MEASURING COGNITIVE LOAD OF SPATIALLY DEMANDING TASKS VIA HEART RATE

By

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ABSTRACT

Organic chemistry is often considered one of the most difficult courses for undergraduate STEM students as it requires significantly different ways of thinking compared with other STEM courses, specifically it has high spatial skill demands. While it is not possible to make the course easier for students by simply removing core content, various teaching methods and tools have found use in organic chemistry classrooms. One learning tool professors recommend to students is the use of molecular model kits to assist students with understanding the three-dimensional (3D) shape of molecules. While the use of model kits is associated with high grades and learning gains in organic chemistry, it is not necessarily clear how this tool aids students, but it may be possible that the use of a molecular model kit may reduce cognitive load as students learn and solve problems in organic chemistry. In this study, we sought to measure the cognitive load associated with various tasks, including solving spatially demanding organic chemistry problems. Specifically, this study's focus was to determine whether heart rate measurements can be used to reliably measure cognitive load. Showing that heart rate is a reliable measure of cognitive load would allow for future studies with specific interventions involving the use of molecular models in problem solving.

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Introduction

Rationale

Organic chemistry is a very challenging subject often known to have a high failure and withdrawal rate. The course is commonly known as one of the hardest undergraduate requirements for STEM students and is a gateway course for advancement into upper-division coursework in many STEM majors. As a result, the class is a great source of stress and anxiety for students. Research shows that women and other underrepresented groups of students in medicine often lose interest in pre-medicine tracks during their undergraduate programs due to various aspects, one of the most significant being one or more negative experiences in a chemistry class (Barr et al., 2008).

In my experience, I found general chemistry to be fairly easy because it was similar to the chemistry courses I had already taken in high school. Despite this I was worried about taking organic chemistry in my third year at the University California Riverside (UCR) because I knew little about it except for the reputation that preceded it. When I took organic chemistry my roommate said that the use of representations in organic chemistry required a significant amount of mental effort. I took their warning seriously and when my professor recommended a model kit to succeed in the class I bought it immediately. The model kit was very useful for the lab, learning the concepts taught in the class, and while completing my homework. I felt that using the kit to complete my work decreased my stress levels, leading my percentage of effort to increase when I was not using the kit. However, even with these incentives to keep using the kit I did not end up using the model for the final exam. However, I did continue to use the model kit after the first quarter of organic chemistry every once in a while for difficult concepts. My personal experience gives me great interest in the potential benefit for my peers and myself if the model kit became a more active part of the class.

Organic chemistry is well known as a subject for requiring a high level of spatial skills. Research has shown that students with high spatial skills are able to perform better on many organic chemistry tasks, such as mentally manipulating two-dimensional (2D) representations and solving questions requiring a sound understanding of three-dimensional (3D) properties (Stull *et al.*, 2018). Due to 3D properties being important for stereochemistry, a model kit is commonly used to aid in students learning this material.

Embodied Learning Tools

Embodied learning is a teaching approach focused on the non-mental factors involved in the learning process. Embodied learning is often achieved using embodied learning tools, which are external representations used to understand a phenomenon, including molecular models used in subjects like organic chemistry (Paniagua & Istance, 2018). The use of molecular model kits as learning tools is not new in organic chemistry. Previous studies on the use of molecular model kits have shown positive impacts on student learning when model kits are incorporated into the classroom and student study time. In one such study, it was found that students were better able to understand the chemistry-specific content with the use of two models; this was specifically shown via student performance on examinations. Students were better at translating diagrams when they first translated 2D diagrams (*i.e.,* confirmations) into 3D models. It was also noted that use of models were valuable even after usage stops because students that had used the model kits previously had better performances on exams (Stull *et al.*, 2018). Many organic chemistry professors allow their students to use model kits during exams as tools in order to bolster their exam performance by allowing students with lower spatial skills to use an external representation to assist with problem solving.

Embodied learning tools have already been found to increase student performance when learning online. A research study found students that used physical molecular model kits had a greater understanding of stereochemistry, better reasoning of reaction mechanisms, and better application of knowledge for more complex concepts compared with students who used interactive virtual models or had no access to models at all (Casselman *et al.,* 2021). It is interesting that digital models were less effective learning tools than physical models, and it is not clear why a physical model would have a significant advantage, but it may be related to how different embodied learning tools help reduce cognitive load during the learning process. We wanted to use a physical model in our study because the research shows that it is the most effective for student learning and mastery.

Another recent research study found that model kits led to an improvement on test scores, on average, of 16%. Specifically, the benefit was great for students with initially low spatial ability, as they were found to have an even larger improvement of test scores on average of 26% (Raybin & Lee, 2010). Some students have low spatial ability because it is a skill that is not taught in a specific class and is more related to what real world experience they may have developed. Based on these previous studies, providing model kits to students during assessments is strongly associated with higher performance, but the performance gains are most pronounced in lower spatial skill students. In recent years, 3D printing has become more accessible and has found its way into some organic chemistry classrooms. Another study found that using 3D printing was an effective tool when teaching about orbitals, stereochemistry, isomerism, and hybridization; all of which are topics that rely heavily on student spatial skills (Penny et al., 2017). This shows that further technology can be used to aid students in learning organic chemistry, and once again shows that 3D models aid in student understanding. While the benefits of model use have significant precedent in the educational research literature, the basis for the benefits is not fully understood, but may be related to a reduction in cognitive load.

Cognitive Load

Cognitive load is the amount of information the brain's working memory can handle at a time. Working memory capacity is often considered limited to less than nine individual items, and is reduced further during problem solving to two or three (Miller, 1956). Because working memory is limited in its capacity, instructors should not overload students with extraneous information that does not aid in their learning process. Working memory is important for planning, comprehension, reasoning, and problem-solving (Cowan, 2013). When working memory is overloaded, students will have a more difficult time learning and solving the material that is presented for them. Organic chemistry is a subject that has a great cognitive load for students. The subject presents students with material that they have never seen before (*e.g.,* the use of many types of representations), and many students do not have the foundational study skills to succeed in the course. Organic chemistry requires mastery of concepts with a lot of practice necessary to succeed in the course.

In order to offset this cognitive load, it is hypothesized that model kits may be a useful tool. In order to gauge the impact of model kits on cognitive load, one must be able to measure the cognitive load. According to a review of methods for measuring cognitive load, eye tracking was found to be the most effective followed by monitoring heart rate (Ayres et al., 2021). Eye tracking is an innovative technology that collects data on pupil dilation, blink rate, and eye fixation on the task to measure cognitive load. Due to the robust data eye tracker provides, eye tracking might be the best biometric available for measuring cognitive load. However, eye tracking systems are prohibitively expensive for a pilot study. Another effective biometric that can be used to measure cognitive load is heart rate, which will be the focus of this research study. One study found that heart rate was an effective biometric for measuring cognitive load while performing chemistry tasks. The study found student's heart rates increased while doing chemistry because of the greater stress placed on the body due to the chemistry problems (Cranford *et al.,* 2014). Additionally, it was found that subjective measures, such as having the participant rank their own cognitive load, were surprisingly accurate in measuring cognitive load and correlated well with other physiological measures. Ayres and colleagues claimed a combination of physiological and subjective measures may be most effective for identifying differences in cognitive load (2021).

In light of the prior research on measuring cognitive load, we plan to use a combination of heart rate (BPM) as a physiological measure and subjective measures in this study. We can attach a heart tracker to the participant's forearm, and track their beats per minute using an app compatible with bluetooth. This method is a cost-effective alternative for obtaining pilot study data sets. The subjective measure was created through devising a paper where students can circle their mental effort on a scale from 1-9. Our hypothesis was that tasks with higher spatial demands on working memory will result in an increased heart rate and also be estimated by the participants to have higher mental effort required on a subjective scale.This study will measure cognitive load associated with low-spatial demand tasks (*i.e.,* coloring), high-spatial demand tasks (*i.e.* building with Legos and solving organic stereochemistry problems.) Higher cognitive load is expected to be measured for tasks, such as Lego building and solving stereochemistry problems. By demonstrating that a combination of physiological and subjective measures can accurately measure cognitive load, the eventual goal would be to determine if model usage reduces cognitive load on students solving stereochemistry problems by conducting similar experiments where students are provided models or not when solving stereochemistry problems.

Methods and Materials

The study was reviewed and approved by the UCR Institutional Review Board, under protocol HS-21-131. This study was conducted with students that have completed organic chemistry in the past two years. Nine of the ten participants completed their organic chemistry education at UCR while one participant studied at a different university. Students that have finished organic chemistry were selected for this study because the cognitive load used on tasks could be variable if students with different levels of experience in the subject. For example, a student in their first quarter of organic chemistry may have a much higher cognitive load than a student that had successfully passed the courses in the subject. The students that were recruited for the study were former students who had completed Dr. Casselman's organic chemistry class in the past two years. Interested participants then scheduled an appointment to meet one-on-one with the researcher in an educational research lab on campus.

All participants were informed of their rights as participants in this study and consent was documented. Participants were then fitted with a heart rate monitor (Scosche Rhythm +) on their non-dominant forearm. This heart rate monitor was connected to an iPad through a wireless connection. Live heart rate data was collected using the UnderArmour MapMyFitness app.

At the beginning of the study session, the participants were given a blank coloring worksheet with colored markers, and they were instructed to complete the coloring sheet for 15 minutes. Coloring worksheets were obtained from the Crayola website. This portion of the study was timed and heart rate data was collected. After 15 minutes had passed, the participant was given a survey to rank the level of their mental effort during the coloring task using a 1-9 scale with 1 being "very, very low mental effort" and 9 being "very, very high mental effort." Using this scale, participants can rank how much cognitive load they spent on their task. At this point, participants were randomly assigned to a subsequent task. Subsequent tasks included: 1) an additional 15 minutes of coloring; 2) the use of Legos to build a model using pictures and an instruction guide; 3) completion of an organic chemistry worksheet with a molecular model kit made available. The Lego set was part of Lego's Architecture line and was known as "London Skyline". The organic chemistry worksheet was on the topic of stereochemistry (authored by Dr. Casselman) and required students to answer multiple-choice questions that were related to complex 3D structures.

After completing the second task, participants were once again surveyed on their mental effort of the second task on a 1-9 scale. At the conclusion of the tasks, the heart rate monitor was removed. Participants then completed the mental rotations test (MRT) online. The MRT test was a six minute test to test the participants' spatial skills (Vandenberg & Kuse, 1978). Participants also completed a demographics survey before the study period was complete.

After analyzing data from the first few participants, some modifications to the protocol above were instituted. High heart rates were noted at the initiation of the study period, so an additional 5 minutes of relaxed time (sitting) was instituted to allow for a more normal resting heart rate to be measured. Another modification made was to record the participants heart rate in a single 30 minute block instead of two 15 minute blocks to avoid any erroneous changes in heart rates that may have been caused by the heart rate monitor restarting.

Data and Results

Demographic Data

The study sample consisted of 10 participants who were either a current undergraduate or graduate student attending the University of California Riverside. 6 of 10 of the participants identified themselves as male and 4 of 10 as female. The ages range from 19 to 28 years old. The race/ethnicity reported by participants consisted of Asian/Asian American (4 of 10) and 30% of White/European (3 of 10), and other identifications (3 of 10). Furthermore, 3 of 10 identified as biology majors, 3 of 10 as neuroscience majors, and the remainder as psychology, chemistry, and biochemistry majors. Additionally, 4 of 10 participants identified as first-generation college students and 70% learned English as their first language. Lastly, 90% last took an organic chemistry course between 2019 and 2021 with one outlier who last took the course in 2013.

Heart Rate Data

The heart rate data (BPM, beats per minute) collected in this study was averaged over each 15-minute period of the two tasks. Individual data for each participant can be found in Table 1. For participants that completed coloring for the second task, it was determined that their average heart rate changed -5.6 BPM (Table 2), which suggests that heart rate decreased by an average of 5.6 beats per minute. Representative heart-rate data for a participant completing only coloring tasks is shown in Figure 1. There is significant variability in the heart rate measured during the first coloring task 50-115 BPM. The average heart rate for the first coloring task was 78.3 BPM and the average heart rate for the second task was 54.9 BPM (Table 1).

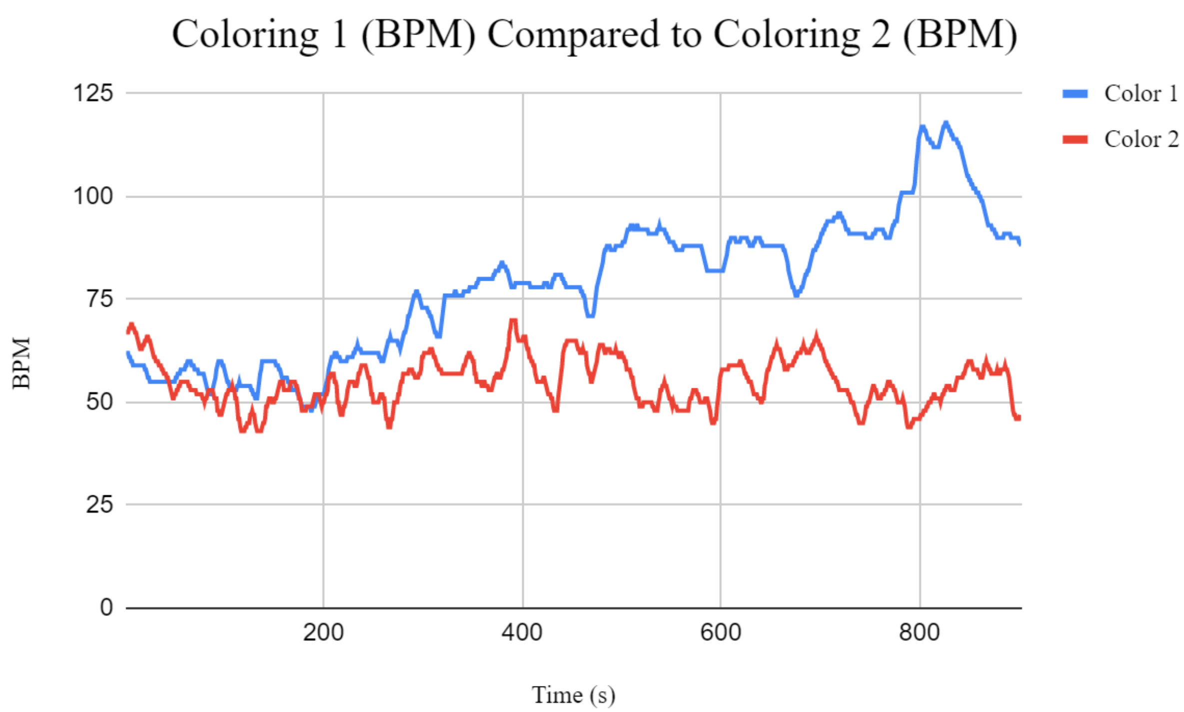

Figure 1. *Graph showing the average beats per minute over 15 minutes with coloring as task 1 and task 2.*

Representative data for a participant completing the Lego task is shown in Figure 2. Similar to the coloring task there is significant variability in the heart rate measured during this task; 70-110 BPM during the Lego task. The data shows that the heart rate during the Lego task was consistently higher than the coloring task. The average heart rate for Participant #8 during the Lego task was 82.1 BPM and the average heart rate for the coloring task was 74.4 BPM. (Table 1). It is worth noting that the participant's heart rate spiked to 110 BPM when first introduced to the Lego task. The overall average heart rate change for all participants on the lego task was +0.6 BPM (Table 2).

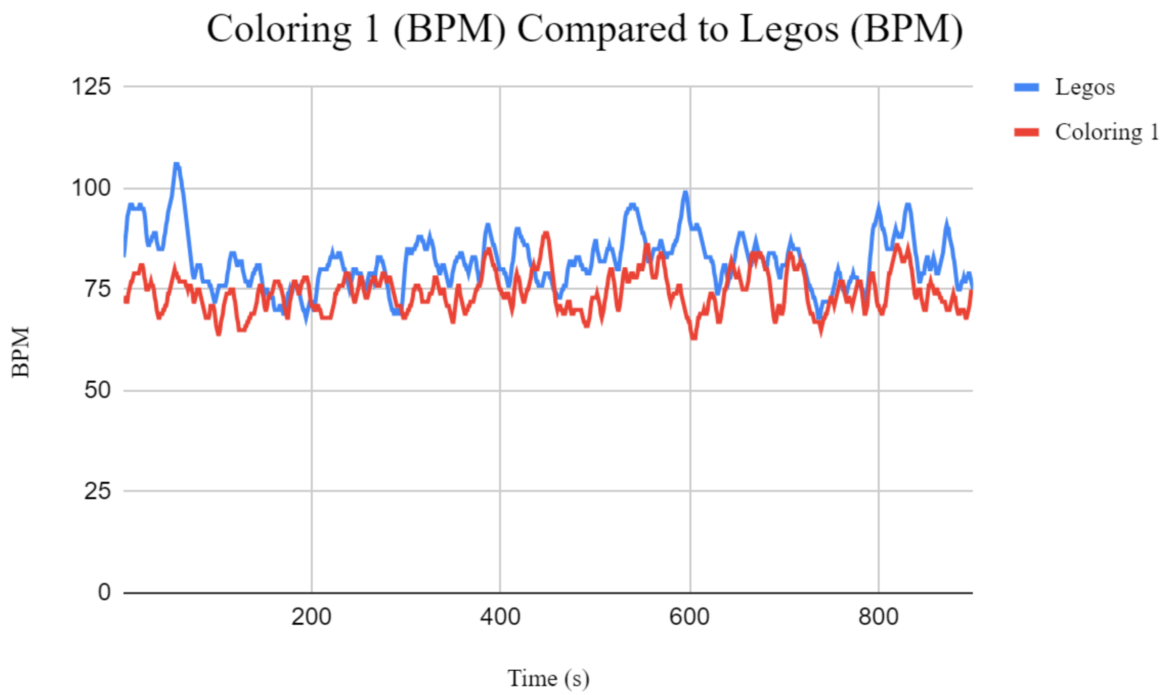

Figure 2. *Graph showing the average beats per minute over 15 minutes comparing lego building and coloring.*

Representative data for the task of stereochemistry problem solving is shown in Figure 3. This participant had an average heart rate of 72.1 BPM for the organic chemistry task, and an average heart rate of 62.2 BPM for the coloring task. (Table 1). Like the Lego task, this participant showed a significant spike in heart rate at the beginning of the organic chemistry task. The participant's heart rate spiked to 115 beats per minute, and then lowered to 48 BPM as the participant continued to engage with the task. The average heart rate change for all the participants for the organic chemistry task is +0.4 (Table 2).

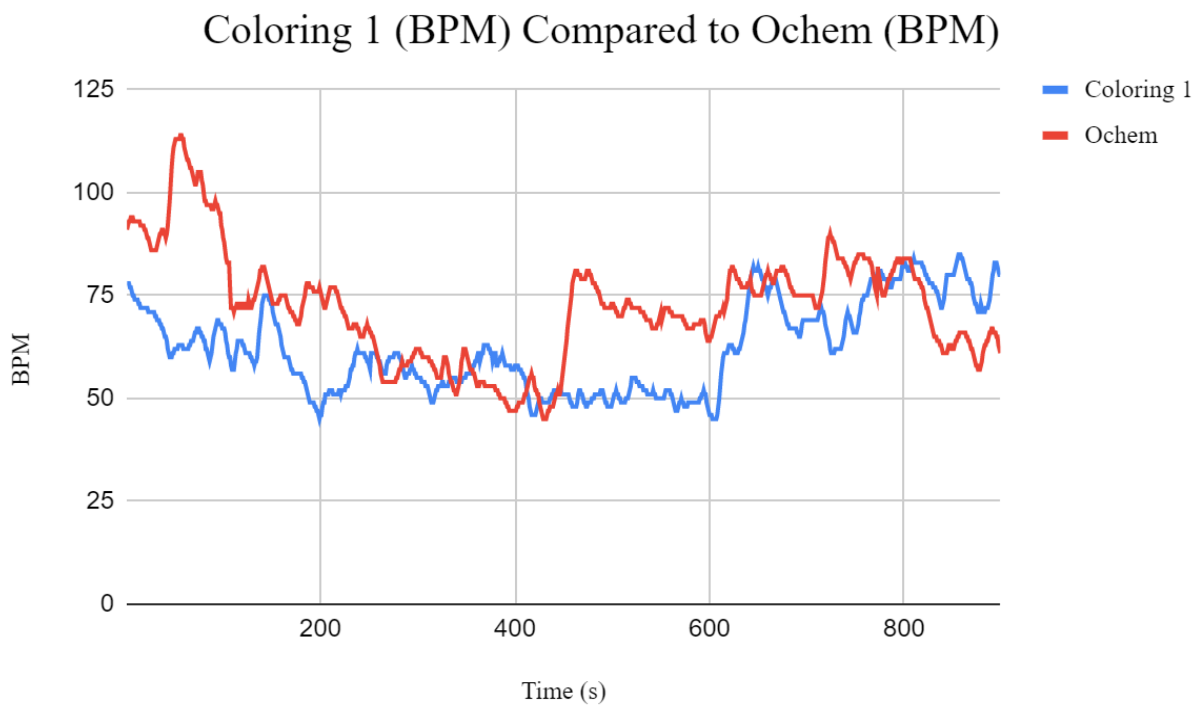

Figure 3. *Graph showing the average beats per minute over 15 minutes comparing organic chemistry worksheet and coloring.*

The average mental effort given for coloring by all participants across groups was a 1.6 on the nine-point scale, which suggested that the mental effort for the coloring task is between “very very low mental effort" and “very low mental effort” (Table 2). The average mental effort for the lego task was 5.66, which is between “neither low nor high mental effort” and “rather high mental effort” (Table 2). This suggests that participants felt building legos was a more mentally strenuous task than coloring. The organic chemistry task had a rating of 5.75. The organic chemistry task falls between “neither low nor high mental effort” and “rather high mental effort” (Table 2). Both tasks considered to require spatial skills were rated significantly higher in mental effort than the coloring task.

Table 1. *Summary of data showing average heart rate, MRT score, and task effort scale. HR means heart rate and MRT is Mental Rotations Test*

Participant # & Task 2	Task 1 Average HR	Task 1 Effort Scale	Task 2 Average HR	Task 2 Effort Scale	MRT Score
#1 Coloring	84.8	1	83.8	1	7
#2 Legos	72.4	1	72.4	5	7
#3 Worksheet	99.5	4	92.2	8	14
#4 Worksheet	71.9	1	70.3	6	15
#5 Legos	60.1	1	54.0	6	12
#6 Coloring	78.3	1	55.0	2	9
#7 Worksheet	92.5	2	94.2	5	15
#8 Legos	74.4	3	82.1	6	13
#9 Coloring	70.7	1	78.4	1	0
#10 Worksheet	62.2	1	72.1	4	11

Table 2. *Summary of data showing average heart rate changes and average self-reported effort scale by task. HR means heart rate and BPM means beats per minute.*

Tasks	Coloring	Legos	Chemistry
Average HR Change (BPM)	-5.6	+0.6	+0.4
Average Self-reported Effort	1.6	5.66	5.75

Discussion

We expected participant heart rates to increase by a considerable amount with the higher cognitive load tasks, but heart rates only increased a small amount for the lego task and the organic stereochemistry worksheet. Also, it was odd that the Lego task and the worksheet task had similar increases for heart rate. However, this may be because participants were not used to building Legos, and they also felt pressured to build as much as they could in the allotted time. Another possible explanation is the stereochemistry worksheet was much simpler than planned for the participants. Interestingly, one participant (#10) who completed the worksheet task had the highest increase of all the tasks compared to coloring which was an increase of +9.9 BPM. This is an example that organic chemistry can have a large amount of cognitive load and that it can be associated with increased heart rate as originally hypothesized. This participant's heart rate also spiked to 115 BPM at the start of the worksheet task when their heart rate was at 76 towards the end of their coloring task. (Figure 3). Their heart rate went from 115 and then lowered as they became more comfortable with the task. This may show evidence of the initial cognitive load of being faced with organic chemistry problems, and the model kit lowering the cognitive load.

The results were difficult to analyze because it appears some of the data may be inaccurate. The expectation is the participant's heart rate should be consistent while sitting in a chair doing a task. However, our data showed large volatility in heart rate. There were times where a participant's heart rate would move from 115 to 48 (Figure 3) which is unrealistic. The other expectation was the participant's heart rate would increase with more difficult tasks. However, from most of the data the heart rate would decrease when doing the second task. Another potential issue was that participants' heart rates may have been elevated when first arriving at the lab. This is because the participants needed to walk a considerable distance to get to the lab, and also needed to climb a flight of stairs. We attempted to alleviate this problem by allowing the participant more time to calm their heart rate by sitting down and filling out the consent form and then waiting a few extra minutes for a baseline resting heart rate.

The self-reported mental effort measures were straightforward to analyze and aligned well with our hypothesis. Unsurprisingly, coloring had the lowest mental effort rating, and organic chemistry had the highest. It was surprising that participants reported that the stereochemistry problem set required only slightly more mental effort than those who built Legos. This may again be explained by greater than expected difficulty associated with the Lego task or less than expected difficulty associated with the worksheet task. Also, the participants doing the stereochemistry worksheet were able to use the model kit to aid them as the cognitive load may have been reduced. This cannot be confirmed as we did not have enough participants to have a treatment group that completed the worksheet without the model set. However, participant #3 did not use the model kit that was provided and they ultimately rated their mental effort at an 8 ("very high mental effort.") The other participants who completed the worksheet used the model kit provided and had significantly lower mental effort scores (6,5, and 4.) This could suggest that not using a model kit was more mentally strenuous, but additional data would need to be collected.

There were some instances where heart rate data appeared to be unreliable. There were many factors that could have caused some of the data to be inaccurate. The heart rate monitor could have been faulty. After participant #5, a different heart rate monitor of the same brand was substituted. This did not significantly affect the heart rate data collected. Another issue may have been the placement of the heart rate monitor. The monitor instruction booklet suggested placing the monitor on the forearm, but this could have caused problems because it seemed that participants could not get a good reading due to different sizes of their forearms. However, when I tried using the bicep the heart rate data appeared increasingly inaccurate. The final attempt to increase the accuracy and reliability of the heart rate data was to change the procedure used to acquire the data. Previously, I recorded their heart rate in two different tasks in 15 minutes blocks within the MayMyFitness app. The change was to take one recording for 30 minutes with both tasks. This seemed to give us data that represented what was more expected because heart rates began to increase with tasks that are to be expected to have higher cognitive load. The average change of heart rate between tasks was less than what was hypothesized. We expected heart rates to increase by a considerable amount with the higher cognitive load tasks, but heart rates only increased a small amount. However, when the aforementioned change occurred to 30 minute recording blocks there was a substantial increase in heart rate for the second task, suggesting that the acquisition procedure may be important for obtaining reliable data.

We were excited to have the study in person due to the easing of restrictions presented by COVID-19. Unfortunately, most classes were online during the time of data collection due to an increase in cases from the Omicron variant. We originally planned on the fact that most classes would be in person for the time of data collection. Many students were not on campus, and students were reluctant to come on campus for a study. This may have played a factor in our difficulty obtaining study participants. Only ten participants were recruited despite using a large amount of effort to find participants. More than half of the participants were friends and roommates that I had to contact because most colleagues did not want to come in person for research. It is challenging to make conclusions using only 10 participants, where individual tasks had only 3-4 per condition.

Despite the challenges for collecting data, I believe we found promising data that should be further investigated. Our data showed that heart rate and subjective mental scales may be good indicators of cognitive load and seem to correlate with each other, and one anecdotal example where it appears chemistry models reducing cognitive load during the worksheet task.

Conclusions

My original hypothesis was that average heart rate would increase with cognitive load for more mentally demanding tasks, specifically those related to stereochemistry problem solving. Preliminary data in this study suggests that heart rate does track with cognitive load and mental effort, and this is confirmed by the level of effort self-reported by participants via a survey. Based on survey results, the Lego task and stereochemistry worksheet required a significantly higher level of mental effort and associated cognitive load. The values were similar despite these tasks being significantly dissimilar in the level of subject-specific knowledge required; what they shared in common was the spatial demands on working memory. The heart rate data in isolation appears to be too inaccurate to make definitive conclusions, as well as sample sizes being too small to make generalizable conclusions. The small sample size was attributed to difficulties in recruiting participants as many students were still attending many of their classes in hybrid mode during the winter 2022 quarter. If additional studies using heart rate data do not show reliability in this physiological measure, it may be possible to use eye tracking metrics to more reliably measure cognitive load or to show strong correlation between other measures.

Future studies should be done to determine how cognitive load is impacted during the stereochemistry worksheet task when a model is not used, or if a virtual model is used in place of a physical model. This research has the potential to impact chemistry instruction in both in-person and online settings, where virtual models are quickly becoming a popular method of visualizing the 3D structure of organic molecules with interactivity. I want students to have less anxiety and stress when studying organic chemistry, and instead have more fun learning the material. This future research could provide students the confidence to utilize this tool to aid themselves in succeeding in this rigorous subject.

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