ILLUMINATIONS

Lighting up the NMJ: developing an LED-based model of the neuromuscular junction for the undergraduate classroom

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Olson HL, Turin DR, Petzold AM. Lighting up the NMJ: developing an LED-based model of the neuromuscular junction for the undergraduate classroom. Adv Physiol Educ 44: 482–487, 2020; doi:10.1152/advan.00094.2020.—Many complex physiological processes can be introduced and explored using the framework of the neuromuscular junction (NMJ), including neurotransmitter release, membrane depolarization, and ion channel activity. While traditionally used instructional tools such as static complex drawings are useful, these images can be incomplete physiological representations due to the lack of physically moving parts. As a result, they often misrepresent the complexity of physiological phenomena to students.

We describe an effort to create a more accurate, dynamic representation of the NMJ to enhance instruction in an undergraduate anatomy and physiology course. We sought to create a unique and memorable moving diagram that combines elements of static images with moving parts. To evaluate the impact of the dynamic model, students were asked about their understanding of the NMJ before and after exposure to the model. In addition, students were asked for attitudinal responses to the model and their preferred method of instruction. Analysis of student responses indicated that students enjoyed the model, although they also had concerns about the speed of the simulated ion movement being too fast. The model has also served as an informal science education art installation in presentations for prospective students, stakeholders in the broader community, including local and statewide politicians, the University president and board of trustees, donors, and other regional economic and educational leaders.

Arduino; informal science education; neuromuscular physiology; visual displays

INTRODUCTION

Extensive research demonstrates that active learning pedagogies increase student outcomes (3). These gains have been demonstrated across a range of disciplines, including anatomy and physiology (6, 15). Despite the overwhelming evidence for adopting a more active and student-centered style of instruction, the most commonly utilized resource associated with college courses is still the textbook (22). When a student does not understand the presented material, they are often forced to go beyond the textbook, exploring online resources in the form of videos, tutorials, and quizzes systems (7). While very well-produced online videos exist (10, 11), many of these cannot be provided with narration by an instructor of the course without extra editing of the video. The lack of course instructor narration makes the material less personal and less tailored to the course (9). Furthermore, these videos are often not taught in the same way, either using different terminology or a different depth of knowledge as that which is used in the classroom, leading to the formation of misconceptions (18). Students have often used static representations to attempt to gain a better understanding of material presented in a lecture, whether it be drawing it out or diagraming it in a different way (12). However, while useful to help visualize basic functionality of static or linear processes, it can be difficult for students to gain an understanding of the sometimes complex interactions happening within physiology (20).

One of the major topics covered in an introductory physiology course is the physiology of the interface between a motoneuron and a muscle fiber: the neuromuscular junction (NMJ). This physiological process allows for the innervation of muscle fibers following an action potential and synaptic neurotransmitter release from a presynaptic neuron (2). (See Fig. 1 for a generic representation of the NMJ that is similar to those found in many textbooks.) The NMJ allows students to explore many of the core concepts of physiology, including the role of the cell membrane in establishing and maintaining concentration gradients, chemical and electrical concentration gradients, and cell-to-cell communication (16). By extension, an accurate and thorough understanding of the NMJ enables students to also comprehend complexities found in other topics across physiology, such as neurotransmitter release, membrane depolarization, and activation of membrane-bound channels (17). However, when introducing these vital concepts in the context of the NMJ, students can be overwhelmed by its complexity (8, 13, 23). For example, it has been shown that physiology students often believe that action potentials themselves travel through the synapse and innervate the muscle fiber rather than using neurotransmitters to relay this electrical impulse (8). By using a moving visual representation of the NMJ, we hope that we can alleviate some of these misconceptions.

The introductory Anatomy and Physiology class at The University of Minnesota Rochester (UMR) uses a variety of high-impact learning techniques to teach physiological concepts. Within this multifaceted instructional space, students receive information in a partially flipped classroom setting, meaning that class time is split between working through activities using knowledge from prior classes or the textbook, and traditional classroom lectures. This practice allows for conceptual exploration through group learning while maintaining individual accountability. When learning about the NMJ, students are first directly exposed to information through a series of punctuated mini-lectures and collaborative group
discussions stemming from prior instruction. This is followed by a case study that focuses on the effect of neurotoxins on the functionality of the NMJ (19). By identifying where the toxin acts, students can work backward to deduce how muscle contraction would be affected. When faced with interpreting these neurotoxin interactions, students often struggle to visualize how they interfere with the standard NMJ mechanism.

To help students better understand the steps involved in the process of the NMJ, we developed and built an LED-based model (Fig. 2C). (A Supplemental Video can be found at https://doi.org/10.6084/m9.figshare.12379748.) This project was developed in a partnership between undergraduate academic assistants (UAAs) who had previously completed the course and their faculty mentor. At UMR, UAAs act in a similar way to learning assistants (LAs): assisting in the classroom by answering questions and grading material. However, not leading a class themselves, they have been shown to provide a student perspective for lessons and engaging more students in the classroom (14). Because the UAAs were driving the process and creating the experimental questions being asked, it could be used as a learning opportunity for both the UAAs and the students in the classroom. Specifically, it provided opportunities for the undergraduate researchers to gain an appreciation for developing research questions/hypotheses, acquisition of new skills, and the creation of a tool that can be used within the classroom and beyond. The beneficial outcomes of the LED-based model reach far beyond the classroom, since it can be displayed to many interested parties—into a single program. Students who enter the BSHS are mostly traditional-aged college students coming from within 50 miles of campus, located in the upper Midwest of the United States. Approximately 70% of students identify as female, and 17% identify as persons of color. The 4-credit Anatomy and Physiology I class is broken into two 75-min lecture periods and a single 115-min laboratory. Lectures average 56 students per section, whereas laboratories average 36 students per section. Enrollment in laboratory sections is linked to a lecture section to allow for group work to span both lecture and laboratories; students must take both lecture and laboratory concurrently. Classes are scheduled to allow all laboratories to occur in line with lectures so that all students will receive the same lecture material before attending the laboratory. Both lectures and laboratories occur in active learning environments that are physically arranged to allow for groups of six to nine students to sit surrounding a table.

**Building the model.** To build the model, we began with a basic diagram of the NMJ (Fig. 2A) and sketched the diagram on a 2x4-ft. piece of ½-in. MDF board (photo of sketching process Fig. 3A). Once the initial sketch was completed, the model was painted in accordance with the sketch using acrylic paint. WS2812b individually addressable LED strips were cut to length and placed on the painted diagram. We used 18G solid “thermostat” wires for connections between each of the LED strips with soldering between each of the three individual contacts (ground, data, power). Long wire runs were hidden behind the board by drilling holes, whereas shorter wire runs were painted during the final paint touch up (Fig. 2B). It was important to check that students actively learning physiology by denoting the different types of molecules involved. By providing moving parts and a visually appealing color palette, it was hypothesized that students would be able to better interpret and comprehend the complexities that exist within the NMJ.

**METHODS**

**Instructional setting.** The Bachelors of Science in Health Science (BSHS) program at UMR integrates diverse areas of health science—natural sciences, social sciences, quantitative sciences and humanities—into a single program. Students who enter the BSHS are mostly traditional-aged college students coming from within 50 miles of campus, located in the upper Midwest of the United States. Approximately 70% of students identify as female, and 17% identify as persons of color. The 4-credit Anatomy and Physiology I class is broken into two 75-min lecture periods and a single 115-min laboratory. Lectures average 56 students per section, whereas laboratories average 36 students per section. Enrollment in laboratory sections is linked to a lecture section to allow for group work to span both lecture and laboratories; students must take both lecture and laboratory concurrently. Classes are scheduled to allow all laboratories to occur in line with lectures so that all students will receive the same lecture material before attending the laboratory. Both lectures and laboratories occur in active learning environments that are physically arranged to allow for groups of six to nine students to sit surrounding a table.

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the soldering was functional after placement of each LED strip (Fig. 3B). In the model and the corresponding Supplemental Video, each colored LED denotes a specific component, ion, or molecule. Yellow indicates an action potential, purple is calcium, orange is acetylcholine, white is acetic acid, green is choline, red is potassium, blue is sodium, and alternating green/red is representative of channel gates. These colors are also the colors used on the NMJ model within the video (see Supplemental Video). B: careful planning to effectively use LEDs and wire them appropriately is needed. Colors also correspond to the number of LEDs in a chain; dashed and solid lines indicate below-board or above-board connections, respectively. Red represents 1 LED, orange is 2, yellow is 3, light green is 4, green is 4, light blue is 7, blue is 11, navy is 13, purple is 15, and pink is 18. C: the completed NMJ model that was developed and deployed in the classroom.

Programming the model. Most of the programming of the model was adapted from the FastLED library found with accompanying demo programs (5). Specifically, we used FirstLight as a template to develop our program. We copied display code, altering the number and color of LEDs to correspond with their placement on the diagram. [The specific code for our diagram can be found in the Supplemental Material (http://github.com/petzo002/NMJLightshow).]

Student feedback. Two feedback instruments were developed to collect student attitudinal data regarding the board, its utility as a learning tool, and potential improvements. Specifically, during the Fall 2019 section of Anatomy and Physiology I, students were asked three 6-point Likert scale questions: “Physiology can only be learned by memorizing diagrams shown in textbooks,” “Rate your under-
standing of the processes at the neuromuscular junction for innervation,” and “If you didn’t understand a concept from class, how likely are you to go to the tutoring center to get the question answered?” Additionally, students were asked about their preferred method of instruction usage. This multiple-choice question gave the options of the following: uses demonstrations and hands-on activities, uses diagrams and graphs, verbally lectures, gives handouts to the class, and an option for “other.” Finally, students were given two open-ended questions requesting, “I learn from a teacher who . . .” and “Approximately how many hours per week do you study for anatomy and physiology?” In addition, a 30-question multiple-choice exam was given to students at the end of the unit. Of this, 11 questions directly related to the physiology of the NMJ, making it pertinent to the model. To assess the student responses, a one-sided, paired t test, assuming equal variances, was conducted with a standard α = 0.05.

Viewing the model. The NMJ model was displayed and available in a number of settings during the Fall 2019 semester. Aside from a video of the model being displayed on the course website with an e-mail “announcement” informing students of its presence, the model was shown and described during the lecture portion of the course. The model was also available for viewing at the “JustAsk Center” informal drop-in tutoring area for 1 wk before the module exam. A sign-in sheet was used to track student usage of the model while it was in the tutoring center outside of class. During this time, either an instructor or UAA was present to answer questions about the model. Finally, it was also presented to the general public and members of the university on a number of occasions.

RESULTS

When asked to respond to the question, “I learn best from a teacher who . . .” by selecting a category, the majority (54%) of students marked that they “learn best from teachers who give demonstrations and hands-on lectures.” The next highest category in this question was the 21% of learners who indicated that they learn best from “diagrams and graphs.” When the Post-Neuromuscular Junction Questionnaire was taken following the NMJ unit, the same question was asked again. The majority (43.33%) of students indicated that they “learn best from teachers who give demonstrations and hands-on lectures.” While the next category of students (29.9%) learn best from “diagrams and graphs.”

Comparison of pre- and post-student responses to the Likert-scale question, “Rate your understanding of the NMJ,” indicated a statistically significant increase in students’ perceived understanding (P < 0.01; n = 127). Of the students who responded to the postexposure questionnaire (n = 127), 25% indicated that they had used the NMJ model in person to study. Thirty-six percent of respondents used an uploaded video (see Supplemental Video) of the NMJ model on the course website (n = 32 respondents who replied they used one or the other). Students who indicated that they did not use the model either in person or with the video (n = 53) were given the opportunity to provide open-ended responses as to why they did not use it. These responses can be categorized into three main categories: not enough time in their schedule to use the model (43%), the model was not helpful (31%), and they were already confident in the knowledge about the NMJ (24%). The rest of the students in the survey (2%) felt that instructors who created videos of the NMJ process were more helpful to their understanding. A number of students did not indicate whether they used the model (n = 42), but answered other questions.

When students who used the NMJ model were given the opportunity to provide free-form responses to the question, “How did the NMJ help with your studying?” students’ responses could be categorized into three main categories: it helped visualize the physiological process, it helped students go step by step through interactions, and it helped them learn at their own pace. Most of the respondents stated that the model helped them visualize the NMJ process (46%). An example from a student response to this category would be; “It was a cookie-cutter visual of what the NMJ process is like. I used it as a refresher study tool right before the exam.”

Following this response, 36% of students said that the model allowed them to learn each process step by step, with students saying, “It showed me the chronological order of the steps of the NMJ reactions.” Finally, 16% of students said the model allowed them to learn the process at their own pace: “I got to go through the [video of the model] slowly by myself and understand on my own instead of going at the pace of the class.”

When asked what improvements could be made to the NMJ model, 28% of students suggested slowing down the lights to avoid rushing through the process as, “It would be easier to see what’s going on if it was slower.” Twenty-one percent of the students recommended introducing the model earlier in the unit; “Bring it out earlier in the discussion of NMJ.” The other smaller groups of students proposed adding more detail to the model, such as, “including the action potential that opens voltage-gated Na+ and K+ channels that creates an action potential to the sarcolemma.” It was also suggested to “display names of receptors and neurotransmitters.”

DISCUSSION

The LED-based board that we created provides students with a physical model of the NMJ, allowing students to actively follow lights on a continuously cycling board in a visually appealing and fluid manner. Student responses indicate that this project successfully transformed a static image from the text into a moving piece of art that has many applications beyond the classroom. While there was not a significant improvement in exam scores for those who used the model, students mentioned being able to better visualize the process, understand ion/channel interactions, and better comprehend interactions on the NMJ with neurotoxins such as sarin, botulinum toxin, and curare. In general, students were appreciative of the model’s ability to help them visualize the process in a stepwise manner: As one student noted; “It showed me the chronological order of the steps of the NMJ reactions.” Still, despite these favorable comments, when comparing the exam scores of students who had used the model in person, used a video uploaded of the model, and those who had not used the model, there was no statistical difference. There may be an explanation due to the fact that, outside of the classroom, students did not spend much time with the NMJ model. Student usage proved to be very low at the tutoring center. As one of the major concerns and potential confounding variables regarding the model was accessibility outside of the classroom, with increased exposure and access to the model, there may be a change in results in subsequent years. This could be done by providing more work time in the classroom with the model, as well as leaving it in the tutoring center during times other than
professors’ office hours to allow for more student flexibility around other classes.

As a student-driven educational experience, the creation of this board provided the developers an opportunity to not only leave a long-lasting impression on the university, but also to learn valuable skills in research design, soldering, and basic computer programming. In addition, the LED board has been useful in a number of non-classroom-related activities. The students associated with the development of the board have been invited to display their board for important visitors to campus as an example of academic research and activities. These visitors included local and statewide politicians, community leaders, board members of local organizations, the university system president and board of trustees, and prospective students (Fig. 3C). The breadth of these visits not only showcased an important aspect of academic activities, but also acted as a bridge between the academic and nonacademic portions of the university. While not directly apparent, these interactions may lead to improved relations between the department and a number of other stakeholders, both within and surrounding the university. Finally, since the board will be displayed as an art installation in the drop-in tutoring center, there is a potential for all students and the public to encounter the complexities of the NMJ and learn informally. Because professors are in this study space alongside the model, it has the potential of helping students in the class, as well as being a visually attractive description of physiology. Additional research and exploration will need to be done to determine how effective this model was in helping students retain and refine information.

Limitations and challenges. There were a number of challenges faced as the model had to be built and programmed to be functional and useful. The lights themselves needed to be placed and programmed, which in itself required developing additional knowledge and skills. Since none of the developers had previously mastered these somewhat niche, but necessary, skills (including soldering), knowledge was gained through trial, error, and instructional videos. As with learning anything, some of the early troubles faced were due to inexperience with the material and skills needed. However, with perseverance, the required skills were adequately refined. Another area that was challenging to work with was programming of the microcomputer itself. If the lack of programming ability is a concern, many tutorials are available through Arduino’s website (1) and the Adafruit Learning System resource pages (4). Furthermore, we have included our program as supplemental data for inspiration (see Supplemental Material); it may not be immediately useful due to differences in hardware and the number of LEDs in each place, but it should give a starting point for editing. Finally, while our institution lacks a Computer Science and Electrical Engineering Department, this type of project could be used as a collaboration with those areas.

Conclusion. This NMJ model has been used for learning and outreach in a number of ways, all of which reinforce the core values of higher education and the mission statement of the University of Minnesota. As a directed study, the students involved in the project were able to reinforce their own knowledge about the functioning of the NMJ for use on standardized exams and gain practical skills. Furthermore, they have been able to use the model as a tool to develop their presentation and science communication skills. As an educational tool, students at the UMR are able to have an additional model that can potentially be used to bolster their studying. From an institutional point of view, this model has been used in a number of situations to interface with outside parties, including local economic leaders, institutional leaders, politicians, and prospective students. The development and building of this model have been a benefit to our class and could likely benefit others as well.

GRANTS
Research conducted in this study was overseen by the University of Minnesota Institutional Review Board when applicable (IRB no. 1008E87333).

DISCLOSURES
No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS
H.L.O., D.R.T., and A.M.P. conceived and designed research; H.L.O., D.R.T., and A.M.P. performed experiments; H.L.O., D.R.T., and A.M.P. analyzed data; H.L.O., D.R.T., and A.M.P. interpreted results of experiments; H.L.O. and D.R.T. prepared figures; H.L.O. and D.R.T. drafted manuscript; H.L.O., D.R.T., and A.M.P. edited and revised manuscript; H.L.O., D.R.T., and A.M.P. approved final version of manuscript.

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