furthest from your eye? Ahh, that would be 8 because, [points to atom 8] 5 is also hashed, [points to atom 5] and it's in the plane, [uses finger to indicate going behind the paper] it's beneath the plane of the paper but it's closer to me, then 8, so 8. Christian: Okay.

9: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eye? From left to right, ah, [points to each carbon in the diagram in turn without lifting hand] well, let's see, maybe it'd depend on which eye I'm talking about. [points back at carbon b without lifting up hand] Looks like, b and c, wait no b and d [pointing to b and d] are coming out of the paper towards me, um, closest to your eyes, [points to b and d again without lifting hands from paper] ah depends on how I'm positioning the paper I suppose, but ah I guess b is as good as d.

9: Look at the following box, if you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces. Hum, let's see, the following box, okay, let's see if I ignore the top and the bottom, [points to the top and bottom of the box] hum. Let's see it doesn't specify, well, I guess I just try these, let's see if we started with 5, [points to the back side of the box] and then went to 2, [points to the right side of the box without lifting hand] then 4, I suppose that would work, [points to the front right side of the box without lifting hand] then 3, [points to the front left side of the box without lifting hand] then 1 [points to the left side of the box without lifting hand]. It could be build that way, I suppose. Let's see though 5, [points at the back side of the box] 2, [points at the right side of the box without lifting hand] 3 [points and moves finger across the front of the box without lifting hand] no it can't be built that way, because that goes over here that would break the continuity. [points at the front side again] Um, 1, [points at the left side of the box] 4 [points again at the front without lifting hand] no that would break it. Ah, 5, [points at the back of the box] 3, [points at front of box again without lifting hand] no, okay, so it's a clearly.

9: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where the paper has been before paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows
the positions of the holes when the paper is completely unfolded. Let's see, let me read this again, on the left are square pieces of paper that have been folded as shown by the dotted line. [points to the first hole punch picture] Let's see, a hole has been punched in the paper as indicated in picture A. [points at picture A] Okay, let's see, okay, so you fold it, [uses pencil to denote a hole punch] punch a hole through it, unfold it, [uses finger to denote unfolding it back] if you're going to have. So that's going to be d.

Christian: So why did you say d again, I'm sorry?

9: Why did I say d again, um, well let's see, this hole, [pointing to the hole in picture A] it's not quite at the center of the paper, ah, or of where it is currently folded, ah, when you unfold it, it's going to be moving one of the two holes that's made back in this direction, [draws an arrow on figure A back where the other hole would be] along this diagonal, so that it would be closer to the edge of the paper that's folded near the center.

Christian: Okay.

9: Two different types of models are illustrated below: space filling models and ball and stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below it are four diagrams of space filling models of that molecule. Pick the space filling model that matches the ball and stick model. Well let's see this looks like methane. [points at reference ball-and-stick structure] um, hum, well, [points at choices without lifting hand] it looks like the hydrogens are smaller than the carbon in this depiction, [points at the top hydrogen and carbon in the reference ball-and-stick structure] but here the, and here the carbon is larger than the hydrogens, [pointing to choice a's top hydrogen and middle carbon] there the hydrogens are larger [pointing at choice c] so that would eliminate that one and this one [pointing at choice d]. And, hum, can't really tell whether the angle is tetrahedral on this one [pointing to choice b], so I'm going to go with a because it appears to have a tetrahedral angle, and the carbon appears to be larger than the hydrogens.

Christian: Okay, thank you.

9: This unit cell is represented by spheres. How many spheres are in this structure? Well let's see, I can count 1, 2, 3, 4, [counts the atoms across the top row] 5, 6, 7, 8, 9, 10, 11, 12
[counts all the atoms on the top layer without lifting hand] on the top layer, there appear to be 3 layers, [counts down the layers] so I'd say 12, 24, 36 [writes 36 on the paper].

9: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? Let's see, if I move, let's see this one is on the top, and it's touched by 1, 2, 3, 4, 5, 6, 7, 8 put it in the center, [pointing and counting from one of the top atoms] there would add a sphere above and beneath that touch it, [points above and beneath the top atom without lifting hands] so I would say 10. [writes 10 on the paper]

Christian: So for the next question what I want you to do is to read through these list of definitions, you don't have to read them out loud. I'm going to give you give you a couple questions back again, I want you to match the definitions to the questions. I mean match the skills to the questions that I'm going to give you back.

9: Could you repeat that again?
Christian: So, here is a list of skills, read through them, you don't have to read them out loud, I'm going to give you a couple questions back, and I want you to match the skills to the questions that I asked you, does that make sense

9: Okay.
Schiltz: Just any skills you think you used on the question.
9: Okay,
Christian: These are the questions
9: Let's see. Did you say you did want me to read these out loud?
Christian: No, you don't have to read them out loud. It's fine, you [mumbling]
9: Okay, [pause while reading skills] Okay, for the, let's see for this one [space filling with face centered cubic], I think that this involves let's see discrimination, form perception, ah yes, discrimination and form perception perhaps, orientation. Yeah, I would say all 4 of those.

9: I think maybe this one was intended [orientation question], let's see, let me think, [pause] I think this one was intended to gauge rotation, or orientation. Test orientation.
Christian: Are there any other skills that you used when solving this question do you think?
9: Ah, lets see, not that I can tell, and that might be why I couldn't figure out how to answer it.

9: Okay, this one [wireframes question], clearly let's see, it is attempting to test consistency, discrimination, form perception perhaps, orientation. Yeah, I would say all 4 of those.
Interview with student 10

10: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K. Where is atom U with respect to atom K? Um, [pointing to atom K and U] the same level.

Christian: Why do you say the same level?
10: Yes.
Christian: So, why do you say the same level?
10: Because they are on the same horizontal line, [points to the line behind U] I don't know [laughs]

Christian: I'm basically like want to know, how you came to the answer, is what I'm asking you to do today so.
10: Oh, okay,
Christian: Does that make sense?

10: If the structure in diagram A were rotated around the Z-axis in the direction that the axeses, or that the axes show, which structure below matches a rotation around the Z-axis? Um, A [pointing to diagram A, and reads question again under breath] [points briefly to the z-axis rotation, and then traces the y-axis rotation without lifting hand]

Christian: Do you understand which one is the Z-axis?
10: I guess that's the Z [pointing to the Y-axis rotation]
Christian: This is the Z right here
10: Oh, okay, turning around the Z-axis, [pointing to the z-axis rotation] oh, okay, um, I would say b because it looks slanted [uses hand to indicate the direction that choice b is in], like it's rotating like z does to the left.

10: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram, um, indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atom, atoms is are furthest from your eyes? Um, well, [points to atom 5] not sure what the, [points and traces the straight lines] just plain lines mean.
Christian: Read the question, Last sentence of the question tells you that.
10: Oh, atoms connected with straight lines, [points back at the structure] okay, in the plane of the paper. So I guess, um, well, one way furthest from your eyes, H is the furthest away from me right now, [points at atom 6] number 6, but then 8 and 5 [points to atoms 8 and 5] are supposed to be going through the paper, [uses pen to indicate a through the paper motion] so maybe 8 and 5.

10: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom is in the drawing, ur, which carbon atom in the drawing is closest to your eyes? Um, I guess a.
Christian: Keep speaking your thoughts.
10: I guess carbon a cause if you’re supposed to look at it from the left, [points at the left most hydrogen] yeah, [points through the whole molecule without lifting hand] the one on the left would be closest. I don’t know, and that’s a.

10: Um, looking, look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Okay, if you ignore the top and bottom of the box what is the order that you could build the sides, um, I guess [pointing to piece 1] 1 would be this piece on the left, [pointing to the left side of the box] because it’s clear, and 5 [point to piece 5] be the one on the back, [point to the back of the box] shaded, than 2 [quickly points at piece 2] looks like the same design,[traces over the right side of the box] and 4, [points to the right front face of the box] same design, [points to piece 4] and 3. [Pointing and tracing the left front face of the box] So, it’s not even an option, hum, okay 1, 3, that doesn’t work, 5, [points to piece 5] 1 isn’t there either, um, 5, 2, [points to piece 2] 4, 3, 1 that one, okay [circles choice a].

10: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. Um, I, hold on, on the left are square pieces of paper, the paper is folded, chose the positions of the holes when the paper is completely unfolded. Um, oh, d, [points at choice d] because the holes should be, [points at figure A] there should be two holes, and they’ll be [uses pen to indicate a it coming towards her diagonally] diagonal from each other.

10: Pick the figure that shows the positions of the holes when the paper is completely unfolded. Um, [points at the first hole punch, then moves on to the other two without lifting her hand from the paper] so there should be, if that was folded once, [points to the first figure and mimes a hole in it] than there should be 2, than 3, 4, [points to the second figure] there should be 4 holes and all near the center so a.

10: Two different types of models are illustrated below: Space-filling models and ball-and-stick models. In the next two questions, you are provided with a ball-and-stick model of a, of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space-filling model that matches the ball and stick model. Um, I guess, it’d either be a or c, and I’m going to go with, um, maybe a because that center ball [points at the central atom in choice a and in the reference ball-and-stick structure] looks like it’s bigger.

Christian: I’m sorry, so why did you say a or c in the beginning?
10: Do what?
Christian: So why’d you say a or c, you said in the beginning.
10: because they have, [points to choice b, and then choice a] um, because the position, [curling hands to indicate balls] positioning of them kinda matches [points to the choices a and c] the positioning of the first picture. [points to the central atom of the ball-and-stick
10: Two different types of models are illustrated below: space-filling models and ball-and-stick models. Pick the space filling model that matches the ball and stick model. I would say, [points to some of the outside atoms in the ball-and-stick reference structure] um, probably d because it looks like there are 5 on top, [pointing to choice d's front side atoms] and than 4, and than 5 more, [pointing to choice d] but it's opposite, [pointing to choice a] well, the top 5 [pointing to choice d's top atoms] look like they are all in the same plane [points to top atoms of the ball and stick reference structure] and that matches the picture.

10: This unit cell is represented by spheres. How many spheres are in this structure? Okay, so there are 9 on this side, [points to the right side of the structure] and 12 on that side, [pointing and tracing the front side atoms] so 12 times, [writes 12 x] 1, 2, 3, 4 [points to the 4 sides that are visible] sides, is 48, [writes 48] and 9 times 2 is 18, [writes 9 x 2 = 18] so that's 50, 64.
Christian: How did you get 64 again?
10: Um, I guess, well I don't know if there are any spheres on the inside? It looks like they are just on the outside, but if there are in the inside, they are more than that.

10: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? So is there just one sphere on the inside? Christian: I don't know there could be more than one.
10: Consider a sphere on the inside.
Christian: How many do you think there are?
10: Um, how many, okay, well if there is, if there is more than one sphere, all the same size as these on the outside, [pointing and tracing one sphere in the middle of 4 of the white spheres] then there's one right there, [pointing and indicating a sphere in the black area] and that would be touching 1, 2, 3, 4, [counting the spheres it is touching] on that side and then two more on the top, and two more on the bottom, [points to and counts 2 more on top and bottom] so that's 8, and then, 10, 1, 2, 3, 4, 5, 6, 7, 8, [counts the atoms again] no, it's just 8, yeah, 8.

Christian: So the last question is a list of 8 skills. I want you to read them through to yourself, and I want you to match, indicate which skills you think match the question, I'm going to give you back, okay?
10: Okay.
Christian: So read them through to yourself, and I'm going to give you a couple of the questions back. [pause while reading]
10: Okay.
Christian: Okay, here are the questions back. I want you to write on the question itself, any skills you think you used to solve the question with.
10: Um [looking at the hole punch question], um, form perception. [writes form perception] Christian: Why form perception?
10: Because, well the paper is being folded so you have to think about, [uses hands to indicate a folding motion] you know, this says it's like 2-dimensional representations or of like 2 or 3-dimensional, I don't know if it really is like that, but I guess when I think about different dimensions, I think about like putting, like having to fold them, [uses hands to indicate a grasping motion] and yeah. And then I guess just association, [writes association] because it's a picture, yep that's it.

10: Okay which atoms are the furthest from your eyes, um, [looking at the ethanol question] this one's form perception [writes form perception] cause you have to think about things coming like towards you, and going back, and on the same level, [uses hands to indicate forward, back and the same level] and then um, maybe just like figure ground too. [writes figure-ground]
Christian: Why figure-ground?
10: Because I guess just again, like I don't know, it says distinguish objects from their background. I guess just cause you have to think about like how it looks, like, [uses hands to indicate a grabbing motion] well I guess it's more form perception, maybe it's just form perception, yeah [crosses out figure ground] okay, yeah.

Christian: One more.
10: Um, where is atom U with respect to atom K, um, [looking at the diamond question]. Form perception again. [writes form perception]
Christian: Why form perception?
10: Because it's supposed to be a diamond inside a cube, and I know a cube is 3-dimensional [uses hands to indicate a box] with all these dashed lines, [points at the cube] and, um, also, maybe, um, discrimination because you have to, [writes discrimination] like, you kinda have to take, like with the cube you have to look at the dashed lines in different ways, [uses hands to indicate the walls of the cube] and it's not necessarily in the same place, like it could be in different places, depending on what way you look at it.
Interview with student 11

(Missed the first part of the interview because I wasn't recording.)

11: Okay, I think, okay, I am assuming that these are the answer choices around [pointing at the answer choices on the orientation question.]
Christian: Yeah, right, um hum.
11: Okay, [drawing an axis] I'm going to have to go with c.
Christian: Why do you say c?
11: Because if it's like this [hand hold out horizontally], it if was, it was rotated across the y-axis it would be like that. [rotates his hand] If it was rotated across the, wait, no. [mumbling], um, okay, so currently it's like this and this [drawing on his axis the molecule A] so if I rotate it. Alright, okay, okay.
Christian: You can cross that out, it doesn't matter [indicating answer choice]
11: I take that back, okay.
Christian: So which direction is the Z-axis rotating in, which direction is the Z-axis?
11: Well, I'm attempting to rationalize that in this plane of thought, and I, it's supposed to be something like. [drawing an axis with a line in the middle representing the Z-axis]
Christian: Right, right.
11: However when you actually put a 3-D model on a flat surface, it's kinda hard to think about.
Christian: Right, right. In this case, the Z-axis is over here, it's like coming out towards you, can you see that?
11: Okay, so it's coming out towards me.
Christian: Yes, the Z-axis is.
11: Okay, so currently will that be the X and Y? [drawing the axis next to figure A]
Christian: Um hum, right, right.
11: So the Z-axis is coming like that.
Christian: Okay, you got it?
11: Oh, than it should be d, shouldn't it?
Christian: I'm sorry why'd you pick d, one more time?
11: Because it's spinning around like this, [using pencil and spinning it] instead of flipping over like that, or flipping over like that. [uses pencil to indicate a flip] It's just going to spin.

11: Are you ready for the next?
Christian: Sure.
11: The diagram below is a stereochemical representation of a molecule ethanol. In the diagram hashed wedge indicates the bond that projects behind the paper, and the bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate bonds in the plane of paper. Okay, alright, bold wedge indicate bonds in the paper towards you, hashed wedges indicates paper, behind the paper [underlining the key words in the question], okay, Which atoms are the furthest from your eyes? H5 and H8 I would say.
Christian: How did you figure that out?
11: Because the hashed wedge is behind the paper, [using hands to indicate behind] so if these are coming towards my face, H9 and H4, [circling atoms 9 and 4] than that would indicate [using hands to show coming out of the paper] that they would be coming out somewhat like this correct? [using a pencil to show it coming out of the paper]
Christian: Um hum
11: Than the other ones would be going back through the table. [using pencils to show it going back]
Christian: You got it.
11: Okay.

11: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? Okay, okay I assume it's the same direction?
Christian: It's the exact same
11: Okay.
Christian: It is the exact same, um, notation.
11: Alright. [pause]
Christian: Keep speaking your thoughts.
11: Right, okay, so if I'm starting here, [pointing to the left most hydrogen] then this hydrogen is going to be facing up, however, it's going to be pulled down by these two hydrogen's here. [pointing to the carbon a's other two hydrogens] It's going to come back up to this carbon, [pointing to carbon b] and then these hydrogens are going to be at a higher level [pointing at carbon b's two hydrogens] than this one [pointing to the hydrogens attached to carbon a]. So this one is taken out, and these are definitely taken out [drawing lines through carbon a and the hydrogens attached to carbon a] um, so it's tied between these two, [circles carbon b's two hydrogens] okay that's pulled back down [points at carbon c and it's hydrogens] [pause]
Christian: Keep speaking your thoughts.
11: Okay, um, I'm going to have to assume that this, [points to carbon a and a hydrogen attached to carbon b] um, carbon b is having more forces pulling it towards me, [uses pencil to show towards himself] than away from me. And I can't rationalize any other being closer to my eye, just by using the best logic that I can assume on this one, I have no knowledge of it, that's what I am assuming.
Christian: Okay.

11: Look at the following box, insert box here. If you ignore the top and bottom of the box, what is the order that you can build the box, what is the order that you can build the sides from the following pieces? Okay, okay I'm assuming that 3 and 4 [pointing to pieces 3 and 4] would need to be next to each other, [drawing lines to indicate them next to each other] and 3 would have to come before 4. [writes 3 and 4] So that is marked out, and that is marked out [crosses out a and c] Okay, then 5 [points to piece 5] would have to be touching 2 [points to piece 2] on one side, [writes 5] 3 and, hang on. [crosses 5 out] alright, 3, and 4,
okay, if I'm facing 3 and 4, [uses hands to indicate facing the cube] than on the left side would have to be 1 [writes 1] on the right side would have to be 2. [writes 2] So 1 and 2 has to be on either side of 3 and 4, 1 has to be next to 3, [points again to piece 3] so okay I kinda messed that up. Okay assuming that 3 and 4 [points to pieces 3 and 4 again] combine to make [circles pieces 3 and 4] the X shown here, correct? [circles the X on the front of the box] Christian: Yes you are correct.
11: Okay, so, 3 and 4 would have to be together in that fashion, okay, 4 should be touching 2. There we go, however, hum, could, alright, well I might have spoken too soon. 1 touches 3, 3 touches 4, 4 touches 2 touches 5, 5 touches 1 that is the correct order just in reverse than the way I would normally think. I'm going have to go with a, but I would normally think of it as in reverse order. [mumbling and going through the rest of the answers] Because 5 can not touch 3, I guess I'm going to have to go with a.
Christian: Okay.

11: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that is shown, that shows the positions of the holes when the paper is completely unfolded. Alright, a piece of paper is unfolded as shown by the dotted lines, the paper, okay. Holes have been punched in the paper, okay, wait, okay, so, hum, alright.
Christian: Keep speaking your thoughts.
11: And, I'm sorry, I usually just try to think through. Alright, so if it was folded in half right there, [drawing a line through the center of choice a horizontally] and this corner was folded up, [draws another line on choice a] then.
Christian: So this is figure A, right here, this is how it is folded, right there.
11: Right.
Christian: Okay
11: That's, it went from this to this?
Christian: It was folded, this corner was folded up, and then a hole was punched in that, in that hole right there
11: Okay, so that is what actually happened in that. [draws an arrow between figure A and choice a]
Christian: Okay.
11: Is that what you are saying, or?
Christian: These are the choices down here.
11: Okay, so figure A does not necessarily correspond to figure a here? [circles choice a]
Christian: No.
11: Alright, so if this corner was folded up, [points at the first hole punch figure] and that was punched in there, [points at the bottom corner of figure A] then logically, [points again at choice a] that would not really work out, because if, hum, oh, yeah that would not work out at all, [points again at figure A] because the paper would not have holes side by side such as that. [points again at the holes on choice a] It would have to be d, [points at choice d] because only the corner was folded up there [draws a line on the choice d between
the holes] and then there would be two holes punched in there, and when it became folded
out again, [used pencil to indicate a fold down] it would look like that.

Christian: Okay, next question.
11: Okay. Two different types of models are illustrated below: Space-filling models and ball
and stick models. In the next two questions, you are provided with a ball-and-stick model of
a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick
the space-filling molecule that matches the stick and ball molecule. Okay, alright, looking at
this, it looks, I can't, I guess it would be tetrahedral. So, tetrahedral should have one ball in
the center then and one on the top, [draws a central bigger sphere, and then 4 smaller spheres
attached to that one in a tetrahedral shape] and they should be pulling away from each other
as best as humanly possible, so, that would definitely be out [crossing out d], that would
definitely be out [crossing out c], and that, I don't even know what they were thinking
[crossing out b], so I'm going to with a [circling choice a].
Christian: So why are you going with a again?
11: Because, it seems to be pulling the furthest away from each other, [points to choice a]
each of the molecules.

11: Two different types of models are illustrated below: Space-filling models and ball-and-
stick models. [laughs] Pick the space-filling model that matches the ball-and-stick model.
Oh boy, okay, so, in this one, there are, okay, there are four corners, then a dot in the center,
so the side should look like that [drawing a picture of four dots on the corners of a square and
a dot in the middle] okay. I'm not entirely sure what is going on here, it kinda just looks like
a crazy conglomerate to me [pointing at figure a]. This does not have enough atoms
[crossing out choice b]. This, [points at choice c] I am not entirely sure what's going on, it
appears to be something to the fashion of this, with one in the center [drawing dots to
represent choice c]. Right now d is appearing to be the best option, in my opinion, because it
appears to have the same format on the sides as that, [circles picture he drew of the side of
the ball-and-stick reference structure] and that matches up to that [drawing an arrow from the
drawing of the side to the reference object].

11: The unit cell is represented by spheres. How many spheres are in this structure? 1, 2, 3,
[points and counts the bottom row going back] 1, 2, 3, 4, [points and counts the bottom front
row without lifting hand] 1, 2, 3, [points and counts the right hand column without lifting
hand] okay, so 3 times 4 is 12, [writes 12 x 3 = 36] times 3 is 36, I believe, just to make sure
[writing 12, below 3, and then 36 below] yep, there are 36 spheres in that structure [writing
36 and circling it on the page].

11: The unit cell is represented by spheres. Consider a sphere on the inside, how many other
spheres will touch it. Okay, alright, so, hum, 6 [writing 6 and circling it].
Christian: How did you get 6?
11: Alright, because, I basically imagined it as the inside of a cube, um, I basically thought,
you know, alright, [drawing a cube] if there was something drawn in that, [drawing a sphere
inside the cube] how many surfaces could possibly be touched. So there is one there, one there, [points and counts his sides of his cube] and yada yada yada, I basically thought of it as a cube.
Christian: And there are 6 faces of a cube?
11: There are 6 faces of a cube, and this structure here is basically forming a rectangular prism there, [circles the structure] so, if one of the portions of it was inside of there, it could be potentially be touching six sides, if it was a perfect sphere otherwise it's not a perfect sphere, and it's a messed up structure.

Christian: I have here a list of eight skills, I want you to read through the skills, you can read them to yourself, and I'm going to give you back a couple questions and what I want you to do is to write on the question any skills that you think you used to solve the question with.
11: Okay.
Christian: So just read them through to yourself [pause while reading]
11: Okay.
Christian: So just assign the skills you think you used when you solved these questions.
11: Okay.
Christian: And write them on the questions themselves.
11: [looking at the box question] Definitely sequencing here, [writes sequencing] and then, yeah, mainly sequencing, and possibly a little bit of association, um, yeah.
Christian: Write association on the question as well.
11: Okay. [writes association]

11: [looking at the n-butane question] Okay, this one, um, figure-ground, [writes figure ground] if I'm understanding these concepts correctly, um, that and I'm not entirely sure if I used form perception, is form perception taking a 2-Dimensional structure and then trying to imagine it 3-dimensional, like I kinda threw in the y-axis on these points right here [writing y on some of the bonds]. Would that be considered form perception?
Christian: That's form perception.
11: Okay [writing form perception on the paper]

11: [looking at the orientation question] Oh boy, um, this one, well naturally orientation, [writing orientation] I probably destroyed that with the spelling, um, orientation, and maybe a little bit of figure-ground trying to figure out which way to look at this. [writes figure-ground] And, definitely constancy, because, [writing constancy] just because trying to relate this to this [drawing a arrow between the z-axis rotation diagram to structure A], kinda confused me, I had to think about it for a second.

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Interview with student 12

12: In the next question the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles. Pick the number of the figure which is unlike or (different from) the reference object. If all figures are like the reference object, choose d. Alright, so, I have the chose of a, b, so a is this, b is this, c is this? [pointing to choices a, b, and c in the table]

Christian: Um hum.

12: Okay, so which one is unlike? Well c looks exactly like the reference object [pointing to c], except tilted down like, [uses hand to indicate a turn] a 90 degree turn [pointing to the reference object], a 180 degree turn, I mean, and ah.

Christian: What are you thinking about?

12: I'm gonna say, I'm going to say a is different, because the base when turned towards this direction the two sides come up like this [indicating with hands a flat base and an angle that is upwards from the base], but in the reference object the two sides would come up like this [indicating with hands a different angle from the base], it would seem that a is different than the reference object.

Christian: Repeat what you said, one more time.

12: But at the same time, that one is different as well [referring to option b]. I don't know. Turned up [turning pen up] so basically I'm just trying to get this base [pointing to reference object] to be along this baseline [pointing to choice b's baseline] you know. And so here, [pointing to choice c] c looks exactly like the reference object. [pause]

Christian: What are you thinking about?

12: I really can't talk out loud at the same time, I mean this is hard for me [laughing a little]. Um, [mumbling].

Christian: Everyone can think out loud, right Holly. I think everyone can think out loud.

12: I really can't think out loud. Okay, different from, so basically all I'm trying to do right now is transpose this image, [pointing to the reference object] oriented like these, a and b, to see if they indeed match up at all points [pointing to object a and b]. But, I'm not seeing that with a and b, because if I turn this base like this [holding fingers to indicate the base of the reference object transposed to the base of choice a], two peaks come up, and it should be horizontal across, not vertical [using finger to trace the peak of choice a]. So it's almost like, does that make sense at all, I mean it makes sense to me.

Christian: Um, do you mean like in this case that this is shorter, this is shorter than this is? [referring to reference object and choice a's base of the pyramid].

12: No, it's makes, okay so like if I take the base, which is you know, the rectangle part, if you put it over here, [pointing to the reference object and choice a] in this case and this case, [points to choice c] they kinda come up, like the two points come up to a peak like this which make a horizontal line, right. [indicating with his fingers the horizontal line of choice c] But in this case, the peaks come up like this and make a vertical line [using his hands to indicate a vertical line and referring to choice a], but I guess this isn't exactly drawn to scale, so I guess that could be observed [pointing again to choice a]. I don't know, triangle, triangle
Christian: Keep going, keep speaking your thoughts. You can draw or whatever you want too.
12: I'm having trouble thinking today. So b, I pick b is different.
Christian: So why is it b?
12: Okay so c is easy, just turn it 180 degrees, [indicates a 180 turn with hand] it looks exactly like the same. And then a, you turn 90 degrees in a counterclockwise direction. [Moving hands to show a rotation]. You get the same thing. But here in b, I pick to be different, because, ah, the triangle is too small. [pointing again to choice b]
Christian: Okay
12: Is that good, can I go on to the next one.
Christian: Sure.
12: It's probably wrong though.

12: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose one best response. View atom letter K, okay here [points to atom K] Where is atom U with respect to atom K? So here [points to atom U]. It looks like.
Christian: Keep speaking your thoughts.
12: Okay, so, I don't know. I've got to trace from another point. So J is on the corner [points to J], and it is connected directly to U. So that would make sense if U is closer to this wall [indicating the front wall of the cube]. And then K is directed towards M, it's just be, that'd be [indicating the wall that M is on, pointing to atom B, the right wall]. So it definitely looks like, because U is connected directly to J, that it would be above K. Do I get an answer sheet in the end?
Christian: No, no answer sheet.
12: Want to know how I did.
12: If the structure in diagram A were rotated around the Z-axis, where's diagram A okay here, around the Z-axis [pointing to choice a]
Christian: No, this is diagram A [pointing to diagram A]
12: Oh, diagram A, this is just a, b, c, d, alright Diagram A, were rotated around the Z-axis in the direction that the axis show [pointing to the diagram of rotating around the Z-axis], so Z-axis of course, like this [waves hand in front of him, indicating the Z-axis] Ah, which structure below matches a rotation around the Z-axis? So, were rotated around the Z-axis, Z-axis, they want it rotate counterclockwise. [uses finger to indicate a counterclockwise spin] Structure in diagram A were rotated around the Z-axis in the direction that the axes show, which matches a rotation around the Z-axis. Okay, so rotation around the Z-axis, the two, um, larger atoms should not move. [points to the two blue atoms in diagram A] Are these, are these lined up on the Z-axis, or is like cause the Z-axis [trying to indicate with hands, whether or not the Z-axis is lined up with the two atoms, or not] is like this. Is it like an angle to the Z-axis, or are the atoms lined up exactly on the Z-axis?
Christian: Well they angled maybe a little bit, down, a little way up.
12: But either way, either way, they shouldn't, they shouldn't move. [points again at diagram
A] they should still be in this general vicinity. [waves pen back and forth] So I'm going to go with b.

12: The diagram below is a stereochemical representation of a molecule of ethanol. Okay, in this diagram hashed wedges indicates that a bond projects behind the screen, and bold indicates that it projects towards you. So, atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms are farthest, furthest from your eyes? Okay, so carbon, [points at carbon 2, 1, and oxygen 7] two carbons and an oxygen are the same distance away. [uses hands to wave and indicate same distance] So things that are projected towards me, should be closer to my eyes, [uses hand to indicate closer towards himself] so that means I have to choose from the two, 8 hydrogen and the 5 hydrogen, [points to atoms 8 and 5] to be farthest from my eyes. Because I have a plane where I have everything is in the page, [uses one hand to indicate in the plane] and the, the, ah solid wedge indicates things that are closer than that [using other hand below that to indicate the atoms that are closer], and the dashed lines indicates things that are behind that [moves hand to indicate the atoms that are farther away]. So then which one's farther away, 5 or 8? Both connected to Carbon, which are right here.

Christian: Read the question again.

12: Okay, I am reading the question wrong? Which atoms

Christian: [points to question] Which atoms

12: is furthest from my eyes, right? So atoms, so it could be 8 and 5 are the same distance away right, I can say that?

Christian: Um hum

12: Which would, would make sense because tetrahedral, so it's a 109 degree bond angle. [using fingers to put together] Meaning that, they should be the same distance. So I'm going to say 5 and 8 are the farthest away.

12: The diagram below is a representation of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to my eyes? Okay, these are all not in the same plane, so hydrogen is, is, going to be, the wedge is kinda towards me, [using one hand to show towards himself] so that means the carbon is going to be behind that, [using other hand to show behind the first hand] and the next carbon is closer up, [same hand indicating closer up] and the next carbon is farther out, [same hand indicating farther back] and the next carbon is closer up, [same hand indicating closer up] and the hydrogen is farther out. [same hand indicating farther out] So which carbon atom in the drawing is closest to my eyes? Not a, and not c. I'm saying not a, because it's behind b, based on the way it's drawn, because if I remember correctly the wedge here means that this carbon [pointing to carbon a] is in front of that carbon, [using hands to indicate in front and points to carbon b] and dashes
mean behind right? [uses hand to indicate behind]

Christian: Um hum.

12: So this hydrogen is behind this carbon. [pointing to carbon a and the hydrogens that are attached to it] Ah, okay, so b's going to be closer than a, [pointing to carbon b and a again] so I'm going to disregard a, which carbon atom is closest to my eyes. So, and it looks like c is behind b, [points to carbon c] but then d is in front of c. [points to carbon d] So I can't distinguish between b and d, unless I'm missing something.

Christian: Do you want to build it?

12: No, I should be able to see this without that. So, I have this hydrogen, and then it's in front of this carbon, and then I have the next carbon is in front of that carbon [using his hands to indicate what is in front of each other], so b is closer than a, so c is behind b, but d is in front of c. [using hands again to indicate what is in front or what is behind] a, b, c, or d, which one is closest to my eyes? Now does that mean, could that also mean that I'm looking at this molecule as like, uh, a, b, c, d, and b would be closer, not because it is in front of, but because it's farther in that direction? [points to the left] So I'm going with b.

12: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? So if you ignore the top and bottom, okay, what is the order that you could build the sides from the following pieces? So top and bottom correct? [uses pen to point to the top and bottom of the box]

Christian: Uh, hum.

12: Okay, so I need to pick, I'm just going to go through these then. So if I'd got 5, that ends up being this shaded region [using pen to point to shaded region on box], then 2, 3, then it's 4, then 3, then 1. So it looks like it goes 5, [points to the back of the box] then 2, [points to the right side of the box] right here and then they cut off this piece, into 3 and 4, down the middle, so 4 looks to be here, 3 looks to be here [pointing and drawing on the box on the front face 4 and 3]. And then 1 on this side, so [writing the number one on the left side of the box] what is the order that you could build the sides from the following pieces? 1, 4 doesn't work [referring to choice c], 5, 2 works, so 5, 2, 4, 3, 1, [referring to choice a] it seems to be a.

12: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the, the dotted lines are where the paper has been before the paper was folded. A hole had been punched in the paper as indicated in picture A for each question. Pick the figure that shows the position of the holes when the paper is completely unfolded. So, apparently they fold this piece of paper like this [pointing at the first hole punch diagram and showing a fold with a pen], so on the left are pieces of paper that have been folded as shown by the dotted lines, okay so they just took this, this edge and folded it to the center. [again showing a fold with a pen] A hole has been punched in the paper as indicated in the picture, and then they just unfolded it again. [uses pen to show an unfold] So it should have a hole here, where they punched it in, and the other one should be one at the corner [pointing to picture A], so it's d.
21: Two different types of models are illustrated below: space filling models and ball and stick models. In the next two questions, you are provided with a ball and stick model. Set out below it are four diagrams of space filling models of that molecule. Pick the following, pick the space filling model that matches the ball and stick. Okay, so basically you just fill in the stick portion, I am not, keeping the bond angles. Here in c, [points to choice c] it looks like, these two balls are too close together [pointing to the balls on top and bottom], so, that's why I say it is not that, and then here [pointing to choice d], it looks like these are too close together [pointing to the two balls on the side of the molecule], and then here, it looks like these are almost at a 90 degree angle to this one [pointing to choice b], and this one [marking on the two balls on top and bottom] so I'm going with a.

Christian: I'm sorry, why are you going with a again?

12: I'm going with a, because every other model looks bad, because the bond angles should be 109.5, here [pointing at choice c], it looks to be really small, between this ball and this ball [marking on top and bottom balls], here these two balls seem to be too far apart [on choice d, marking on the top and bottom balls], and these are too close together [writing on the balls on the left and right in the molecule.], and these two balls seem to be too far apart [writing on the top and bottom atoms on choice b]. I don't know if it is the orientation, but I'm going with a.

12: Alright now, same thing, except I have a different molecule, so I need to keep, um, the angle between the carbons, which I am assuming they are carbons, here [pointing to the ball and stick reference picture], and this space filling model only shows three and they are all in line [pointing to choice c], so I'm going to say that b is not the right. C, so in a, I have no idea what a is showing [pointing to choice a], but it doesn't look anything like the molecule up here [pointing to the reference molecule]. So I'm going to go between, no, I meant to do c here, not b. So now I'm going to go between, a and c are wrong, b and d. I'm going to try to look at and see if they are the same. And it looks like these all match up [referring to choice b] and it also looks like [pointing to choice d]. I don't know I'm having a hard time distinguishing between b and d because they look similar. But based on this orientation, it almost looks like this first hydrogen is behind this carbon [looking at the 3rd Carbon attached to it's hydrogen from the left side of the molecule] and you can like can barely see this other hydrogen here, which when you have a space filling, ah, model you shouldn't be able to see at all. And the same with this, yeah I don't, I can't really tell a huge difference between b and d except for this atom right here. [referring to choice d the second hydrogen from the left.] looks like d is wrong, because [drawing on the 2nd hydrogen from the left side of the molecule], this hydrogen is too close to me [indicating too close to the front of the paper] So I'm going to go with b.

12: Two different types of models are illustrated below: Space-filling models and ball-and-stick models, okay. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below it are four diagrams, so it's the same concept. So now, I just have to look to see which one is which. So, I'm assuming that no balls are displaced,
[pointing at an upper corner atom on the ball-and-stick reference structure] so b is wrong, [points at b] because it doesn't account for all the balls. And a is not anything like the cube, [points at a] and c doesn't look anything like that at all. But d accounts for every ball, [points at d] so I'm going to go with d.

12: This unit cell is represented by spheres. How many spheres are in this structure? Okay so it looks like that there are 12 on this side [pointing to the side that we can see all the spheres]. And it looks like it repeats itself three times for the diagram. And, I'm assuming these black spaces mean that balls are not in between. [points to a black space] So it's not a wall [using hand to indicate a wall] and then 6 balls, [points and counts 6 black spaces] and then another wall, [using other hand to indicate another wall] and then 6 balls, and then another wall. If you understand what I'm saying. This black means there's nothing there. [colors in a black section] Then I go, so, 12, 12, is 24, I'm going to go with 36. If that makes sense.

12: [pause looks at previous question] This unit cell is represented by spheres, how many spheres are in this structure? Okay, okay, alright, this unit cell is represented by spheres. Consider a sphere on the inside, consider a sphere on the inside, how many other spheres would touch it? On the inside, I guess there is only so many places, and they would all be the same. So if you were to put a sphere in here there are only certain places you could put it. [points to a black part of the structure] And each one would be identical to another one. And it would touch 8, I do believe, 4 from one side, [points to 4 front atoms] and 4 from the other side, [points and indicates 4 behind] so I'm going to go with 8, yeah.

Christian: So for the last question I am asking you, I'm asking you to assign these two questions that you did into these categories of skills. [I give him the two questions he had trouble with number 1, and number 9]. So my test has eight skills I am trying to test.
12: And they are listed here?
Christian: And they're listed here right, right. And I want you to try to assign these questions to these 8 skills.
12: Just these two?
Christian: Yeah, just these two does that make sense?
12: So, association is, is it well I guess I'll see that, is relate concepts which are shown in pictures and written words.
Christian: Just go through all the skills before you..
12: Relate concepts which are shown in pictures and written words. Okay, constancy is see diagrams of objects that are the same size, shape, or color from others that are not. See diagrams that are the same size, shape or colors from others that are not, well that would be one [writes constancy on the discrimination question] constancy right. And then discrimination perceive dominant features in objects and to discriminate one object from another that would be nine to me, I had to see. I don't know dominant features, perceive dominant features in objects, yeah, I perceived what I considered to dominant features. I don't know if they are supposed to be in here, but I'll put it here [writing discrimination on
the second butane question]. Distinguish objects from their background, I don't think we had to do that. Interpret two dimensional representations of two or three dimensional objects, yeah, that was in both of these [writes form perception on each question 1 and 9]. Form perception. Recollect the dominant features of a diagram. Well if you have to do discrimination, you have to do memory, I don't see how you couldn't, because you have to transpose to the next model [writes memory on both of the questions]. Rotate and reflect the positions of objects in space, so this is orientation [writing orientation on discrimination question], well these were not changed in orientation, just field [referring to discrimination question]. See objects in a particular order, I don't know, maybe I could put sequencing here since there connected [going to draw it on the 2nd butane question]

Christian: So all these skills don't fit all these questions

12: Is it only one per?

Christian: It is only one per skill but that's okay.

12: Really? Cause I just picked the best one, based on my reading, it seems like you could use multiple per question.

Christian: You could definitely.

12: So I only need to pick one?

Christian: It's okay, so these questions that only fit one question per skill, but if you want to pick more than one, it's okay.

Schlitz: That can be good information for us, but you don't have to try and work all of them into one...

Christian: I agree.

12: Well I didn't know, I didn't know it was just one per, maybe you said that and I didn't pick it up, but it seems, it definitely seems to me that you could say that one question is, requires more than one skill, but see objects in a particular order. I don't think that was required, we didn't have to see anything in a particular order, so now do you want me to pick one from each of those

Christian: If you want to, I don't care.

12: I don't see the reason, unless you want me to.
Interview with student 13

13: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question, choose the one best response. View atom letter K. [points to atom K] Where is atom U with respect to atom K? [points to atom U, and draws lines around the box] Um.

Christian: Keep speaking your thoughts.
13: Okay, I'm crossing that because it seems like it's cutting that cube in half, so, K [pointing again at K] and K, K and U [pointing again at U] touch the same lines so I would say same level.

Christian: Okay.
13: Do I circle it?
Christian: Yeah, circle it, that'd be great thank you.

13: So, if the structure in diagram A were rotated around the X-axis, Z-axis in the direction that the axis show, which structure below matches a rotation around the Z-axis? Turning around the X-axis. [points to the z-axis rotation diagram]

Christian: So it's around the Z-axis, you get that, right?
13: Z, yeah, I keep saying X.
Christian: [laughs]
13: So if the structure in diagram A [points to diagram A] were rotated around the Z-axis, which is this one [drawing a line on the Z-axis], in the direction that the axes show, which structure best matches, [points again at the z-axis] so Z-axis.

Christian: Keep speaking outloud.
13: Okay, so, does it start like right here, [draws a dot on the z-axis] is that where it starts and I'm just rotating it?

Christian: It doesn't really matter.
13: Oh, okay, so if I'm starting here, and basically rotating, cutting that cross section [drawing the Z-axis across diagram A], and rotate it like that, [drawing an arrow to indicate direction of rotation by diagram A] it should look something like that [rotating the paper around], it would be b.

Christian: Why you'd say b again, I'm sorry.
13: Because I cut it right there, [retraces line through diagram A] since it's turning like that, I turned the page to look at it like that, [turns page again the same way] and it's sorta slanted, or you can look at it like that slanted [turns the paper the other way], at my point of view, which this one is slanted. Right?

Christian: [mumbling] Sounds good.

13: Okay, the diagram below is a stereochemical representation of a molecule of ethanol. In this diagram slashed wedge indicates that a bond projects behind the paper, and the bold wedge indicates that the bond projects out of the paper towards you. Atoms connect with straight lines indicate that the bond is in the plane of the paper. Which atoms are farthest from your eyes? 8 and 5 because it says it's behind the paper, [circles the bond connecting to
atom 5] and these are towards, these are towards me [uses hand to indicate closer to her eyes] so they're closer to my eyes, [draws on the bond with atom 4] these are like in the middle since they're on the paper, [points to the paper and draws on the straight line in between carbons 1 and 2] and the hashed wedge are behind the paper [points again to atom 5] which means they are farther to me, from me, [uses hand to indicate farther from herself] so, which this is 5 and that's 8, yeah.

13: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? So from left to right, [points to all carbon atoms in the diagram] which carbon atom is closest, kay, [draws a line between carbon a and carbon b] so, that one has 2 close 2 far, [points to carbon a] that one has 3 close, 1 far, [points to carbon b] 3 far 1 close, [points to carbon c] does it matter that the length is smaller in this one? [points to the bond connecting carbon c and carbon d]
Christian: It does matter.
13: What does that mean?
Christian: It means it's not, it's not as far forward.
13: As in, towards me? [uses hand to indicate towards her]
Christian: Towards you, um hum.
13: Kay, so if you visualize the molecule from left to right which carbon is closest, so that means this one is farther, [points to carbon d] and these are behind, [draws on the lines around carbon c] and this has 2 close to me [draws on the lines around carbon b] and 1 far, so it will be b.
Christian: So why you'd pick b again?
13: Because this one, I said, ah, these two were close to me, this one has 2 close 2 far [points again to carbon a], 3 close, 1 far [points again to carbon b], this one has 3 far [points again to carbon c], and that one's farther than this one [points to carbon d and the left most hydrogen bond to carbon a], and these have three close and one farther [points again to carbon d]. So I had to choose between b and d, [points to both b and d] but then you said that one was farther from me, so that means this one should be closer to me.
Christian: Okay.

13: If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces?
Christian: So read the question again, I'm sorry.
13: So look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Okay, I'm not really understanding. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces?
Christian: Here is a little box right there. [gives the little box]
13: Okay, so if I ignore the top and bottom, I'm just wanting to make the sides, which is this right here? [indicating on the box with a pencil where the sides are]
Christian: Um hum, the sides, um hum.
13: And from my perspective. Okay never mind, this is the top, and that's the bottom, [crosses out the top and the bottom] so that means I have this is toward me, that's in front, [draws the front of the box with the X pattern and writes front above it] and then there's a normal one that's to the side left, [draws an empty square and writes side above it and left below it] and then that one looks like that, and that's side right, [draws the pattern of the right side and labels it side right] and then the shaded one, looks, that's the back. [draws the shaded back and writes back beneath it]. So 5 is that, [points to piece 5] 2 is that, [points to piece 2 and her drawing of the right side] and then it would be 4 and 3, [points to the front piece she drew] no, you put these two together. [indicates with hands the pieces 3 and 4 coming together] Can I like turn them, like that? [turns paper]
Christian: Sure, sure.
13: Okay, so 5 is, [points to her back side] 5 does it matter the order?
Christian: It does matter the order, you're trying to put them in order.
13: In order how?
Christian: In order of the box, so they fit together to make the box. Make sense?
13: Could I start with the back, and then the 2 sides, and then the front? [points at the box]
Christian: No, you want to go back, you want to go around the box, when it goes back, side, front, side, does that make sense? Or you want to go front side, back, side, you want to go all the way around the box.
13: So I would go back, side, front, side? [points back to the box and indicates the order of the box]
Christian: Right.
13: So it's back, [draws four arrows in a square] side, so the back is 5, and then the side to the right is that one, [points again at her right side] which is two, [points again at piece 2] and then the front is that one, and then that is, well since I'm going what way, that would be 4 and 3, [writes on her front piece where 4 and 3 are] which would be that one [circles a].

13: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the position of hole when the paper is completely folded.
Christian: Unfolded.
13: Unfolded, so, this is folded, [points at diagram A] can I fold this?
Christian: Sure.
13: [starts folding the bottom of piece of paper] Okay, so that's where the paper was, so now, this is dotted, [draws a dotted line on her physical representation] that's where it was, and then punched a hole in here. And then [uses pen to punch hole], now when it's unfolded, it should be d.
Christian: Why you'd pick d again?
13: Because kay I folded this paper, so as this shows this is where it was, and this is where it is now. [colors in her fold] So that's my folded part, and then it says a hole has been punched in the paper as indicated in the picture. So once it punches it, it punches through the whole
thing. And then it says pick the figure that shows the position when the paper is completely unfolded. So I unfolded it, and one is right here, and one is right here, [circles the two holes on her physical representation] which is the same as this one [indicated d].

13: Pick the figure that shows the positions of the hole when the paper is completely unfolded. Okay, so, wait,
Christian: It's folded the bottom in.
13: Does it matter if is not a square?
Christian: It doesn't matter, no.
13: So, that, Wait.
Christian: [mumbling, hands interviewee another piece of paper] a blank piece of paper, whatever you want.
13: So it's been folded here, [folds it down once], so I have to do it here, right? Sorry I have to make it a square so I can see it. [rip bottom off]
Christian: It's alright.
13: So, that's my square, yeah, so now it's folded, so it can have, that, [folds it 2nd time]. So there's where it is in the original picture, then it has a hole here. [puts hole through with pen]
Christian: That's awesome.
13: That's a big hole, and then when I open it, well it was like this, so when I open it it should be like this, and like this, [opens up the physical representation] which means there's 4, right there, it started like that, and it matches up with a. And I didn't do it like that, or it would have matched up with e [rotate paper around], cause I started off like that, so that gives me a. I like that one.
Christian: So you liked that one.
13: Yeah.
Christian: So you're definitely a very kinesistic learner, you like to work with your hands. I like that.
13: Uh, huh, cause these are sorta harder for me.

13: Two different types of models are illustrated below, space filling models and ball and stick models. If the next two questions you are provided with a ball and stick model of a molecule. Set out below, in the next two questions you are provided with a ball and stick model of a molecule. Set out below it are 4 diagrams of space filling models of that molecule. Pick the space filling model that matches the ball and stick model. Can I use these? [reaches for the model kit]
Christian: Sure.
13: I just don't really know how to use them.
Christian: It's okay.
13: Wait, if there's, that's 1, 2, 3, 4 [pointing and counting the atoms on the ball and stick model], 4, and they have these, these act as molecules right?
Christian: Atoms.
13: Atoms, and that one goes there, um..
Christian: Keep speaking your thoughts.
13: Okay, I'm trying to look up at it to get the same angle as the picture, and it seems like it's like that. So in these the whiter bubbles are these, [points to choice a and her model] so if it's like this, I'm just imagining these being bigger, [using hands to indicate bigger atoms around her physical representation of the molecule] so that would give me a. Because this one, from this point of view, seems to, it's going to overlap, [using pen to indicate a bigger central atom] that one if it's going to be a bigger bubble, [using pen to indicate a bigger top atom] and this one going to be farther out, [indicating with pen a bigger atom about the side atom] and this one going to be farther down. [indicating with pen a bigger bottom atom] And that one um, that one doesn't show, [pointing to choice b] or that one, [pointing to choice c] or that one [pointing to choice d].

Christian: Okay, I'm sorry what do you mean that doesn't show, what doesn't it show?

13: Like I'm covering, I mean I'm not seeing it from both eyes, like it's staring at me, so I'm covering my left eye, and I'm just imagining that these were bigger, [uses pen again to indicate a bigger top atom] like bigger balls, and this one would be on top of that one, [indicates that the top atom will be on top of the central atom] and that one would just be outside, [indicates the right side atom] but this one shows it like would be like this, [rotates the model] and that's not how I'm looking at the molecule [pointing again at choice b], and that one just doesn't seem right [pointing again at choice d], and those, don't leave any space for those 4 [pointing again at choice c] you see right here, [pointing to the gray spaces in choice a] yeah.

13: So, two different types of models are illustrated below, space filling models and ball and stick models. Pick the space filling model that matches the ball and stick model. Wow, so 2 different types models are illustrated, space filling models and ball and stick. These are the space filling right, and this is the ball and stick?

Christian: Um, hum, um hum.

13: Pick the space filling model that matches the ball and stick, so I have 1, 2, 3, 4, [points and counts the atoms on the corners of the front face] 4 in this rectangle, um, square, like at the ends, [tracing the front square] here's could be 1, 2, 3, and 4, [circling the front atoms of choice d] this one shows that it's sticking out more than that one [pointing to the central atom of choice d]. This, You see that one, this one seems that it seems to be sticking in, [pointing to the central atom of choice b] this one seems to be sticking out. [pointing again at choice d]

So, and this one, so it's that here, [drawing lines between the four corners and the central atom on the face of the ball-and-stick reference object] it sorta seems to be sticking in, this one right here, [circling the central atom in the ball and stick model] so here's the 1, 2, 3, 4 [counts the corners of choice b] and then there's this one [circling the back corner of choice b], this one, [circling the back corners of the ball-and-stick] and this one is like that, [draws a line on the back of the ball-and-stick] that could be like that [draws lines in between the back atoms of choice b]. And I can see this one, [points to the lower back corner of the ball-and-stick] but here I can't see it [pointing to the missing lower back sphere on choice d], and I can see it here [pointing to the lower left sphere in choice b]. I definitely don't think this ones it, because the two bottom ones seem to be sticking out more than the top, [pointing to choice c] and this one seems to be sticking out more than the bottom, or at least the same [pointing
again to the ball and stick]. So those, [drawing another line between choice b's bottom atoms] let's see 1, 2, 3, [points and counts the atoms of the ball-and-stick] is it okay if I count them [laughing]? Christian: It's fine I don't care, whatever you want to do [mumbling].

13: 1, 2, 3, 4, 5, [counts again] well never mind wait, from the top view of the cube, [traces the top of the cube] it seems like there's 5, [circles the middle atom of the top face of the ball-and-stick] from the top view of this, I only see 4 and then a middle one [pointing to choice b], and 4 down at the bottom, here, I see the four in the front, the four at the top, [pointing to choice d] the middle one which is that one. [pointing to the central atom of the top face of the ball-and-stick] And these all seem to be cluttered up, it doesn't look like a cube [points to choice a]. So I'm thinking it's d.

13: This unit cell is represented by spheres, how many spheres are in this structure? That does mean within the structure too?
Christian: No, I mean like in whole the structure, just not within it, like with the whole. 13: Like outside including inside? [pointing at the whole structure]
Christian: Um hum.

13: Okay, so that's 1, 2, 3, 4 [points to the back row of the object] 1, 2, 3, 4 across the top, [drawing 4 spheres next to the object] 3 going down the bottom, [drawing 3 more spheres going down] and so that means there's 3, 6, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, [points and counts all the rows of the object] 12 times 3 is 36. [writes 12x3] Did you see how I got that?
Christian: No, not really, I'm sorry.

13: Um, I so there's 3 going down, [points to the left back side row] across, I mean up and down, so there's 3 here, 6, 9 here, [points and counts the left side of the object] and then, so I just counted by 3, there's 1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 12 columns,[counts the 12 columns of the object] and each column has 3,[points and counts down the front column] so 12 times 3 is 36.

13: The unit cell is represented by spheres. Consider a sphere on the inside, how many spheres will touch it? Wait, consider a sphere on the inside, how many spheres will touch it. And there's a lot of spheres on the inside?
Christian: Well, there are only 36 spheres you said in this structure, so if there is a sphere on the inside how many other spheres would touch it.

13: So consider A sphere.
Christian: One sphere on the inside, yeah.

13: So I'm just considering one?
Christian: One, right.

13: So it's basically this 1, 2, 3, 4, [points and counts 4 spheres on the front face of the structure] 4 yeah.
Christian: 4, okay.

13: Because this can be just pretending to be a cross section of the unit cell, and if this would be the inside, [pointing to the front face] this would be my sphere that I chose, [drawing on a front sphere] so there's 1, 2, 3, and 4. [marks on the spheres next to the one she chose]
Christian: Okay.

Christian: Last question is a list of skills, I want you to read them over to yourself, and I'm going to give you a couple of the questions back, and I want you to assign these skills that you think you used to solve the questions with.


Christian: Okay, so write on the question, any skills you think you used to solve the question with. [mumbling]

13: Write it on here?

Christian: Write it on the question itself.

13: [space filling with the methane molecule] So form perception means that interpret 2-dimensional representations, so basically looking at a 2-D and seeing it as 3-D.

Christian: Yep, um hum.

13: Okay, so, [writes form perception = made ball and stick model similar to the space filling model] ball and stick model, similar to the space.

Christian: You can say it, I will transcribe what you say, so you don't have write all that stuff if you don't want to write it.

13: Oh okay.

Christian: I mean I will transcribe it so [laughing].

13: So do I just tell you?

Christian: Yeah, tell me that's fine.

13: I guess, I used the form perception model because I used these, um,

Christian: Model kit.

13: Models, to represent the 2-D model so I can actually see it, [points to the question with her pen] and um, and orientation also. I'll just write down which ones I use, and then I'll explain. Orientation, now I used orientation, because it says right here, rotate or reflect the positions so I found that [points to the ball-and-stick reference object] one equal to that one, [points to choice a] and then if I rotate [uses hands to show a rotation] it to equal to that one [points to choice b] it was not the same, [points back at the ball-and-stick] and that's that.

13: And this one [the harder paper folding question] relate concepts which are shown in pictures, so it's basically looking at the pictures and knowing what you are doing?

Christian: Um hum, um hum.

13: Definitely that one, [writes association] because it showed me the dotted lines, where to fold, how to fold and where I was placing my the hole, [pointing at question with pen] see diagrams same size, also form perception, because I had to do it myself, [writes form perception] okay.

13: Oh, and this one [the box question], constancy [writes constancy] because I had to, ah, separate the front from the side, from the back, and decide up and down, well not forgetting about the up and down, [pointing to the box] um, and orientation, [writes orientation] and sequencing. [writes sequencing] Would this one have one right answer, or two right answers?
Christian: Just one, all the questions have one right answer.
13: Oh.
Christian: So why you'd say orientation with this question?
13: Because rotate or reflect the positions, because I had to, um, rotate or reflect the positions of objects in space in relation to other objects and the observer. I had to, when it says rotate or reflect the positions of the objects, I had to reflect on where it was on the cube in my perspective, [points to box] yeah, because at a certain point, this seemed like it was the top, the shaded area seemed like it was the top, and this X-ed out area seemed like it was the bottom, at some point, and at then another point it seemed like this, [pointing to the box again] so that's why I was asking because there could be two perceptions.
Christian: Yeah, there could be.
13: Yeah.
Christian: And why you'd say sequencing again?
13: Because I had to go from back to side, to front, to side, and I needed to see it in order in order to look at it.
Interview with student 14

14: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. View atom letter K. Where is atom U with respect to atom K? Well, here's atom U [pointing to atom U]. And I feel like atom K [points to atom K] is on the same dotted line, but it almost looks like atom U is slightly above it with respect to the shape of the line. [points to the line behind K] But I think it's a mean that they are on the same dotted line [points to the line behind K again] so I'm going to go with c.

14: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Alright, there's the Y-axis, the X-axis and the Z-axis [pointing to the x-axes diagram], so around the Z-axis, would be, the X-axis, on the X-axis would be that way, [uses hand to indicate the x-axis] Y-axis, [uses hand to indicate the y-axis] and the Z-axis would be over [uses hands to indicate a rotation] and across, [pushes hand to indicate an across motion] so I feel like it would go diagonal, [using pen to indicate a z-axis rotation] so b.
Christian: So why did you pick b again?
14: Um, because I feel like the X-axis, um, would rotate underneath, [uses hands to indicate an underneath rotation] and the Y-axis would rotate across, [uses hands to indicate an across rotation] so, the Z-axis [pointing at the z-axis] would rotate in a diagonal form, such as, um, because that would rotate around, instead of this way, instead of bottom, [uses both hands to indicate a bottom and then up movement] d and then, across and then that one would be up, [uses pen to indicate up] so it would be a diagonal. [points to choice b]
Christian: Okay.

14: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms are furthest from your eyes? Okay. [pause]
Christian: Keep speaking your thoughts.
14: Do what?
Christian: Keep speaking your thoughts please.
14: In this diagram a hashed wedge indicates that a bond projects behind the paper, [points at the figure] and a bold wedge. Behind the paper, behind the paper [writes on the figure that bonds 8 and 5 are behind, okay so the bond projects towards you, towards, towards. [writes atoms 9 and 4 are towards] Atoms connected with straight lines indicate that the bond is in the plane of the paper, so that would be plane, plane, plane. [writes plane near atoms 6, 7, and 3] So that, if those two are towards me, [waving pen at himself] and then it's behind, [uses pen to indicate behind the paper] and that's on the, these two are on the plane, so these
two 9 and 4 are facing me, [points to atoms 9 and 4] 6, 7, 1, 2 are on the plane, [points to atoms 6, 7, 1 and 2] and then behind me the ones furthest away can either be 5 or 8. [points to 5 and 8] I feel like it would be, um, atoms 8 and 5 because those would be the ones furthest away, not pointing towards me.

14: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from your left to right, which carbon atom is drawing, in the drawing is closest to your eyes? If you visualize the molecule from left to right, starting from the left, [pointing at the left most hydrogen] and there’s 1, 2, 3, 4 carbon atoms in which it could be either a, b, c, or d. [pointing to all of the carbon atoms] Well if these two, these must be pointing away from me, [pointing to the hydrogens attached to carbon a] and those are also pointing away from me, [pointing to the hydrogen atoms attached to carbon c] so I feel it wouldn't be either a or c, and since it is from the left to the right, I'm go with, um, carbon atom c, [pointing at carbon b] which is letter b, so go with b, because it is the closest one from left to right, on the plane.

14: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? Look at the following box. If you ignore the top of the box, what is the order that you could build the sides from the following pieces? Well, if you ignore the top of the box, so if I was going to ignore the top of the box, I'd start from the bottom, so I would probably start with.

Christian: Read the question again.

14: Okay, look at the following box. If you ignore the top of the box, what is the order that you could build the sides from the following pieces?

Christian: Ignore the top and bottom of the box, read that again.

14: Oh, top and bottom of the box, okay, so if I ignore the top and bottom of the box, [pointing to the top and bottom of the box] I would probably start now from the back of the box, to make it easiest, so I'd start with box 5. [points to piece 5] That eliminates c, so I could have a, b or c. And then I would go, um, to the right, [pointing to the right side of the box] around cause I can see that that piece is most similar, [pointing to piece 2] um, to representing the right side of the box, so I'd go with 2. [points again at piece 2] That would eliminate d, so it could be a or b, and then I would keep continuing around from the right [points again at the box] and I would, and that would create box, um, 4 [points at piece 4] to enclose as the triangle, [points at the front right side of the box] and so that would eliminate selection b, and so it would have to be a. Continuing around cause then the left side [points to piece 3] could be the left triangle, [points to the left side of the front of the box] and then answer 1 [points to piece 1] could fill in, um, this left side of the box. [points to the left side of the box]

14: On the left are square pieces of paper that has been folded as shown by the dotted lines. The dotted lines are where paper has been before, the dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is
completely unfolded. Okay, I'd first start by thinking this wording is kinda tricky, so I'd make sure I understand what's going on, on the left are square pieces of paper that have been folded as shown by the dotted lines, so the dotted lines are folds. [draws a line underneath the first hole punch picture] The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A. Pick the figure that shows. Okay, well if the paper is folded from, [points at picture A] if you have a solid piece of paper, [drawing another square piece of paper] before it has been folded, with no dotted lines, [draws dotted lines in his figure] and then you fold it over there would have to be two holes, [folding corner of the piece of paper that the question is printed on] cause there would have to be two pieces of the paper like so, so if you punched a hole through right in that place [points again at picture A] It, there would be a hole as in where d would be, [points at choice d] no wait, for that one, and then there would be a hole right there, where the paper went through, so I'd go with answer d.

14: Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, so we start with, this is a fold, [points at the first hole punch picture] so the paper looks like this, [drawing a square next to the question] we folded the paper, this way, completely over, and then, if you folded the paper completely over, and then folded the paper this way [folding the paper that the question is on different ways] and then put a hole in the right, [points at picture A] that would mean, the piece of paper would have four holes if you folded it twice. Um, because of there would be four layers of paper, [using fingers to indicate the thick paper] and if you went to unfold back this way, [using hands to indicate unfolding] I feel like that hole would be best represented by a, [points at choice a] it wouldn't be as far away from, [points at choice e] or as close to the corners, it would be more in the center of each line like shown in picture a.

14: Two different types of models are illustrated below: space-filling models and ball and stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space-filling molecule that matches the ball and stick molecule. Well, I'm not quite sure about this one, I feel like the ball and stick molecule [pointing to the ball-and-stick molecule] is a trigonal planer, and I feel like d would represent the best trigonal planer, [points to choice d] but it's kinda of a guess. Can you guess?
Christian: Sure.
14: Okay, It would be a complete guess for me.

14: Two different types of models are illustrated below: space-filling models and ball and stick models. Pick the space-filling models that matches the ball and stick model. Well, I know the space, so the ball and stick model, I can see, has quite a few atoms, [pointing at the ball-and-stick reference object] with different 1, 2, it looks like, 1, 2, 3, it looks like 4 layers, [points and counts the layers] with quite a few atoms in the, um, in the ball and stick model. So I feel like selection a has the most molecules, so I'd go with a.
14: The unit cell is represented by spheres. How many spheres are in this structure? How many spheres are in the structure of the unit cell. Um, is this talking about each individual sphere? [points to the structure] Or, I guess that's what I'd think, it doesn't say anything about how many atoms are in it, it just says spheres.

Christian: Ah, a sphere is, ah, one of the atoms is a sphere.

14: One of the atoms is a sphere, okay, so I'd start with 1, 2, 3, [counts down the left row] 1, 2, 3, [counts across the top row] so there's rows of, columns of 3, rows of 4, [points again at the front face] so that would be 12 on each side, 12, 24, 36, 48, [points to the different sides of the object] then 1, 2, 3, 4, 5, 6, [points and counts the black space in the middle] 48, 54, 60, not quite sure if, I guess these individual, atoms individual are counted as spheres, so I'd go with 66.

14: The unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it. Well, if there’s a sphere on the inside, [points at the structure] um, and it’s on one row [uses hands to show the different rows] of 4 comma 3 on the sphere, or the inside spheres, are located on the second layer. There would have to be this sphere on this corner [pointing to the left bottom sphere] touching it which would be 1, the sphere this side up, [pointing to the sphere next to the left bottom one] the sphere above it, [pointing to the sphere above] this sphere on the backside, [points to the one behind] so 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, [points and counts the spheres in the left hand corner of the structure] would be touching.

Christian: For the last question, I’ve given you a list of 8 skills, I want you to read through the skills, I’m going to give you a couple of the questions back, and I want you to indicate which skills you think you used to solve the question.

14: Okay
Christian: You can read through them to yourself.
14: [pause while he reads them] Uh, huh,
Christian: Okay
14: So I’ve got to read it out again?
Christian: No, just try to rationalize which skills you're using to solve the question. And can you write on the question any skills you think you used to solve the question as well, write on the question itself, like, any skills you think you used.

14: [looking at the hole punch question], I'd say sequencing, [pause] I'd say orientation, because I was having to rotate [uses hand to rotate] and visualize the space, and form perception.
Christian: Why that one as well?
14: Do what?
Christian: Why form perception?
14: Why?
Christian: Why, yeah.
14: Um, because I'm taking this 2-dimensional representation and I was, um, [picks up the paper the skills are on] using the piece of paper to actually physically interpret the 2-
dimensional representations into 3-dimensional. I would say that was about all.

Christian: Now, this one.
14: This one?
Christian: Yeah.
14: [looking at the box question], I'd say I started with sequencing, from the back, so I knew where I was going start, and keep going the same order and orientation as well, because I looking at a box [pointing to the box] and having to rotate the sides, [using hand to show a rotation] and I'd say memory cause you had to memorize, to remember where you started, and, um, which pieces you already used and where you need to go. Um I feel that that wouldn't be a 2- that's 3-dimensional, so?
Christian: Uh hum.
14: Than I say, figure ground because I was starting from the back, I'd say, I'd say that's all.

14: [looking at the orientation question]. Um, I'd say orientation because I was trying to visualize what rotations the individual axes were doing, um, and memory because I'd have to remember which way the axes was rotating, [uses hand to indicate a rotation] Um, I'd say, form perception because it was 2-dimensional, and I was looking at a 3-dimensional, um, answer, and watching how it, um, how it actually, how I interpreted it's movement around the axes, um, I think that's about all for that too.
Interview with student 15

15: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question, choose the one best response. View atom letter K. Where is atom U with respect to atom K? Well, U is kinda adjacent to K, but not on the same plane. So, it looks to me like it's above, but it depends probably where you're viewing it from, because the angle's different. But it looks above, but it might not be drawn to scale, so I feel like you can't determine, without seeing all angles of the cube. So I would choose d.
Christian: Okay.

15: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Turning around the X-axis, so, it's kinda hard to see cause it's like computer made, so it's three-dimensional, which means, it would be easier to see if I could see it all, see it like, I don't know a different model. But if you rotate it around the Z-axis. Christian: You might want to use a model kit the gold one matches it pretty well over there, that one matches the molecule pretty well. [Picks up the molecule and pauses]. Keep speaking your thoughts if you would.
15: Oh, okay, um, kinda just, just looking at it, cause I don't really understand the question, so I probably would make an educated guess.
Christian: Okay, so around the Z-axis, this is the Z-axis right here.
15: Uh, hum.
Christian: And this is diagram A right here. The Z-axis, which model, which, would show, after you've done that.
15: Oh, okay, okay um, I would say b.
Christian: Why would you say b?
15: Because it kinda looks like, it's titling to the left, which seems that the Z-axis is rotating that way, so yeah.
Christian: Circle it on the paper

15: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram the hashed wedge indicates that a bond projects behind the paper, and a bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. So which atom or atoms are furthest away from your eyes? Well the hashed wedge means that it's further away from you because it is behind the paper, and those are the CH, CH2, or C2H5 and CIH8, so, and the bold ones are towards you so it can't be those, and then the regular ones are just on the paper. So, I feel like the ones that are behind the paper are going to be the furthest away. So I guess I'll circle, can I circle?
Christian: Sure.
15: So I'm going to circle that one and that one [circling the whole hashed bond including the C1 and the C2].
15: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? From left to right, well, the first carbon has, well that means that the second carbon [pointing at carbon b] is going to be, towards coming out of the paper, because it has a bold line connecting to it, and that H is coming out, then there's the H and then C, and then H, H and then C, [using pen and hand to indicate the different atoms' positions] so, I feel like because the line is drawn longer, that means it has a longer bond, so, I would say that the b, carbon b came out more.

Christian: Okay.

15: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? So no top and bottom, so I'd put 5 first, and then, 2, then, hum, probably 4, 3, 1, because, just looking at it, like 3-dimensionally that is how I would built it, so 5, 2, 4, 3, 1.

15: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, this question is a lot of steps, so that's kinda hard to think about. Um, that's a lot for my brain to process, so I'm just reading the question again to see if I can process it.

Christian: Okay.

15: So, the dotted lines are where paper has been, before the paper was folded. And a hole has been punched in the paper as indicated, so I feel like when the paper is completely unfolded it's going to be d. Because there's a hole where it is now, [points at figure A] where, and it's folded up, so when you unfold it, there's also going to be a hole there, [uses finger to indicate an unfold of the paper] and where you first punched it. So I choose d.

15: Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, so, the way it folds it is into a triangle, so when it's unfolded there's going to be a dot there, a dot there, [draws on picture A two of the holes] and then, so unfold, and then, there's going to be a dot there, ur and there, hum. [drawing on picture A the other two holes] I actually think that there just be two, because if you punch it there then you unfold it, so that's it there, like in the corner, and then you fold that corner up so there would just be two, so I pick c, but c and d look exactly the same.

Christian: Yeah, sorry about that, I messed that up.

15: Two different types of models are illustrated below, Space-filling models and ball-and-stick models. In the next two questions, you are provided with a ball-and-stick molecule of a molecule. So, set out below it are four diagrams of space-filling molecules of the molecule. Pick the space-filling molecule that matches the ball-and-stick molecule. Well it has one central molecule and then one on top, and two to each side. So, it seems like it would be a,
because b looks like, it has one on top, that's not right, because it looks like it has one on top and bottom so that doesn't look right, and then I mean with c, it looks like it's under there, but then it depends on if the middle molecule is bigger than the other two, and you'd figure it would be, just cause. So, I'd pick a.

Christian: Okay.

15: Two different types of models are illustrated below: space-filling molecules and ball and stick molecules. So, it's like the same thing, but this is in red, which makes it hard to look at. Oh goodness, okay, so if you take it plane by plane, you have 3 on the bottom, wait there are 4 on the bottom. So, right now I'm looking at d, because I can't really read a, so I'm kinda looking at d, because that could be 5, well, then it looks like the second has 4, so, 1, 2, 3, 4. I would pick d, just cause a, and c are kinda harder to read. So.

Christian: Why you'd pick d again?
15: Because it looks like from a picture, like what would be on the first plane, but I can't really see like behind d, which makes it kinda hard to find out, but yeah, that's what I pick. I think it's like the best guess.

15: It says the unit cell is represented by spheres. How many spheres are in this structure? Well, there's 4, so that's 4 times 3 so that's 12 on the front, and 12 on the back. [writes 12, 12] And then it's three high. [points to the three left side atoms] so, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, [points and counts all the atoms of the structure] so 36.

15: The unit cell is represented by spheres. Consider a sphere on the out, inside, and how many other spheres will touch it? Um, I think it depends on how big the sphere is going to be, it is going to be the same size as the other ones or is it going to be two wide?

Christian: It's going to be the same size, they are all the same size spheres.
15: Okay, [points at the structure] so, it's kinda hard for me to visualize, because I don't know, like, if like, if there's one on the inside there's going to be a lot of space around it, because it's not like, it's not 3 wide, it's only one wide. So if it's sitting in the middle, is it like 2 one side, like which side would it be on?

Christian: I guess it would be on the middle plane, in the middle.
15: Well then I feel like if it's in the middle, is it on like, cause you know you have your planes, and this would be the middle, [draws 3 lines] but is it on, like if it's in this middle, it's not going to be touching the top ones, [draws an dot on the middle line] and these are the other spheres. [draws two lines to connect the two top lines] So it doesn't look like its touching any, because it would have to be like, [draws a circle on her middle line again] on this side to touch these sphere, and on this side to touch this sphere.

Christian: Can you explain that one more time, I'm sorry.
15: Like if it was, in the middle, um like you said, like, all of these spheres are up here, [points to the top of the structure] so it can't like reach those because, it's little, it doesn't touch it, and then all these spheres on the side are over here, [points to the side of the structure] but if it was like, you said it was the middle sphere, so if it was over on this side, it
would touch these, but being in the middle, like, it doesn't look like it touches anything. But like it depends on which side it's on. So, I like, don't know if I'm like, thinking about it too literally.
Christian: No, it makes sense.
15: So, I guess it depends on like, where it would be in the middle plane, like it is going to be on the left side, or the right side, [waves pen to indicate left and right side] or in the middle and the question doesn't really give you that much information besides saying there's a sphere on the inside.
Christian: I don't know.
15: Okay, well, I mean, since it needs an answer, I guess I would have to guess, but, so I would say zero, just because of the position it's in.

Christian: Okay, here is a list of skills, I want you to read through them, read them to yourself and I'm going to give you a couple of the questions back, and I want you to assign the skills you think you used to solve the question.
15: Okay,
Christian: Okay? [pause while reading]
15: Okay what? [laughs]
Christian: So, I'm sorry, I'm sorry, there's a list of 8 skills here, and I want you to write on the question, any skills you think you used to solve the question.
15: Okay, so just look at my questions and pick the skills.
Christian: Right, right, exactly right.
15: Okay, um, I think I used, I definitely used form perception, so do I need to write that down? [writes form perception]
Christian: Yes, um, hum.
15: Okay, because I was trying to see this not as just like 2-dimensional, but like, up in the air, like in 3-Dimensional, where I could turn it and see like all different kinds of planes. [using hands to indicate different planes] And, um I used orientation, [writes orientation] because I was trying to see they were like related to me. So I think those are the two that I used for that one [space-filling question with the face-centered cubic].

15: And then, I used, memory for this one, [writes memory] because I remembered that it has the hole, so when you unfold it there's going to be another hole, so that's all I used for that one [hole punch question].

15: And then this one was hard, so, I used, I used form perception again, [writes form perception] and orientation [writes orientation] and yeah, those are the two [the orientation question]
16: Okay. So, pick the number of the figure which is unlike the reference object. If all the figures are like the reference object, choose d. Okay, so, um, I would say a is like the reference object, it looks like if I would look at it from either directly above it or directly below it, um, b is I would say is like the reference object, um if I just turn it upside down, and c is also upside down but head-on, so I would say it is d. That's what I'd say.

16: Okay, ah, the diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the one best response. So, atom letter Q lies in the same vertical plane as atom letter blank, so Q, um, Q looks like it could be in the same vertical plane as S, but also E um. But it looks like since R, since the line from Q to R looks like it facing away from me, um, and N as well. Gosh it's hard to tell, um. [laughs] I don't know if it is the correct answer, but, I would say, that um, it looks like, I guess, just to make a decision, S, ah, S to Q might be in the vertical plane, um, as S and N. So, but I don't know if that is one of my choices is it?

Christian: The choices are down here [pointing at the choices]
16: I see, yeah, okay, um, so P, R, T, and H are my choices, right. [laughs]
Schlitz: You can draw on the figure if that will help you.
16: I means it's P, R, T, and T is, [pointing rapidly at the figure] T is, okay up T here [points to T and circles it]. I might conclude that T and H are in different planes because they are in different choices. So that maybe T is in this back wall, [points to the back wall], and H is in this middle plane, [points to the middle plane] um, yeah, I guess I'd go with H, because I don't think it's R [points to R] or T [points to T again] if T is in the back wall and I don't think it's P either, but it could be. So I think I'd go with H, should I circle it?
Christian: Yea.

16: [laughs] Okay, if the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis?
Okay, so diagram A, rotated around the Z-axis, Okay, um, well, in the direction of the Z-axis, the blue molecules are inline facing away from me, and to rotate them would just cause a different angle between me and the white molecules, or the white atoms, so I'd have to go with b.

16: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge equals, or indicates that a bond projects behind the screen, and bold wedge indicates that a bond projects out of the screen towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms are, or is furthest from your eyes. Hum, so a hashed wedges projects behind, ah, so the one furthest from me would most likely be a hashed wedge. Um, and since the main strand is in the plane of the paper, I would have to say H8 and H5, would be away from me, yeah.

16: The diagram below is a representation of a molecule of n-butane. If you visualize the
molecule from left to right, which carbon atom in the drawing is closest to your eyes?  Hum, so, so I’d guess the bold is still facing towards me, and so I’d say that Cb is closer than Ca, and than Cd could be the same as Cb.  Um, I guess [pause]  
Christian: Keep talking  
16: I guess, if H, sorry, if the H near the Cd is facing away from me, then, I think they’re equal. But, um, I guess I would say Cd, only on the basis that the H connected to Ca that’s facing towards me, is facing toward me, and not away from me, like Cd, I don’t know, that’s my best guess.  
Christian: That’s fine.  
16: Okay, look at the following box, if you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces?  So, okay, we’ve got 1, 2, 3, 4, 5, 3 and 4 have to go next to each other, um, and 2 would have to connect to 4, and 5 would have to connect to 2, uh, so out of our choices, d is impossible, 1, and c is also impossible, so 5, 2, 4, it would have to be 5, 2, 4, than 3, than 1, so a would be the correct answer.  
16: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, A, ah, the hole punched would have to be towards the center of the paper, and towards the edge of the corner folded, so it would have to be d, yeah.  
16: Two different types of models are illustrated below: Space-filling models and Ball-and-stick models. In the next two questions, you are provided with a ball-and-stick model of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space-filling molecule that matches the ball-and-stick model. Uh, well I’ve got a gray atom with 4 atoms around it, one facing towards me, and the other 3 in a trigonal shape. Um, so, I don’t see any specific difference between a and c except for the size of the, um, spheres, but since the spheres in the model are, the white ones are smaller than the gray one, I’d have to go with a.  
16: Two different types of models are illustrated below: Space-filling models and ball-and-stick models. Don’t want to read it twice. Pick the space-filling model that matches the ball-and-stick model. So, um, I see a chain of 4 grays, with ah, white atoms surrounding. And the only distinctions I see, are they are 3 on each the end, and then 2 in the middle 2. Um, and again the whites ones are smaller than the gray ones. Ah, there’s only 4 gray ones, which makes c incorrect, and d as well, a is a little hard to tell, it looks like there are only 3 grays, so I’d have to go with b.  
16: Same question I guess. Pick the space-filling that matches the ball-and-stick model. Ah, okay so it looks the, that each side would have 5, 5 balls, yeah, so each has a corner and then one in the plane of each yeah, of each wall so it looks as if d would be the correct
answer, I don't think b or a, b would be if only 4 balls were in each plane, so I'd have to go with d.

16: Okay, this unit cell is represented by spheres. How many spheres are in the structure? Um, so there's 4 by 3, by 3, which is 36, I believe yeah, 4 by 3 by 3. 4 times 3 [Writes 4 x3], is 12 times 3 is 36, yeah.

16: Okay, this unit cell is represented by spheres, again. Consider a sphere on the inside, how many other spheres will touch it? Um, so one sphere would have, it seems from the face of this object [points hand down] that the one sphere has 1, 2, 3, 4 spheres touching it, in it's own like in a vertical plane, um and the, I guess there's four outside of it that aren't touching it. Um, and if you would rotate that 90 degrees [using hands to show a rotation] you would gain 2 spheres. So I would have 1 if this is the middle sphere, I would have 1, 2, 3, 4, and then 5, and 6 [drawing the central sphere, and having 4 on the sides, and one behind and one in front touching the sphere]. Um, yeah, I'd say six.

Christian: So for the last question I want you to read through this list of skills.
16: Okay.
Christian: And I'm going to give you a couple of questions, and I want you to assign the skills that you think match the question.
16: Okay.
Christian: And I'd like you to assign multiple skills to the questions if that would be possible in anyway.
16: Okay.
I: So here are the questions, you don't have to read them out loud, you can read them to yourself.
16: Sure. [pause while reading ] Okay, okay, cool.
Christian: So here are a couple questions, I want you to assign those to.
16: Okay, so, this question, [the box question] definitely off the bat I'd say it involves rot, like rotating in your mind, so, um, orientation, cause each, I'm looking at each answer this way, but I have to think about them that way, [uses hands almost off screen to indicate a rotation] um form perception as well, so orientation first, and then form perception, Um, I think because I'm looking at, these are all two dimensional and that's three dimensional, [points to the choices] and sequencing as well, cause I have to order them, and I guess association, um, because it is asking me what to do in words, obviously and I have to select pictures, and then translate back into numbers. So I would say those are, yeah those are it.

16: Okay, um, so this one [n-butane question] is a I wouldn't say orientation, um, yeah, I would say form perception because it is drawn in 2-dimensionally, and I have to interpret it in 3-dimensions, um, ah, I guess association, because I'm associating different shapes, with well I guess. Relate concepts which are shown in pictures and written words [reading skill again]. I'm not sure how association would necessarily apply to that except for the asking of the question itself, cause I'm relating an image to a verbal question, so I guess that does
apply. Um, I think that's it.

16: This question, [diamond question] [laughs] it's my favorite, um, so yeah definitely association, um relating the idea of vertical plane verbally to visually, or spatially, um, discrimination, definitely, um, because you have to, it forces you to eliminate choices [uses hands to motion] based on just your perception of their relation to each other in space, ah, and I guess form perception, definitely, um, cause I mean physically it's not in 3-dimensions, but we have to interpret it in 3-dimensions. Ah, there's no rotation or reflection, or sequencing I don't think, so yeah, I'd say association, and form perception, and discrimination.
Interview with student 17

17: In the next question, the framework of a wire figure reference image is drawn on the left. On the right are three diagrams suggesting how this hollow wire model might appear when viewed from different angles. Pick the number of the figure which is unlike (different from) the reference object. If all figures are like the reference object, choose d. Okay, um, okay, so this has three squares sides, and two triangle sides [pointing to the reference structure], yeah, no, yes, [laughs] um, and, there's gonna, one side, two side, three side, four side, five side [drawing and counting the reference object's sides] yeah, okay, um, and then this one has like rectangular sides, and you can't really see the bottom, but I suppose you could assume that its rectangular [drawing on choice a's sides] and then it looks like there's a triangle right here, and then a triangle over there, [taking apart the wireframe with her hands] so I guess I would say that one. And than again this one has rectangle, rectangle, rectangle, and then triangle, triangle, so that could work [drawing on choice b]. And then this one's very smushed, but it looks similar as well. [pointing to choice c] so I'll say that all of them [circling d]. Okay.

Christian: Okay [mumbling with separating sheets]

17: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and are all within the cube. For each question choose the one best response. Atom M, atom letter M lies on the same horizontal plane as atom letter Q, or S or U. Okay, so M is here [circling M], um, R is here [circling R], S [circling S] and U [circling U]. Horizontal plane, okay, um.

Christian: Keep speaking your thoughts.

17: [laughs] I'm trying to think, I'm trying to think of what I want to say out like. Okay this, um, this is on, no, this goes up like that, so I'd don't really think that would work, okay, and then this seems to be the most direct route, doesn't necessarily mean it's right, and then horizontal plane, so this horizontal [drawing lines between M and the other atoms] and then where's U, no Q, oh yeah, Q right there, [circles Q] and then this, um, goes like that, [draws a line between Q and M] I'm not good with spatial problems but [laughs], um, I mean R seems like the most direct route, ur, no, yes, yes, R seems like the most direct route. I'm probably wrong, but.

Christian: What do you mean by direct route, I'm sorry?

17: Like, like the easiest way to get there, like it goes along this horizontal plane, than this, it doesn't look like it's on the same plane, but it's still, like it's easier to get there like than this, like, horizontally [drawing lines between M and the other atoms again] I mean, instead of like that, which is at an angle, or like that, or like that. [drawing lines between atom M and R, and atom M and Q] So I guess I would say R, but I'm probably wrong, but [laughs].

17: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Turning around, X-axis goes that way, Z- axis, [uses pencil to imitate a rotation around each axis] okay, which matches a rotation around the Z-axis. So I want to match this [circles reference object] to one of these rotated around the Z, okay.
Christian: Correct.
17: The X is, so, if it goes, turning around the Z-axis [pointing to diagram A and the Z-axis rotation], then it goes like that, then it'd go like that, [drawing an arrow around diagram A] which would put this, [pointing to choice d] okay, like that, and then turn that. I forgot I had this, duh. [Tries building it with the model kit] Why can't they look exactly like the drawing? Okay, I need, maybe, would that work, oh whatever [dropping the models back in the container] Okay, like that, so then it seems like this would go over like that, but this over here. [pointing again to diagram A] So from the way I'm thinking it seems like maybe that, maybe d, I think.
Christian: Why is it d?
17: Because if it goes like that, like this is showing it like that, [retracing arrow] and then it puts that puts, this atom, [circling the back left white atom on diagram A] over, like okay rotated like that. [uses pencil to indicate rotation] It puts that over there, and then this. I don't know
Christian: Okay, just keep speaking your thoughts
17: [Laughs goes back to trying to build it]
Christian: Maybe if you had a different atom it would be better?
17: Huh, [still trying to build it], okay, like, if you had, no, no, no, no, no no, that doesn't make, crap.
Schlitz: Maybe if you say what you are thinking about or what you are trying to figure out?
17: Right now, I'm trying to figure out how to build this thing. I've never been good with model kits never. Um, okay, so I want a conector thingy, and I definitely want two atoms, one at each end, okay so that would, that could work, I think. Yeah, that works well enough, if you do that, no, it's like this [has a model that appears to match the diagram] if you rotate it around the z-axis so, then if I am doing this correctly, than it seems that d might actually be it. [laughs]

17: Among the molecular representation choose which one you would get after reflecting molecule A in the mirror. Well, if you reflect it, then it's just going to be this, like flipped. [uses pencil to indicate a flip] And then this is going to be closer to the mirror, [drawing atoms on the other side of the mirror] because it wouldn't just automatically appear over here, it stays there, and then this, and then, trying to, no, if you reflect it, then it's going to be, [drawing more atoms] like, [mumble], and then, that, so seems like, well, it wouldn't be d, I know that. And this is, okay wait, this is flipped like that, [uses hand to indicate a flip] so, and this stays there, and if you flip it, and that goes, there
Christian: What do you mean by flip it?
17: Well, like it's just going to be the opposite of this, [circles reference object] so it's just going to be flipped, like, like that, [flips hand over] so this is going to stay there and not move, like that, Um, and then, this if you reflect it and then it's going to be, so right now.
Why is my brain not working right today?
Christian: It's okay.
17: It's because it is a Monday.
Christian: Just keep speaking your thoughts, keep thinking about the problem
Mirror problems should not be this hard, [laughs], it's cause it is a Monday, and Monday's hate me. Okay, so flip that yeah, [flips hand over again] so it's going, no, c, because it is just going to be flipped, [circles different parts of choice c and the reference object] so this like that, so everything's just like opposite, so I would say c.

The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projects behind the screen, and bold wedge indicates that a bond projects out of the screen towards you. Atoms connected with straight lines, um, atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atom or atoms are furthest from your eyes? Okay, so bold wedges is into the plane, [points to bond on atom 9] or into the screen towards me, so if its coming towards me, [uses pencil to indicate towards herself] then it's not going to be farthest away from my eyes. [crosses out atoms 9 and 4] And this one is going away from me, and this one is going away me. [drawing arrows by atoms 5 and 8] Um, am I looking at this from?

Christian: Above,
17: Above, okay.

Christian: Right, right.

17: So, both of those are going away so, looking at this from above, then, atoms, ur, 5 and 8 are going to be the farthest, but then the question is one of them further than the other one?

Christian: Read the question again.

17: Hum?

Christian: Read the question again, the question right here

17: Which atom or atoms are furthest from your eyes, right.

Christian: There could be more than one.

17: Yeah, so, yeah but I guess based on like chemical bonding and stuff one could theoretically be longer, like further than the other one, so that's where I'm going with that. I guess, maybe not and then, okay so I would just say 5 and 8 because they are both going out of the paper away from me, so.

The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon in the, carbon atom in the drawing is closest to your eyes? Okay, which carbon atom, um, carbon a, both the hydrogen's are going out, [drawing arrows on the two hydrogens attached to carbon a] carbon b, both hydrogen's are coming in, [drawing arrows on the two hydrogens attached to carbon b] and that's going out, that's going out of the paper. [drawing an arrow by the bond that connects carbon b and c] So, these two h's are going out of the paper, and that's going into the paper, and that's going out of the paper. [pointing to the hydrogens by carbon c and d] So carbon a, there's the carbon, and then two hydrogen's going out, [pointing with finger] so it's going to do like that, [pointing with finger again off screen] and then this hydrogen is up, and this carbon is up, so, [building it with the model kit off screen], that's like carbon and hydrogen's, and then this carbon over here is coming up and so is, or this hydrogen is coming up and this so is this carbon, so like that. And then so the hydrogen's, both of those are coming into, and what happened, crap, okay, coming into, so, um, trying to, it's not going to work, oh, duh, smart,
okay, that's going up, and that's going up, and that's going down. [still building it with the model kit off screen]. Okay, so this carbon, from to that carbon is going down, and then to that carbon is going back up. [points to carbon d] Okay, and then, hydrogen's down, up, so, might as well add those two, just for visual reference. Okay, two more. So, definitely not, visualize from left to right, so not a, [crosses out carbon a] and, okay, so based on this, assuming that I build it correctly it looks like it could be b.

17: Okay, look at the following box, if you ignore the top and bottom of the box, what is the order that you build the sides from the following pieces? Okay, ignore the top, and ignore the bottom [crossing out the top and bottom]. So, then you would need, what is the order that you could build the sides. Then you would need 1 [writes 1] and then 2, um, flip those.

Christian: Keep speaking your thoughts.

17: Um, 1 would just be this side, [pointing to the box and side 1 and writing 1 on the left side] and than 5 is this side [point to the back side of the box], and then 2 is this side, [points to the right side of the box] and then if you flip, [pointing to piece 3] um, 3 or 4, no, never mind, they're good. Um, you could put 4, yes, put 4 and then 3 [writing the numbers on the box on the front face]. So, 1, 5, no, if you started with 5, then 2, then 4, than 3, then 1. So that would be 5 which is good, [circling the back wall] 2, [circling the right side] and then 4, [circling the front right side] which is that, [pointing to side 4] and that would be good, 3, [pointing again to the left front of the box] and then 1, [pointing to the left side of the box] so a.

17: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was, where paper has been before the paper was folded. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes where the paper is completely unfolded. Um, so, a hole has been punched in the paper. So, the hole is there, [pointing to picture A] so when you unfold it, then the hole is going to be here, [pointing to choice d] where it shows in the picture, [circling the hole on picture A and on choice d], or there, or there, or there, or there [circling the holes on the other choices]. Okay, but then, when you unfold it, it's not going to go up [drawing an arrow on picture A], so it can't be that [ruling out option e]. And it's going to have two holes, because it's folded over, and so you punch it, and it's going to be punched through both things, [uses hands to indicate a fold and a hole punch] so it's not going to be c. And if you unfold it, it's not going to go this direction, because you're not unfolding in that direction, so it's not b. And again if you unfold it, it's not going that way, [drawing another arrow on picture A] so it's not a. So it has to be d, because that is closest to the corner of the paper, [circling the hole on choice d] and when you fold it up it's gonna have a hole there.

17: Pick the figure that shows the positions of the holes where the paper is completely unfolded. So, it's folded in half, [points at the first hole punch picture and imitates a fold] and then folded in fourths, and then cut near the corner. [points at picture A] So if it's cut near the, um.
Christian: Do you want to try it? [Indicating to a piece of paper]
17: Yes, oh, grr, I can't really. I'm assuming you don't need this piece of paper.
Christian: No it's yours.
17: [ripping the piece of paper] well that didn't work out so well, Dangit, okay, I'll try this side [rips the other side] because it didn't mess up as bad, and then, I'm attempting to make a square it's not working very well. Well. I'll pretend this is a square [laughs]. Fold it like, in half, and then, okay, in half like that, and then, fold it in half so that it looks like this. And if you [pause]
Christian: Keep speaking your thoughts.
17: Fold it in half, and it's, it's not, well, like, if it was. Okay, so fold it in half like this, and than it could just be folded in half again, but then it seems it wouldn't look like that. It seems like it'd be, like, no, what am I trying to do. [ripping the piece of paper off screen] Okay, well I'm going to go with that. And if you put a hole there.
Christian: You can do it with a pencil here if you want to.
17: Yeah, I'm assuming it works. And it's not [trying to get pencil through paper]. Usually that works, okay, trying to force a hole in here.
Christian: We should bring a hole puncher.
17: Huh?
Christian: I was just thinking about, we should bring a hole puncher, for next time.
17: Okay, well, anyway if you, unfold it, there's going to be hole there, and a hole there, and if you unfold it again, yeah, okay. So assuming that I did that correctly, there should be four central holes, like a.

17: Two different types of models are illustrated below: space filling models and ball-and-stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space filling model that matches the ball and stick model. Okay, so, there's four [circling white atoms in the ball-and-stick reference structure], well, okay, five, so we want five down here. Um, if you squish this together, [uses hands to indicate squishing] it's not going to end up like this, [crosses out b] because it's not off to the side, [points to one of the side atoms on the ball-and-stick] like that, it doesn't do that. And then if you [uses hands to indicate bringing down] bring this down, than that's going to be on the top, and that going to be on the side, on the side, and right there [drawing lines on the ball-and-stick]. So it seems like, um, well it's not, um, it wouldn't be d, because again, it's not, it doesn't go like that, [points to choice d] yeah, so it's either a or c, and I'm wanting to go with a, no, okay, push that in, [points to another side atom on the ball-and-stick] look like that, [circling a side atom on choice a] but then that could look like that too, [circling a side atom on choice c] um, I'm going to say a, because these are smaller than that [pointing to the relative size of the gray sphere in the middle to the white spheres that surround it], and that is the way it's represented [points to the gray portion of choice a] but then this it looks like it's bigger, [points again at choice c] or like more crowded than it should be, [uses hands to indicate crowding] so I'm going to go with a.
17: Two different types of models are illustrated below: space filling models and ball-and-stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below it are four diagrams of space-filling models of that molecule. Pick the space filling model that matches the ball and stick model. Okay, um, so we have, these atoms out here that, [circling some of the outer atoms on the ball-and-stick reference object] project, like outward, [uses hands to indicate outward motion] so we'd expect to see 1, 2, 3, 4, 6 of those. [counts the 6 outer atoms on the ball-and-stick] Um, so, that's going to be one, two, three, four, five, six, [counting the outside atoms on choice d] so that could work, and then there's three like that, [pointing to the face atoms on the ball-and-stick] okay that works, um, because if you take this backbone back here [pointing to choice d]. And then, this one right there, [points back at the ball-and-stick] goes up like that, and then, um, [pointing back at choice d] this one [circles another face atom on the ball-and-stick] looks like it's right there, [crosses off the face atoms on choice d] um, this one is right here, this one is right here, and this one is right here, this one's right there. [circles the outside atoms on choice d] Um, this, this one doesn't look like it even has enough atoms, [pointing to choice b] you have the six ones, and then you just have, like what appears to be just like one in the middle [writing on choice b], so that wouldn't be it. And then so right now, I'm leaning towards d. Um, it's seems to be the best bet, I don't know, um, this one, you can't really necessarily make out, [pointing to choice a] where the, where these corner atoms are, um, unless it like those, but then where did the other ones go, is it like that? [circling some of the atoms on choice a] Um, so, don't think it's b, don't think it's c because that just doesn't, doesn't look right, [points at choice c] so right now I would go with d, because I can actually point out, I think where all the atoms actually come from.

17: This unit cell is represented by spheres, how many spheres are in this structure? Okay, um, so, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, [draws on all the top atoms] and then [points and counts the other layer to 24]. And then, are there, there are no spheres in the inside of this, [uses hands to indicate the inside of the structure] are there?
Christian: Yes, there are.
17: There are?
Christian: Yes, it's like one unit cell, like one block unit cell, so.
17: I remember building these in 101
Christian: 102, right.
17: [laughs] Okay, um, so [counts up to 24 again], and then you have to have the same thing on that over there, so 5, 6, 7, 8, and then this over there as well, 29, 30, 31, 32, 33, 34, 35, 36. [pointing at the unit cell while counting without lifting hand] So far there's 36. And, then I wish I had one of those models right now. Okay, um, so on the outside there's 36, if I am doing that right. And then on the inside there should be, maybe, 2, ah, okay, so on the inside it can only fit like, [drawing on the structure] 2, or otherwise, yeah, okay, and then 2 there, [draws on the black parts] and then there's 3 rows, maybe 38, I think. I don't remember this at all, but I think. [laughs]

17: This unit cell is represented by spheres. Consider a sphere on the outside, how many
other spheres will touch it?
Christian: Read the question again
17: Consider a, oh a sphere on the inside, duh, how many other spheres will touch it? I
knew the outside thing didn't make much sense, okay, inside, so, it's inside, [pointing at the
reference object] then it's going to have this one touching it, and this one touching it, and this
one touching it, and that one, and that one, and then the other inside one, [drawing lines on
the spheres touching the inside sphere] so, 1, 2, 3, 4, 5, 6?. Um, so it'd be that one, that one,
and that one, that one, that one, that one, that one, [pointing back at the atoms on the
structure] so, okay.

Christian: Last question, here I have listed a list of skills these questions fit into, I'm going
to give you a few questions back, and I want you to go through and fit the questions to the skill
categories. Okay? The first is these two [both rotation and reflection question]. What fit to
they have to the skill categories.
17: Do you want me to read these out loud?
Christian: That's fine, you don't have to read it out loud, it doesn't matter if you read it
out loud.
17: [reading the skills definition out loud, under her breath] Okay, um, do you want me to
write it on here?
Christian: Yes, that's fine
17: Okay, [writes orientation on both the reflection and the rotation questions] does one of
these fit with these, or could it be like multiple?
Christian: Well it's only supposed to be one, but if you want multiple, that's fine.
17: No, that's okay I was just asking.
Christian: So why do you think these are both orientation questions to you?
17: Rotate or reflect the positions of objects in space in relation to other objects and the
observer, okay, well this one, you're reflecting it in the mirror, so you want to see what it
looks like after it's reflected, [points at the reflection question] and then, um, um, this one,
um, is being rotated over the Z-axis, so if you rotate it you want to know what it looks like in
relation to the original molecule, um, after it's rotated. [points to the rotation question]

Christian: Okay, and these two questions as well [first the unit cell, and then the paper
folding].
17: Okay, um [reading skills again] These two are not necessarily going to be the same are
they?
Christian: No, they don't have to be the same or whatever.
17: Okay, um, relate concepts which are shown in pictures and written words, see objects in a
particular order. Hum, um, okay, the unit cell one, um, um, perceive dominant features in
objects and to discriminate one object from another, well, okay, this one it's not it, it's not
constancy, [throughout all this, reading skills before answering] perceive dominant features
in objects and to discriminate one object from another, um, it could be that one, like maybe
these are the dominant ones, and you have to like discriminate, like from, I don't know, from
the inside ones which you really can not see, which then, maybe that would be memory
because you have to like think and remember, you know, what's like on the inside or whatever. Um, so for some reason, I'm going to go with that. [writes memory on the unit cell question] And then this one, [reading skills again] um, discrimination, I think, [writes discrimination on the paper folding question] um, because you have to be able to like pick and choose with one of these is the correct one, so like you know, know this one is not right, or that one is not right, and then you have to, get like, you know, relate it to that one, and discriminate that this one is what you're going for, I guess.
Interview with student 18

18: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the best response. Kay, which, view atom K. Where is atom U with respect to atom K? So atom U and atom K (pointing to atom U and K) So, this ones on the corner, (pointing to the line behind atom K) and then this one is in the middle. (pointing to atom U again) Oh no, okay so the choices are above, below, same level, and can't determine. Okay, hum, so it's in the shape of a diamond, so I think it's below.

Christian: Okay.

18: I think.

Christian: Okay, I'm sorry why'd you say below again?

18: I just, it just looks like it. (points to K and U again) because this is in the corner, (points behind K) and then this seems to be in the middle, and then that line over here seems to connect it, (points to atom U again and the line behind it) and that seems below this one, I don't know, it's basically a guess.

Christian: Okay.

18: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Okay, if the structure in diagram A rotated around the Z-axis, this one right? (pointing to diagram A)

Christian: Um hum, um hum.

18: Around the Z-axis, so, Z-axis (points to the Z-axis rotation figure).

Christian: Um hum.

18: So that way, and that way (showing rotations with her fingers). Which structure below matches a rotation, so, this would go here (using fingers to indicate the rotation), rotated that way (again, using hands). Oh, gosh, well if I visualize it, so these two are here, (points to the two blue atoms) so if you put it, (points with hands that the 2 main atoms are on the Z-axis), you're just flipping it around that way (using hands to show the "correct" rotation).

Christian: Okay.

18: But they don't look like any of them. (laughing) So this would go here, so I think that one (pointing to choice a).

Christian: So why do you think a?

18: Because when you're turning it over here, this would be here, (using hands to indicate a rotation again) cause you're rotating it that way, (uses pen to point to the z-axis and turn the rotation) right?

Christian: Um hum, um hum.

18: So if you rotate this that way, (indicating a rotation with her hands again) this would be somewhere here, (moving one white atom to the other side) that will be here, (moving another white atom to the other side) so this one looks kinda like that, or this one [pointing to choice c], I don't know. I think it would be this one [circling c]. I'm going to get all of these wrong.

Christian: It's okay.
18: Oh my gosh, okay, the diagram below is a stereochemical representation of a model of ethanol. In this diagram hashed wedge indicates that a bond projects behind the paper, and bold wedge indicates that the bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. So, which atom, atoms are the furthest from your eyes, okay, so I am listing more than one?
Christian: Yeah, you can do more than one.
18: Okay, so, H, [points to hydrogen 6] since H is in the plane of the paper, it's still farther from me, since it's over there, so H and then, am I listing just the atom or the bond, just the atom, right?
Christian: Just the number, like the number of the atom.
18: So just 6 right?
Christian: Just 6.
18: Okay. Okay, um, 8 since it's away from the paper, [uses hand to show away from the paper] that way, okay, 7, okay I think that'd be it.
Christian: I'm sorry, why did you say 7 as well?
18: Because it's still away from the paper, so 7 is this? [pointing at atom 7 and the line connecting it to atom 1]
Christian: So 7 is that oxygen, 7 is that O right there.
18: Oh.
Christian: Where it says that the numbers correspond to the atoms, they're representing.
18: Okay, so the 6 is the H? [points again to hydrogen 6]
Christian: The 6 is the H.
18: So, I think it just be the 6 and the 8.
Christian: Okay
18: Are the furthest.
Christian: Okay

18: Okay, the diagram below is a representation of a model of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is the closest to your eyes? Left to the right, kay, I think it would be, left to right, I think it would be c.
Christian: Why c?
18: Because this means that it's [points at the bond connecting carbons c and d] coming towards you right? [uses hand to indicate coming towards her]
Christian: Um, hum.
18: So, what, what would make, what is the difference between c and a? [pointing to both atoms a and c]
Christian: Um, I don't know. Well in this case, the difference is, is that the bonds to a are a little bit longer, and the bonds to c are a little bit shorter.
18: So then it would be a, because it's longer, so it would be closer to me, [uses one finger to wave towards herself] because it's coming to me, it's away from the paper towards me, [uses hand to indicate coming towards her] so it'd be a I think.
Okay, looking at the box. Um if you ignore the top and the bottom of the box, what is the order that you could build the sides from the following pieces? So we're ignoring the top and the bottom, um, this is.

Christian: Here's a little box here [handing her the small paper box].

18: Oh, okay, I can't open this right?

Christian: No, you can't.

18: Um, we're ignoring the top and the bottom so these mean like folding here right? [pointing to pieces 3 and 4]

Christian: No, no, no these are the sides, these are the sides I'm showing you here.

18: Oh, okay, okay, hum.

Christian: Keep speaking your thoughts.

18: Hum.

Christian: Keep speaking your thoughts please.

18: Oh, yeah, sorry.

Christian: It's okay.

18: Um, okay, so this is just a plane, one piece of paper? [pointing to piece 1], and so this would be the bottom? [pointing to the box].

Christian: Ignore the top and bottom.

18: Yeah, so we're ignoring number 1. [pointing again to piece 1]

Christian: No, we're ignoring the top and bottom of the box.

18: Oh, okay, so this would be like one of the sides? [points to the left side of the box]

Christian: One of the sides.

18: Okay, so, this 5 here is that? [pointing to piece 5 and the back of the box].

Christian: Um hum, um hum.

18: Okay, um, so we could do these, this one is over here. [pointing to piece 2 and the right side of the box].

Christian: Um hum.

18: So, build the sides from the following pieces, so we could do the 5, and 2, [points to piece 5 and 2 again] 5 and 2 and then, so where's the 3, [pointing again to piece 3] the 3's here? [pointing to the right front half of the box]

Christian: Look at the orientation on the box.

18: Can I look at this one, is it the same?

Christian: Sure.

18: Hum, cause the 2, that's the 2. [pointing to the right side of the box]

Christian: Um hum.

18: So, okay, so, the 3, so we have 5, 2, [writes 5 and 2] I think 1 would be last, [writes 1] 5, 2, 1, and I have to figure out the 3 and the 4. Kay, so that would, this is hard, um, I think the 4 would go first.

Christian: Why would the 4 go first?

18: Because of the, since 2, so the 4 would go first because it's on that side, [points to the right hand corner of the box] and then it would be the 3. Is that even an option? 5, 2, 4, 3, 1, yeah, [laughing] okay.

Christian: [laughing]
On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before the paper was folded. A hole has, has, a hole has been punched in the paper as indicated in the picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. Okay, so the left, on the left are pieces that have been folded [points to the first hole punch paper] so it's folded that way, [uses pen to indicate a fold] and the dotted lines are where paper has been folded, okay, um, a hole has been punched in the paper so a hole was punched here, [points at the hole on figure A] and, pick the figure that shows after so it would be this [pointing to choice d].

Christian: Why would it be d?

18: Because when you unfold it, this hole punch would be in the corner. [points to the hole again and the corner of figure A]

Christian: Okay.

18: And it's being punched here, so, [points again to choice d] in the middle.

Christian: Okay.

18: Is this like rotated afterwards? [uses pen to indicate a little rotation]

Christian: No, not rotated, it's the same orientation.

18: Okay, so it would have to be this, yeah. It's punched like through here, right? [points at figure A again]

Christian: Yea, it's punched all the way through - like 2 holes, right, right.

18: I don't want you to trick me [laughing].

Christian: I'm not trying to trick you.

18: Pick the figure that shows the positions of the holes when the paper is completely unfolded. So that was completely unfolded too right? [referring to previous question]

Christian: Um, hum, right.

18: Okay, so, it's folded this way, [pointing at first hole punch paper] and then it's folded that way, [uses hand to indicate a fold] and then it's punched in the middle. Can I use this? [reaching for another piece of paper].

Christian: Sure.

18: So first it's folded this way. This is not going to work out, but [trying to make a rectangular piece of paper look like the square piece of paper].

Christian: You can make it a square if you want to, you know.

18: Yeah, I should do that. [Folds it and rips off the bottom of it] Okay, so, here's my square, and it's folded this way first, and then this stays the same, it's folded like. Oh no, how is this folded?

Christian: You were right.

18: Was I right?

Christian: Um hum, um hum.

18: Okay, so then it's folded this way, so if the hole punch is here [uses pen to punch hole all the way through the paper] Okay, it should look like that [circles a and laughing].

Christian: I want to keep, want all the props you use, so [laughs]
18: Okay
Christian: Thanks a lot.

18: Okay, two different types of models are illustrated below, space-filling models and ball-and-stick models. In the next two questions, you are provided with a ball and hand stick model of a molecule. Set out below it are four diagrams of space filling models of that molecule. Pick the space filling model that matches the ball and stick model. Okay, 1, 2, 3, 4, [pointing and counting atoms around the central atom on the ball-and-stick reference object] okay, I think that it would be this one [points to choice a].
Christian: Why a?
18: Because it looks like their at the same angle, [points to the bonds on the ball-and-stick] so, I think it would be that one.

18: Two different types of models are illustrated below, space-filling models and ball and stick models. Pick the space filling model that matches the ball and stick model. Okay, this ones a bit confusing um, so it has 2, 3, 4, 5 [pointing to the top of the ball-and-stick reference object] on the top, so this one doesn't have the 5 pattern, so I don't think it's this one [points to choice b]. Okay and then 4, [points to choice c] I think it's one of these two [points to choices a and d], because this one you can clearly see like, the 5 pattern [points at the ball and stick model] and then you can see it in these two too [points again at choices a and d]. And then, hum, 5 and 5, [points to the top of choice d, and choice a] and then there's 5 in the back, and 5 in the back, [points to the back of choice a and d] and then in the middle are 1, 2, 3, 4 and 5, and then 6 all in one, [points to the middle of the ball-and-stick] so there's one here, I'm pretty sure there's 4, [points at choice d again] I think it's this one [circles choice d].
Christian: Why that one.
18: Because it has 5 here, and then it has 5 here, [points to choice d and the ball-and-stick again] and then, you know that since there's 5 here, there's 5 over there, just like this one, so there's 1, 2, 3, 4, 5, here, and there's 5 over there, and so there has to be 5 on the bottom. You can kinda tell that there's 5 here, so there has to be 5 on the other side, just like this one. [points back and forth between choice d and the ball-and-stick counting atoms]

18: Okay, this unit cell is represented by spheres. How many spheres are in this structure? Okay, so, 1, 2, 3, [points and counts on the back right row and writes 3] 1, 2, 3, [points and counts the back right column] so 3 by 3 so 9, so there has to be 9 on that side, [writes 9 by the other side] so 1, 2, 3, 4, [points and counts the back row] 4 by 3, so like, 12, 12, [writes 12 above and below the object] so there's 12 and 12 here, 9 and 9 here, so it's a 9 by 12, right? I think it's a 9 by 12.
Christian: Keep speaking your thoughts please.
18: Okay, yeah so, since there are 12 here, [points to the top] and there's 9 here, [points to the right side] I think that it would be a 12 by 9 so or, hum, I think it's a 12 by 9, so 108, I think.
18: Okay, consider a sphere on the inside, how many other spheres will touch it? Oh gosh, so the one sphere inside it? [points to the inside]
Christian: Um, hum.
18: Okay, so, how many spheres will touch it, so over here, [drawing a circle in the middle of the front face] I think that 2 and 2, 2 from this side will touch it, and then 2 from this side, and then 2 from the top, and 2 from the bottom, [pointing to the reference structure again] I think, so I think 8.

Christian: The last question, I want you to read through these list of skills to yourself.
18: Okay.
Christian: And then I'm going to give you a couple questions back, and I want you to indicate which skills you think matched the question.
18: Okay.
Christian: Okay.
18: So I read through this.
Christian: To yourself, if you would. [pause while reading]
18: Okay.
Christian: Here are the 3 questions, now what I want you to do is I want you to write on the question, any skills you think you used to solve the question with.
18: Okay, so any of these?
Christian: Any of these, and write on the question itself.
18: And more than one?
Christian: More than one is fine.
18: Okay, so sequencing. [Looking at the box question]
Christian: And explain to me why you think you used to solve them.
18: Sequencing because we had to like use a specific order in which to put it together, and um, hum, I think kind of constancy, because of how I had to, since you put these on there, I had to know like which one goes with which, [points to the box] so like the shape of it, and the size of it. Kay, um, form perception so 3-dimensional, this would be a 3-dimensional object, so. And orientation, because kinda rotating which way, whatever ways seeing how it would go in there. Kay.

18: Okay this would be, [ethanol question], um, association, because I had to read this, [waves hand around] and then apply it to the figure, hum, form perception, because this would be 3-Dimensional, and that's it.

19: Okay this would be association [diamond question] because I would have to know like the shape of a diamond and whatnot, um, form perception because it would be a 3-dimensional object. Okay.

Christian: So for each question, now I gave you I want you to list, I want you to list, I want you to write the main skill you think you used to solve it with.
18: The main skill?
Christian: Yea, the one main skill.
18: Okay, so should I just like star it?
Christian: Circle it or star it, yeah.
18: Okay, um, [stars form perception on the diamond question] Um, I think it would be form perception [ethanol question].
Christian: Okay, for this one.
18: Sequencing [box question]
Interview with student 19

19: The diagram below is an illustration of the structure of a diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question choose the best response. View atom letter number K [points to atom K]. Where is atom U with respect to K? [points to atom U, and finds it in respect to atom K] So this is one level, [pointing to the line that K is on] and, I believe that K and U are on the same level. [points to K and U again] So I just answer it, like this?

Christian: Yeah, circle it, yeah.

19: If the structure in diagram A [points to diagram A] were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the X or Z-axis? The Z [pointing to the Z-axis] so, turn this way [using her hands to show an z-axis rotation], if it's turned that way, it would look like a. [points to choice a]

Christian: I'm sorry, why did you say a again?

19: Hum.
Christian: I'm sorry why'd you say a again?
19: a?
Christian: Why did you say a again?
19: Because when it's turned, like you have it like this, and you turn it this way, it becomes flat [indicating with her hands the rotation].
Christian: Okay, thank you [hands me the last question]

19: The diagram below is a stereochemical representation of a molecule of ethanol. In the, this diagram hashed wedges indicates that a bond projects beyond the paper, and bold wedge indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that bond is in the plane of the paper. Which atom or atoms, are, is or are furthest from your eyes? [laughs] So, if you have this piece of paper, [picks the piece of paper up and holds it parallel to her] and it's the wedges, the hashed wedges are coming out that way [pushes hand away] and the ones that are bold are coming out towards me, [brings hand in toward herself] and hum, it would be the ones furthest from my eyes would be the two hydro, hydrogen-carbons with hashed wedges, 8 and 5.

19: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom is, in the drawing is closest to your eyes? Which carbon atom? Okay, I can use these, right? [starts taking the atoms out of the model kit]
Christian: Sure
19: Okay, um.
Christian: Carbons are usually the black ones with four pegs on it, but you can use whatever color you want.
19: For carbon.
Christian: Yeah, for carbon, usually the black ones are for carbon.
19: Yeah, yeah, yeah, okay, [reaching for black atoms], and then have you have hydrogen here, [adding a hydrogen to the carbon], and then you have another hydrogen here [adding another hydrogen], so that goes beyond the paper, actually that's how it goes [adding hydrogens on while she is talking about it] so then you would have another hydrogen, and then, hold on, you would have a hydrogen sticking out on this side, and you would have two behind the paper, and then you would have another carbon atom, on this side [adding carbon #2], and then you would have two hydrogen atoms right here, and the one back here would be connected to an, a carbon atom. Okay so you have 2 sticking out like that, behind the paper, [uses hand to indicate an outward motion] you have this one, behind the paper, one in front of the paper like that, then you have these which are sticking out from the paper, and this one goes behind the paper, like that, [adding 3rd carbon atom] and then this one, you have 2, these two behind the paper, two hydrogens, [adding hydrogens attached to the 3rd carbon] and then you would have 2 hydrogens behind the paper, and then you would have carbon atom sticking out from, above the paper, [adding 4th carbon] and then you would have a hydrogen atom going back towards behind the paper, so it would be. You have one sticking out, two back, one sticking out from the paper, here you've got this one sticking out from the paper, these two sticking out, and this one behind the paper [referring to carbon c], and then you’ve got these two behind, this one sticking out, and then you’ve got this one behind, and these two sticking out this is going to be the one back [referring to carbon d]. So the carbon atom that is furthest from sight is c [goes to circle c].
Christian: Read the question again, I'm sorry.
19: If you visualize the model from left to right, which carbon atom in the drawing is closest to your eyes? Closest, so, the one closest would be d [circling d].
Christian: Okay. [student taking model apart] I'll take it apart later.

19: Look at the following box. If you ignore the top and the bottom of the box, what is the order that you could build the sides from the following pieces? Hum, [picks up the physical paper cube] ignore the top and the bottom, kay, what is the order that you could build the sides, this is that side, [points to piece 2 and to the right side of the box] this is that side, [points to piece 5 and the back of the box] so this is 5 [referring to the physical cube], 5, this is 2, this is 4 and 3, and this is 1, so 1, you could do it 1, 3, 4, 2, 5, [writes these numbers down] or 5, 2, 4, 3, 1, [writes these numbers down] and that would be a.
Christian: Okay, thanks a lot [handing me the question]

19: On the left are square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are where paper has been before paper was folded. Okay, a hole has been punched in the paper as indicated in the picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. So, if you have a hole right there in the corner, [uses both hands to indicate a hole punch] you unfold it, [indicates an unfolding with her hands] it's going to be down here and here, [indicates a hole punch in the places with her hands] so it's d.

19: Two different types of models, models are illustrated below, space-filling models and,
ball, ball-and-stick models. In the next two questions, you are provided with a ball and stick model of a molecule. Set out below, it, set out below it are four diagrams of space-filling model, models of that molecule. Pick that space-filling molecule that matches the ball-and-stick one. You have one big atom, and you have, small, four small, four small ones, so, hum, you would have, their smaller, so the space-filling fills it up, [using hands off screen] so it would be c.

Christian: Why'd you say c?
19: Because like, this one has [pointing to choice b] is the four of these are equal, [points to the four white atoms of the ball-and-stick reference structure] and this one shows that it is elongated [pointing again to choice b and using hands to indicate elongated], this one [points to choice d] doesn't show it's equally surrounding the small one [uses hand to indicate bigger atoms], and this one [points to choice a] doesn't look like it's, um, doesn't look like it's actually taking up the space [using hands to indicate space of the molecule] of the, of the molecule.

19: Two different types of models are illustrated below, space-filling models and ball-and-stick models. Pick the space-filling model that matches the ball-and-stick one. Okay, um, okay so on the bottom layer you have 1, 2, 3, 4, 5, [using finger to count away from the structure] so you have 5 on the bottom [writing 5], then you have 1, 2, 3, 4, [pointing to the ball-and-stick reference structure and counting atoms] on top, [writing 4] like that, and then you have 1, 2, 3, 4, 5, [pointing and counting again on the ball-and-stick] again, [writing 5] so you would have to have [pointing at choice d] a molecule that has that, so b can't be it because there's not enough, [crosses out choice c] um, c, no actually that's c, but um 1, 2, 3, [pointing and counting the atoms in choice b] hum, it looks like it would be a, or no it's c, because a looks like it has too many molecules for each layer, [points to choice a] b doesn't have enough molecules, and so it would be c.

Christian: Do you mean d, I'm sorry do you mean d?
19: Yeah, d.

Christian: Sorry about that, I'm going to relabel them. I messed that up so sorry about that.

19: This unit cell is represented by spheres. How many spheres are in this structure? It's a unit cell, so it would have 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, [pointing and counting that atoms on the top of the structure] it has 12 on top, so that means it has 12 throughout the whole thing. 1, 2, 1, 2. [pointing and counting down the structure] So 12, 24, 36. 36.

19: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? If you have a sphere, and you have all those, [using hands to indicate an inner sphere] so, say the one right there, [pointing to a sphere on the outside], you would have 1, 2, 3, 1, 2, 3, [pointing and counting on the outside of the structure] and you would have 1, 2, 3, 4, [pointing and counting again] touching it on bottom, four touching it on top, [pointing to the bottom and top of the structure] and hold on a second, you have a sphere on the inside, [uses hand to indicate a sphere] so if you have a sphere on the inside, [drawing a circle below the question] you would have one directly on the top, and one
where did you get those 2 from, i'm sorry?

19: from the top and bottom, right here, i drew one, it looks funny, but i drew one from the top, and one from the bottom. [referring to her structure]

christian: okay.

christian: for the last question, i have a list of eight skills that i want you to read through by yourself, and then i want you to indicate which skill you think match the questions i am going to give you back, okay?

19: okay

christian: so read through the list of skills to yourself, i'm going to give you a couple questions back. [pause while she reads]

19: okay.

christian: i want you to write on the question, i want you to write on the question, any skills you think you used to solve the question.

19: okay.

christian: okay? those three right here [mumbling].

19: [looking at the space-filling with the face centered cubic question] alright, um, do you want me to?

christian: that's fine, and please explain why you think what they are also, match the skills.

19: okay, association, [writes association] because you have pictures, and it tells you what the pictures are, so you're trying to figure out which one is which. [using hands to indicate a box] um, um, consistency, because they are all red, constancy [writes constancy], i guess discrimination, because you have to pick the correct object. [writes discrimination]

19: look at the following box, um, [looking at the box question] i guess this would be, figure-ground, [writes figure ground] because you had to figure out, like you had to distinguish from its background, because this it can look like a different shape because it's on, [points at the box] 2-dimensional. [waves hands around] and sequencing [writes sequencing] because you got to find out how to make the box using the different sides.

19: [looking at the n-butane question]. this one we had to use, um, association because you had to understand the question to be able to understand what you're looking for in the picture. [writes association] um, you have to use discrimination, because you got to understand that the dashed lines are behind the page, and the bold lines are above the page. [pointing at figure and using hands to indicate behind and above the page] [writes constancy] um, also have to use, um, not constancy [crosses constancy out, and writes discrimination] um, form perception, because you had to be able to see it in 3-d, [writes form perception] or use something to help you see it in 3-d, and, um, you had to use orientation to take the 3-d
object that you made [used hands to indicate a bigger molecule] and make sure that it matched the picture [writes orientation].
Interview with student 20

20: The diagram below is an illustration of the structure of diamond. Each lettered black dot represents an atom of carbon and all are within the cube. For each question, choose the one best response. View atom letter K. Where atom U with respect to atom K? Alright, U [points to atom U] atom letter K, where, is [mumbling], with respect to K [points to atom K], ah, beside it, above, below, same level, same level. [circles c]
Christian: So why did you, why you'd say, why you'd say same level?
20: Because they're right beside each other. [pointing to atom U and atom K again]
Christian: Okay.

20: If the structure in diagram A were rotated around the Z-axis in the direction that the axes show, which structure below matches a rotation around the Z-axis? Z-axis, here, doing a rotation [pointing to the Y-axis rotation and diagram A]
Christian: The Z-axis is actually this one right there
20: This one? [pointing to the z-axis rotation]
Christian: Yeah, that one.
20: Hum, so are we rotating this? [pointing at diagram A again]
Christian: Yes.
20: So would it be b? [points to choice b]
Christian: Why do you say b?
20: Because we're rotating it this way, right? [using fingers to show a z-axis rotation]
Christian: Ah, hum.
20: So if it's this way, [pointing at the z-axis diagram and rotating with her fingers] like again, within rotated this way [mumbling] I don't know, [laughs] I think it's b [cell phone rings], I don't know I'll just go with b.

20: The diagram below is a stereochemical representation of a molecule of ethanol. In this diagram hashed wedge indicates that a bond projected beyond, behind the paper, and that one indicates that a bond projects out of the paper towards you. Atoms connected with straight lines indicate that the bond is in the plane of the paper. Which atoms are furthest from your eyes. These two are coming out of the paper towards me, [points to atoms 9 and 4] to me, that's behind the paper right? [pointing to atoms 8 and 5]
Christian: Um, hum. Keep speaking your thoughts.
20: So, a weak, is this showing, are we supposed to telling me, like which ones are the whole bond, [points to the bond connected atoms 1 and 7] which ones are showing?
Christian: The questions are which atoms
20: Which atoms? Oh.
Christian: The questions says which atoms are furthest from your eyes.
20: 4 and 9, 4 and 9, because they are projected out towards me.

20: The diagram below is a representation of a molecule of n-butane. If you visualize the molecule from left to right, which carbon atom in the drawing is closest to your eyes? From
left to right, are we still going with the same thing as the dark ones? [pointing to the left most hydrogen carbon bond]
Christian: Yes, are coming out towards you, and the dashed ones are behind the paper.
20: [mumbling and speaking very softly]
Christian: Keep speaking your thoughts.
20: Sorry, I want to say carbon c if we're going left to right, [circles carbon c] because there's two to the right, and it's got the one sticking out, [points to the bond in between carbon c and d] so c.

20: Look at the following box. If you ignore the top and bottom of the box, what is the order that you could build the sides from the following pieces? So we're ignoring the top and bottom. [pointing to the top and bottom]
Christian: Here is a little box. [handing the small box]
20: Okay, so, this is the backside [pointing to piece 5] [mumbling and talking softly], 5, [writes 5] 2, [points to side 2] [mumbling] Is this a side too? [pointing to side 1]
Christian: Yes, they are all sides?
20: [mumbling]
Christian: Keep speaking your thoughts.
20: I want to say it's 3, [mumbling] well, [going to look at the choices]
Christian: Those are the choices.
20: Yeah, it says 2 2's, 4 til, it's 2 the second, [laughs], 2 then [mumbling] it's 4, [points to side 4, and writes 4] and 3, 1. [writes 3 and 1]
Christian: So what answer is that again?
20: The answer is a.

20: On the left are squares, square pieces of paper that have been folded as shown by the dotted lines. The dotted lines are [where the paper was folded-mumbled]. A hole has been punched in the paper as indicated in picture A for each question. Pick the figure that shows the positions of the holes when the paper is completely unfolded. Hum, so it should be in the lower square, [points to figure A] so it should be one in the corner [draws on the corner of figure A] and one in the middle, so d.

20: Pick the figure that shows the positions of the holes when the paper is completely unfolded. The paper is folded into a triangle, [uses hands to indicate a hole punch] so there should be one in each hole, [pointing to figure A] each corner, no, in the middle, like in a diamond, yeah, I think it's a.
Christian: So why is it a again?
20: Ah, no, I think it's d, no it's d because that's at the corner at the ends, I meant e, not d.

20: Two different types of models are illustrated below, space filling models and ball and stick models. In the next two questions you are provided with a ball and stick molecule, model of a molecule. Set out below it are four diagrams of space-filling molecules, of that, models of that molecule. Pick the space-filling model that matches the ball-and-stick model.
Hum so, we have this central, [points to the central gray atom on the ball-and-stick reference structure] [mumbling] which we, hum, [mumbling] these two [pointing to choices a and c].

Christian: Keep speaking your thoughts.

20: Ah, this one, I think it's a.

Christian: Why do you think it's a?

20: Um, because the space-filling molecules they're just going, like the balls there's no sticks right? [using hands to show compression around the central atom]

Christian: No sticks, right.

20: Okay, so the balls [pointing to the four white atoms on the ball-and-stick] should be on the same place on the molecule so.

20: Two different types of models are illustrated below, space filling models and ball and stick models. Place the space-filling model that matches the ball-and-stick model. Hoo, haw, that's a lot. [points to ball-and-stick reference structure] Ah, what do we have? I'd say it's just a big cluster, um, definitely not, no, cause you have 9, 10, 11, 12, [points and counts the atoms in the ball-and-stick] [mumbling] um, not b, [points at choice b] that is not, it doesn't have enough, um, this one, and that one, hum, I don't, I just don't {know}.

Christian: Keep speaking your thoughts.

20: [laughs] I don't think it's c, [points at choice c] I don't think it's that one. And then, ah, I don't think that's the shape of the thing [pointing to choice a], because it comes in, [points back at the ball-and-stick and uses hands to show compression] it's got 2 up top, [uses hands to show the atoms at top coming in together] and then like 1 in the middle, and 2 on the bottom, [uses hands to show the two on the bottom coming in together] so that's definitely not that shape, so d.

20: Okay, this unit cell is represented by spheres. How many spheres are in this structure? Are we actually doing unit cell-like calculations?

Christian: Yes, right.

20: Dammit, um, I had a hard time with this one [laughs] Okay there's 1, 2, 3, [points and counts the top right row of atoms and counts the rest of the top of atoms] okay so there's 12 of them. How many have corners? Oh, god I've got to remember the thingies, corners [writes c below the question] you had 1/4 in there.

Christian: I'm sorry, I really want to know, how many spheres are in this structure total, so don't worry about the unit cell, so how many spheres are in the thing

20: Oh.

Christian: But I agree

20: 12, oh, 12 times 3. I'm sure there's 12 right, [points and counts them again and mumbles counting the numbers] 36?

20: This unit cell is represented by spheres. Consider a sphere on the inside, how many other spheres will touch it? What do you mean on the inside, like right in the middle?

Christian: In the middle, right, right, yeah

20: Hum.
Christian: So like 2 spheres in the middle.
20: [drawing on the figure] A sphere in the middle up here, and it's probably being touched by, 1, 2, 3, 4. [pointing and counting the number of atoms on the top] [mumbling and drawing a circle off to the side].
Christian: Keep speaking your thoughts.
20: Oh, [drawing 3 smaller circles below the bigger one] I'm just trying to make a picture of it, and but that's going to be all the way up [laughs]
Christian: So all the spheres are the same size, right?
20: Huh?
Christian: All the spheres are the same size you get that right? All the spheres are the same size. [points back to the middle of the object]
20: Yeah, okay so the spheres are going to be the same size as it too,
Christian: Yes, they are all the same size.
20: Let's see, so how it is going to be in the middle, middle? [draws a circle in the middle of the structure] Put it right there, so it's going to have 5, 6, 7, 8, 8, 9, 12, I would say 12.

Christian: I want to read through, I've got a list of 8 skills here. I want you to read them to yourself, I'm going to give you a couple questions back, and I want you to match the skills you think you used to solve the question.
20: So, do you want me to read them out loud?
Christian: No, you can read them to yourself.
20: Okay. [pause while reading] Do you think that might be some that's more than one.
Christian: Yeah, or however many you used to solve them with, it doesn't matter. So basically I want you to match, so basically what I want you to do is write on the question, any skill you think you used to solve the question with.
20: With all of these, or just these 4 right here.
Christian: These 4.
20: This one is, [unit cell question] definitely form perception, [writes form perception] um, orientation, [writes orientation and memory]
Christian: So why did you put those skills down, I'm sorry, why you'd put those skills down?
20: Why I'd put the skills down, said form perception because I did had to interpret this 3-D model of these balls [points to the object again] and memory because I had to remember how many would be touching it at the same time, [points back at the structure] and orientation because, um, I had to think about the position of the object when I put it in the middle.

20: Okay, this one was definitely [the space-filling with face centered cubic cell] um, [mumbling] is definitely try to see this as one form, [writes constancy off screen] and try to condense it down into another form, and ah. Form perception to figure out what shape it was going to form after it condensed. [writes form perception] [mumbling] Memory, memory, [writes memory] um.
Christian: Why memory?
20: Because you had to recall the domn, dominant features [laughing] of the diagram.
20: This one [the box question], sequencing because you had to know which order [mumbled and laughs] sequencing because you had to, ah, [writes sequencing off screen] determine the order these objects worked to build the box up. And [mumbling] form perception, I had to use that one on all of them, [writes form perception] and hum, and, [mumbling] hum, hum, that's all I can think of.

20: This is hum, [the n-butane question], okay so, form perception, because you have to, and ah, [writes form perception] hum, try to see this flat object as a
Christian: Three-dimensional object
20: 3-dimensional object, and ah, um, [mumbling], oh figure ground, [writes figure ground] up close you had the others.
Appendix VII: The original definitions of the eight visual-perceptual skills and the difficulties students could have from the Rochford and Archer paper
Table 5
Theoretical analysis of a visual perception handicap into possible sub-categories of deficits

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<table>
<thead>
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<tbody>
<tr>
<td>(a)</td>
<td>Visual discrimination problems involve an inability to perceive dominant features in different objects and, thus, to discriminate one object from another. A typical visual discrimination task involves matching various shapes, designs or objects. Students with a problem in this area could experience difficulties with inversions and reversals, with subsequent confusion of symbols or diagrams.</td>
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<tr>
<td>(b)</td>
<td>Visual figure-ground problems occur when an object cannot easily be distinguished from its background. Students with difficulties in this area may experience problems perceiving parts and wholes.</td>
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<td>(c)</td>
<td>Visual orientation problems involve position in space. Students with disorders in this area usually record difficulties with spatial relations. The ability to perceive the positions of objects in space in relation to other objects and to the observer is affected.</td>
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<td>(d)</td>
<td>Visual form perception problems involve inaccurate two-dimensional representations of two- or three-dimensional objects.</td>
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<td>(e)</td>
<td>Visual sequencing problems include omissions, insertions or substitutions of symbols or connecting parts of diagrams by students.</td>
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<td>(f)</td>
<td>Visual memory is the ability to recollect the dominant features of a stimulus item or to recall the order of a number of items presented visually. Students with problems in this area may have difficulty recognising geometric objects and symbols accurately, or misremembering them.</td>
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<td>(g)</td>
<td>Visual constancy problems involve the misinterpretation of changes in size or shape or colour.</td>
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<td>(h)</td>
<td>Visual association and visual closure problems occur when a student is unable to identify figures that are presented in fragments, or unable to visualize the missing portion of a partially incomplete object or diagram.</td>
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<tr>
<td>(i)</td>
<td>Problems can occur with rate of processing of visual information.</td>
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