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INNOVATION ARTICLE

An Interactive Patch Clamping Simulation to Teach and Train Electrophysiology

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Abstract

Purpose Patch-clamping is a foundational technique in electrophysiology that requires substantial training due to its complexity and resource-intensive nature. This study evaluates the effectiveness of an interactive patch-clamping simulation in improving accessibility, skill acquisition, and educational outcomes compared to traditional training methods.
Methods A virtual simulation replicating key aspects of patch-clamping was developed, incorporating detailed tutorials, realistic pipette manipulation, and feedback through simulated electrophysiology traces. Two evaluations were conducted: (1) a user trial involving experts ($n = 5$) and novices ($n = 5$) performing standardized patch-clamping tasks and (2) a curricular integration study with electrophysiology students ($n = 10$) using the simulation in a classroom setting. Telemetry data and qualitative feedback were analyzed to assess performance and usability.
Results The qualitative feedback emphasized the tool's effectiveness for building patch-clamping proficiency in a risk-free simulated environment. Students highlighted the simulation's ease-of-use and educational value, and experts noted that it mimicked real experiments. Therefore, unsurprisingly, experts were proficient in the metrics tested from the beginning, exhibiting only slight improvement over time. Novices, however, significantly reduced patching time from 3.1 to 0.9 min ($p = 0.001$). Students showed a similar trend in improvement (6.0 to 1.8 min, $p = 0.01$). Pipette breakage dropped 96% across all users between the first and final attempt.
Conclusion The patch-clamping simulation enhances training efficiency, reduces barriers to skill acquisition, and complements traditional methodologies by providing a scalable, cost-effective, and realistic alternative. Its implementation in neuroscience and medical curricula could broaden access to this gold-standard technique, underscoring its potential to transform electrophysiology education.

Keywords Patch-clamping · Electrophysiology · Simulation · Education · Neuroscience

Introduction

Patch-clamping is a cornerstone technique in electrophysiology that enables recording of ionic currents in individual cells by bringing an electrode into contact with the cell's internal fluid. This capability, since its inception, has led to countless scientific discoveries and developments. The use of patch-clamping by Erwin Neher and Bert Sakmann was awarded the Nobel Prize in Physiology or Medicine in 1991 for their "discoveries concerning the function of single ion channels in cells". Thus, patch-clamping has been pivotal in advancing our understanding of cellular functions and intercellular communication [1]. Since its invention, patch-clamping has advanced over decades to include in vivo and in vitro recording, automation [2, 3], parallelization [4],

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integration with other experimental methods such as optogenetics and imaging [5] and has enabled many scientific discoveries [6]. However, despite these technological advancements, patch-clamping is still a highly manual technique that is difficult to learn and requires extensive hands-on training to execute consistently.

The traditional training process for patch-clamping is both time-consuming and expensive. Patch-clamp rigs require significant equipment as well as maintenance, consumables, and reagents [7]. Moreover, the intricate nature of the technique demands extensive one-on-one mentorship. During the process, novice researchers first observe the expert to try to understand the visual cues associated with success and failure. Only after they have developed an understanding of these, does the researcher move on to manual manipulation of the physical controls and mechanics of the rig with expert supervision. Due to the difficulty of the technique and fragility of the equipment, this process often requires weeks to months of dedicated, supervised practice to achieve proficiency through trial and error. Thus, in research laboratories, training throughput is limited to a few individuals at a time, restricting dissemination of the technique [8].

Despite the method's foundational role in neuroscience and physiology, there are few formal educational pathways to aid in curricular learning of patch-clamping. Outside of highly specialized workshops such as those at Cold Spring Harbor Laboratory [9], most university curricula rely heavily on lecture-based content or video demonstrations, with limited or no access to physical rigs. As a result, hands-on exposure to patch-clamping is typically deferred until students enter research laboratories—at which point opportunities for trial, failure, and repetition are constrained by equipment availability, time, and mentoring capacity. While anecdotal reports and opinion pieces acknowledge the difficulty of patch-clamp training (e.g., high failure rates, extended time to competence), there remains a lack of systematic literature examining training outcomes, learning curves, or best practices across institutions [8].

A key obstacle in patch-clamp training is the prevalence of failure modes, which are often poorly characterized in educational contexts. Common issues include pipette clogs, crashing the pipette and breaking it, cell-to-cell patch-ability and failure to recognize pressure/resistance cues. These events are typically only communicated to trainees through one-on-one mentorship or trial-and-error experience, limiting the development of standardized instructional materials. The ability to recognize, diagnose, and respond to common failure modes is key for researchers to successfully perform patch-clamp experiments independently. Simulations provide an opportunity to scaffold student understanding of these failure types, offering consequence-free repetition and explicit feedback on the necessary visual cues associated with the technique. By incorporating visualizations of pipette position, seal resistance, and electrophysiological traces seen during both successes and failures, simulations can make learning patch-clamping more accessible to learners.

Kolb et al. has shown that experiential learning enhances student understanding and development [10, 11]. Thus, understanding of patch-clamping could be improved with a more engaging, experiential learning environment. Hands-on learning is particularly important in scientific education, as it enables students to actively engage with the material, leading to better retention and understanding of complex concepts [12]. Further, simulation-based training, especially for expensive, difficult-to-access techniques, offers a promising solution to challenges in both the laboratory and the classroom. Educational simulations have been increasingly adopted across various scientific disciplines to enhance learning outcomes and provide hands-on experience in a risk-free environment [13]. Also, its been shown that surgeons who play video games perform better during medical operations [14], suggesting that simulation-based training may similarly benefit students who need precise skills. In the context of patch-clamping, a well-designed simulation can replicate the complexities of the technique, allowing researchers and students alike to practice and refine their skills without the associated costs and resource constraints of real-world equipment. Additionally, simulations can be easily scaled, providing access to a broader audience and ensuring that more students can gain familiarity with patch-clamping before handling actual biological samples. By introducing virtual interaction and guided feedback, simulations may also reduce training disparities between institutions with varying levels of resources.

We developed and implemented an interactive patch-clamping simulation to teach and train patch-clamp electrophysiology. This software enables users to visualize a cell-covered coverslip, manipulate a virtual patch pipette, and experience the process of whole-cell patch-clamping in a controlled, virtual environment. The software includes graphical cues, such as resistance changes and pressure fluctuations, that mirror the visual cues associated with success and failure patch-clampers must learn before conducting real experiments. The inclusion of electrophysiology traces gives users immediate feedback on their performance. User data indicates that this simulation not only improves technical skills but also boosts confidence among trainees, suggesting that it could significantly enhance traditional training programs. By integrating this tool into neuroscience and medical curricula, we aim to provide students with a hands-on learning experience, ultimately enhancing their understanding and engagement in electrophysiology. Looking forward, the combination of simulation-based pre-training with subsequent in-person mentoring may accelerate the transition from novice to independent experimenter, lowering the threshold and expense of training. This approach is particularly relevant for institutions with limited access to patch-clamp rigs or instructors, and aligns with growing interest in scalable, inclusive laboratory education models.

Methodology

The materials and methods section explains the simulation software that we developed (i.e., our intervention), the user testing that we performed (i.e., data collection), and how we analyzed the resulting data. The software is available via GitHub, using the following link: https://github.com/FlipFloop/holypipette-game/releases/tag/exe-release. All aspects of data collection and analysis were conducted in accordance with Georgia Tech IRB approval H24078, ensuring ethical handling of participant data.

Simulation Software

The simulation software was developed to replicate key aspects of patch-clamping procedures within a virtual environment, adhering to technical specifications and design principles aimed at providing a realistic training experience. In particular, this simulation is modeled after the holypipette electrophysiology rig interface [3]. The primary interface includes a simulated microscope field and simulated micromanipulator both controllable via keyboard inputs, mimicking real-world experimental conditions. The software displays simulated current responses, pressure readouts, and pipette resistance, providing users the full visual experience they would have during a real patch-clamp experiment. Built into the software are common patch-clamping failure modes, paired with their visual cues, which experienced patch-clampers must learn to recognize (Fig. 1).

During the training, whether in-person or virtual, the user first finds the tip of the pipette and drives it to hover over the cell of interest. Using positive pressure to prevent the pipette from clogging, they then carefully lower the pipette until contact with the surface of the cell, which is indicated by a slight increase in the pipette resistance. The user then attempts to gigaseal the cell by applying negative pressure, drawing the cell membrane into contact with the edges of the pipette tip and forming a giga-ohm seal. They can then attempt to break-in using a built-in automated pressure profile used in the author's lab to break into real cells. Successful break-in allows fluid transport between the pipette electrode and the interior of the cells and allows the user to record the electrophysiology of the cell, effectively establishing a whole-cell patch. To reflect the difficulty of mastering this process, failure points in the simulation are set to mirror those in in vitro training, with common mistakes resulting in failed patches. For example, failure to apply positive pressure causes the pipette to become clogged, resulting in an inability to successfully complete any further steps without cleaning or replacing the pipette. To facilitate learning, the software features a tutorial window providing comprehensive instructions covering both theoretical aspects of

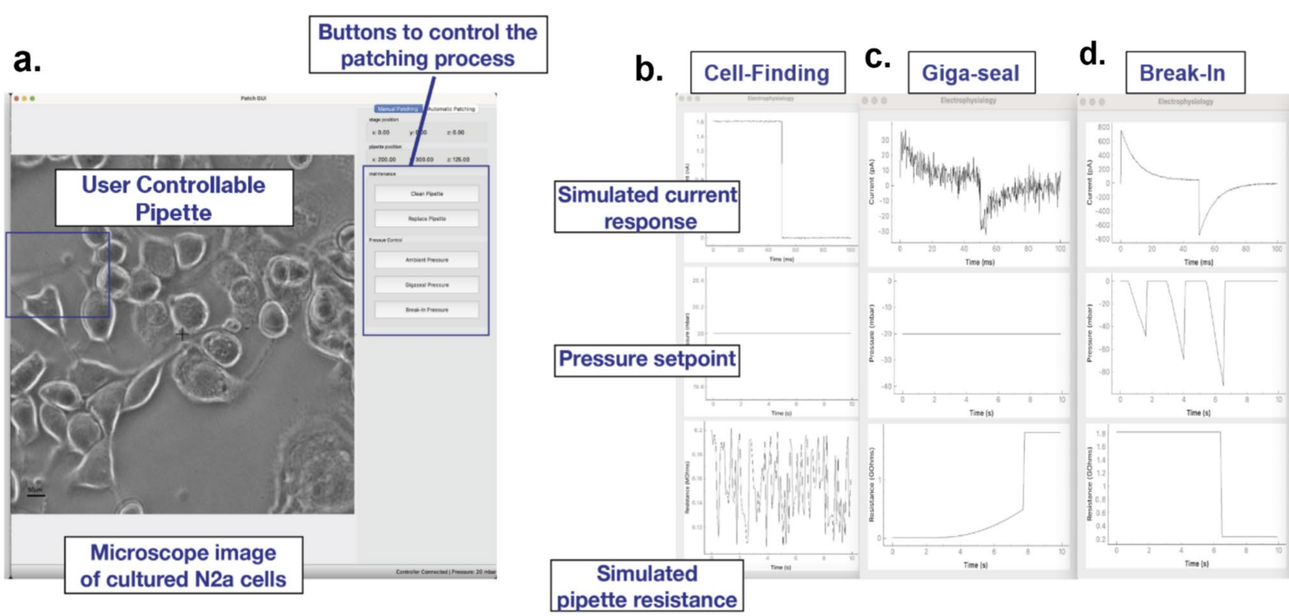


Fig. 1 Simulation Software Display showing the automated patch window including the cell surface as viewed through the microscope, a not-yet in focus micromanipulator, and the control buttons for the pressure profile and pipette (**A**), and in the next window the recorded current, pressure, and pipette resistance during cell-finding (**B**), Giga-seal (**C**), and break-in (**D**)

patch-clamping and practical steps for running experiments in the simulation. The tutorial includes sections on moving the pipette and stage to access more cells, the basics of patch-clamp, detailed guides for the manual patching practice, and common pitfalls to avoid.

The user interface allows users to visualize a real image of cells on a patch-clamping rig, manipulate a patch pipette, and observe electrophysiology traces. In Manual Patching mode, users manually position the manipulator, detecting changes in pipette resistance as they approach a cell and manually adjust pressure settings to establish a gigaseal and break into the cell. Users can perform tasks such as cleaning or replacing the pipette and adjusting the pressure setpoint through a column of interface buttons. The software notifies users as they establish gigaseals and break into cells. It also allows them to view readouts which simulate the resistance changes and pressure variations encountered during real experiments.

Various failure modes, including pipette tip clogging and breakage, are also simulated to provide a realistic training experience (Fig. 2). The current version does not simulate seal instability over time, cell-to-cell patchability or spontaneous cell death, which are known real-world failure modes and may be considered in future iterations. In Fig. 2a, we show the drop in resistance and visual pipette deformation resulting from a simulated broken pipette. Figure 2b shows the progress bar notification "pop-up," which displays when a user is attempting to "break into a cell".

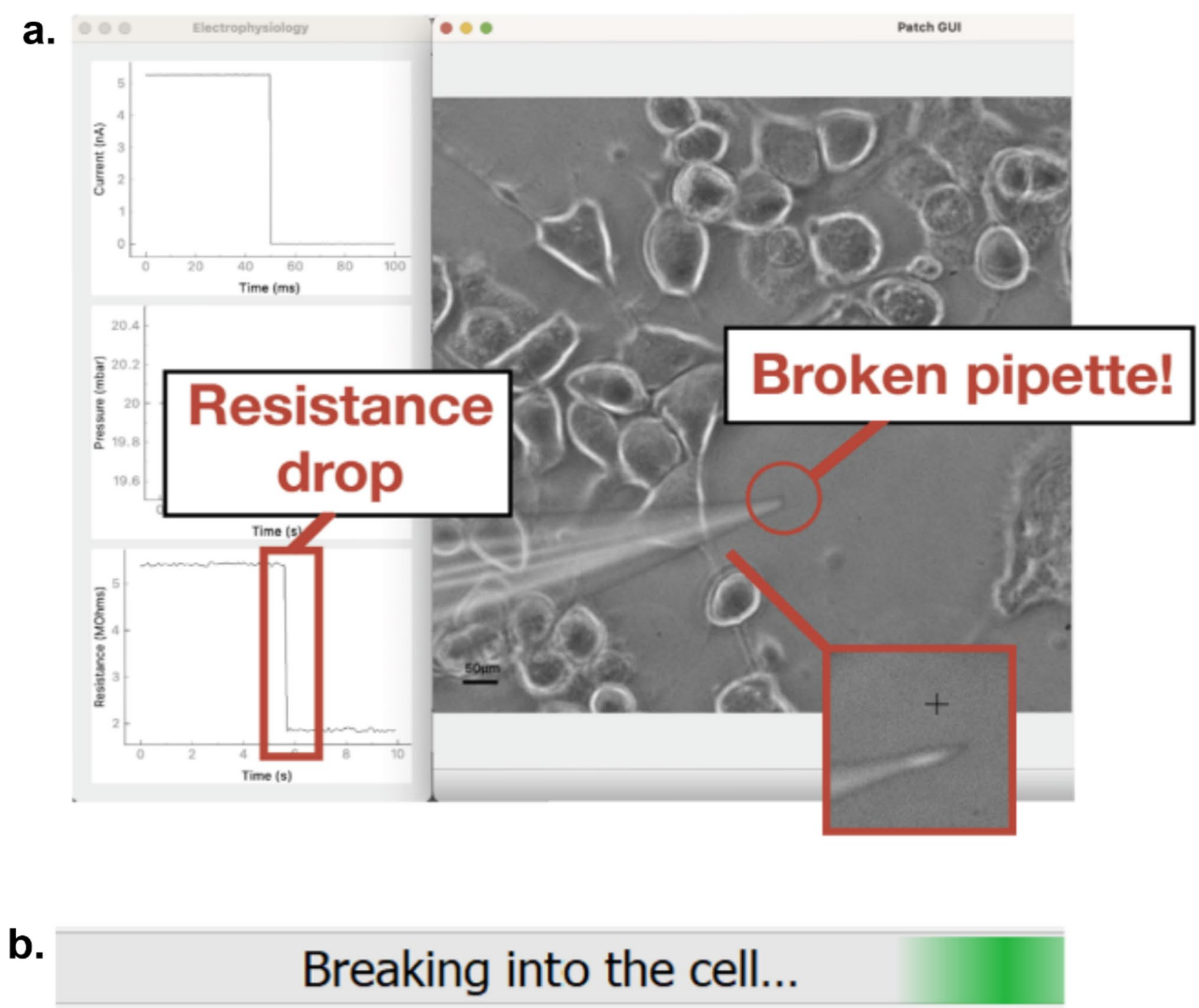


Fig. 2 An example of the display notifications in the simulation including **A** Pipette has broken and **B** User is breaking into cell

User Testing

The software was introduced to three populations of students from two settings representing our two use cases, namely: laboratory students can practice and refine their patch-clamping skills in our controlled, virtual simulation before transitioning to actual laboratory equipment, while students in education can use the hands-on training to solidify their understanding of this gold-standard technique, minimizing risks and costs associated with training on real equipment. To better understand usability across experience levels, we evaluated 20 users with a range of experience, using both formative and summative approaches. In a research lab setting, the simulation was recorded while being used by five patch-clamping "Experts" and five patch-clamping "Novices". In a classroom setting, the simulation was given as a take-home assignment to "Students" who had not encountered the patch-clamping prior to the class. User instructions and support materials were provided equally to all users, as they are essential for effective implementation of the training software. The tutorial window within the software provides step-by-step instructions and theoretical background (Fig. 3).

In the first study, the research setting, supervised user trials were conducted with two groups of five: Experts (professional users with 1+ years of patching experience) and Novices (users with limited or no familiarity with

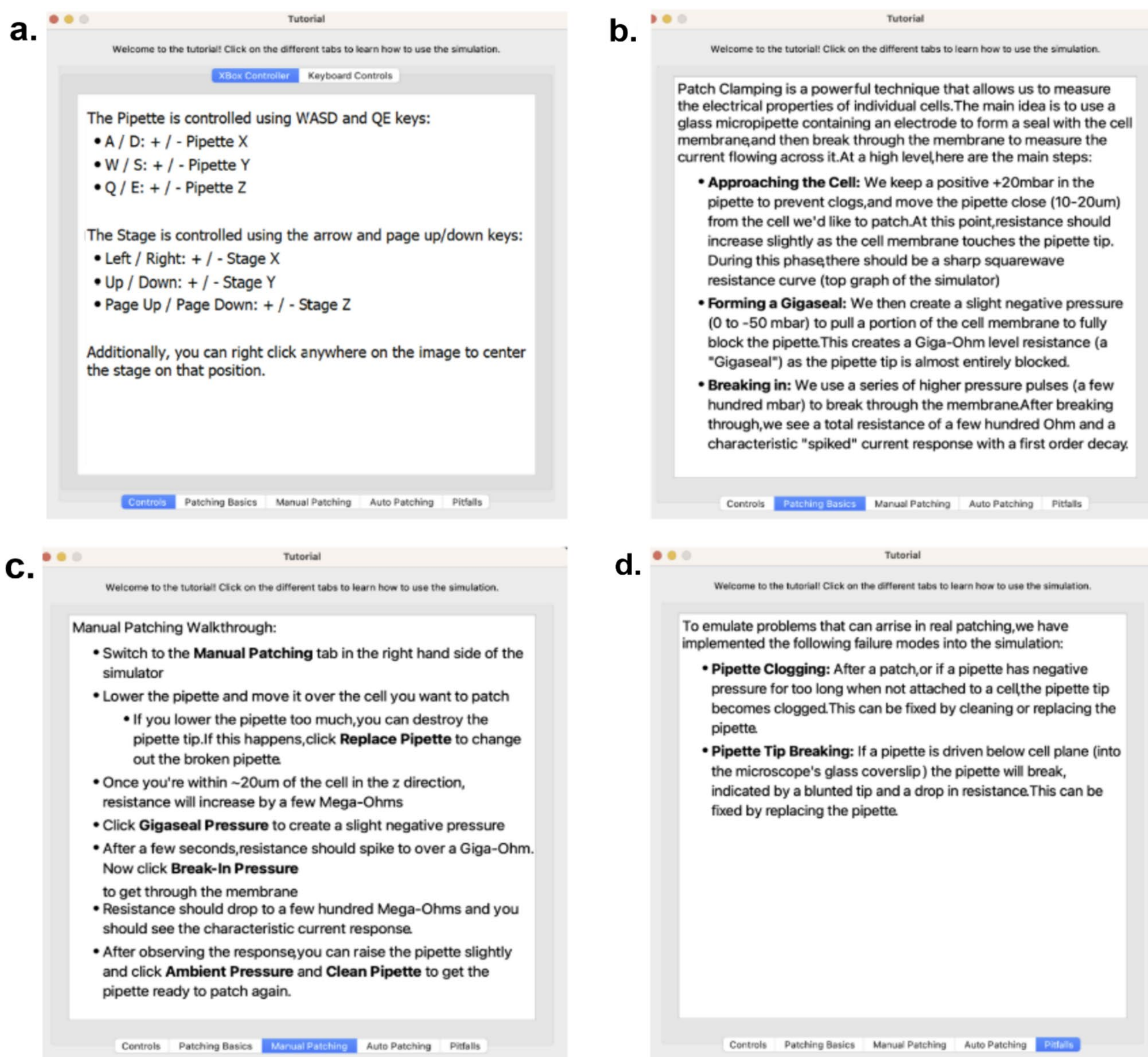


Fig. 3 Screenshots of the tutorial window as viewed from a Mac interface, showing the information given to users prior to attempting to patch **A** Control Tutorial, **B** Patch-clamping Basics, **C** How to Patch in the Simulation, **D** Common Pitfalls to avoid when patching

patch-clamping). Users were instructed to review the tutorial for 2 min before attempting to break into five different cells as quickly as possible, spending on average 10 min total with the software. The software logged key events and timestamps, such as gigaseal formation, cell break-ins, and pipette crashes and the proctor recorded comments during and after use. The proctor was instructed not to answer questions or provide guidance in any way.

In the second study, the simulation was introduced to students in a graduate-level Cellular, Developmental, & Molecular Neuroscience class during their electrophysiology section. The 10 consenting students were asked to provide feedback on their experience, and telemetry data was collected similarly to the first study. Students were given an initial tutorial session and then asked to use the simulation at home to practice patch-clamping until they successfully achieved five whole-cells. Post-study surveys asked students to rate their confidence and assess the contribution of the simulation to their overarching understanding of patch-clamping as a technique. Their feedback and performance data were collected to assess the software's educational impact and usability. As this was an optional assignment given to a subset of the class, participants were made aware of the learning objectives, but a rubric was not provided other than credit given for completion of the activity at the instructor's discretion. Also, in contrast to the first study, the students were not supervised by a proctor and, therefore, their adherence to the recommendation of reading the instructions was variable.

To support implementation by other instructors, we structured the simulation activity around clear learning objectives aligned with common pedagogical and technical goals of introductory electrophysiology training. These included: (1) identifying viable patching targets on a field of cells; (2) maneuvering the pipette carefully to avoid crashes; (3) recognizing gigaseal formation from resistance changes; and (4) successfully achieving whole-cell break-in. These objectives mirror the technical steps required for experimental success in real patch-clamp recordings and are intended to strengthen student understanding of the technique. Instructors may allow students to explore freely or assign a set number of successful patches to complete, depending on curricular goals. Our recommendation is that the simulation be used as a "participation-based" assignment, with the in-class deliverable being screenshots of different events occurring and/or student reflection on their experience using the simulation.

Data Analysis

To store telemetry data for participating users, we used PostgreSQL relational database through a Supabase instance, which is owned and managed by the author's lab. As the entire program is python-based, we use Supabase's official python client, supabase-py, to connect to the PostgreSQL database. This client makes it trivial to connect to the Supabase instance, and offers ready-made methods for data upload, storage, and real-time data streaming.

When the program is first launched, an encrypted hash is generated, representing a user ID. This unique identifier enables differentiation between machines, without knowing anything about the user or the computer itself. Every time the program is started, a unique session ID is generated as well to differentiate between sessions for each user. The database contains multiple tables, including one that keeps track of every session and their associated owner. This session ID tags significant telemetry events that are pushed to the database in real-time. Telemetry events are logged with information including the event type, time since the session has begun, and time of event. Events are logged at the time that they occur, and can be triggered by the user interactions and failures with the simulated pipette, when the pipette pressure is altered in the simulation, or when the user achieves gigaseal. Patch failures and the mode by which they occurred are logged and noted, as they may indicate a user is still learning the correct patch-clamping workflow.

For this study, we defined two performance metrics. The first metric is "time between break-ins". Because efficiency in patch-clamping affects the amount of data collected in a day, time *between* consecutive successful patch attempts is a good metric of user ability. Therefore, our primary metric, time between break-ins, was chosen as a proxy for increasing proficiency. In practicing electrophysiology, minimizing this time reflects increased skill, steady pipette positioning, and fewer failed approaches or crashes—thus serving as a meaningful, quantifiable indicator of patch-clamp proficiency. The second metric is "number of pipette breaks per break-in." We measured how many times the user breaks the pipette tip off prior to the next successful break-in. This metric, a proxy for pipette handling proficiency, resets after each successful break-in. These metrics allow us to evaluate not only individual outcomes, but also overall user performance as experience is gained via successful break-in.

After confirming normality on each population, independent 2-sample t-tests were used to assess statistical significance in comparison of novices and experts in both round 1 and round 5, and paired t-tests were applied in order to assess statistical significance in comparison of both novices and experts from break-in 1 to break-in 5. Qualitative survey data were also analyzed to quantify user perception of their own learning, simulation realism, and usability. All feedback was anonymized and aggregated to identify commonly cited strengths and suggestions.

Results

Quantitative

The spatial arrangement of patch-clamp attempt for the student population is shown in Fig. 4. Of the 136 total patch attempt, 76 (56%) were successful. Most often, students attempted to patch cells that were centrally located in the field of view. Failed attempts arise both from missing a cell body entirely as well as pipettes clogging or breaking despite accurate pipette location on the cell body. The most common failure mode was pipette breakage.

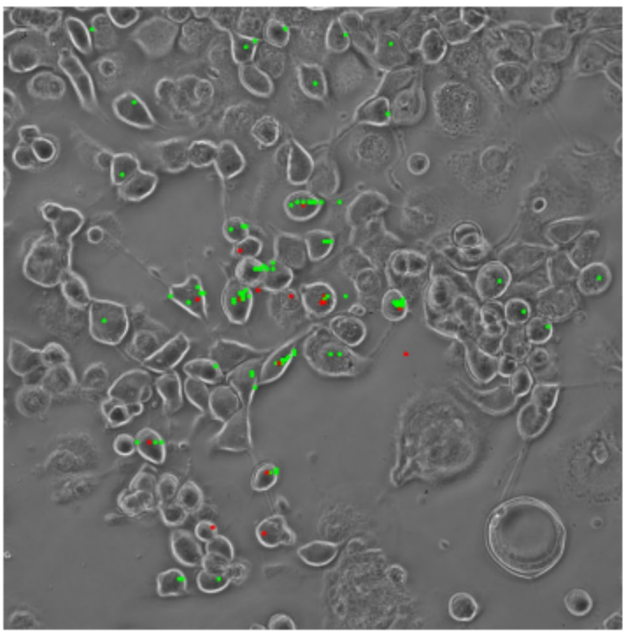


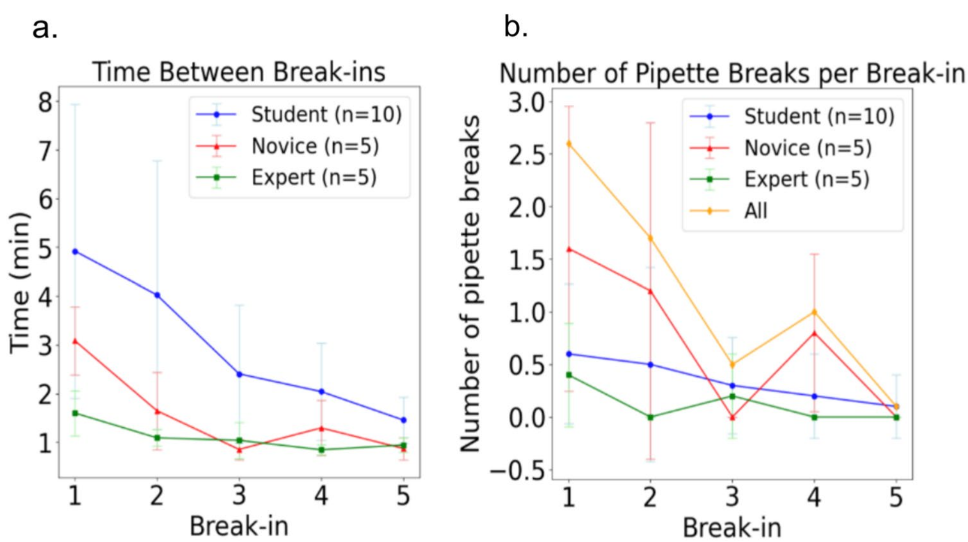
Fig. 4 Student patch-clamp attempt locations. Markers show 76 successful attempts (*green*) and 60 unsuccessful attempts (*red*). Attempts not over a cell are always failed attempts, as the simulation will not allow a user to patch an area without a cell

Average time to break-in was reduced from initial to final break-in in all groups (Fig. 5a). Experts demonstrated an evident but non-significant reduction from an average of 1.6 min between break-ins in the first break-in to an average of 0.9 min in the fifth break-in (p-value 0.07). Novices showed a significant improvement, reducing from 3.1 min between break-ins on the first break-in to 0.9 min on the final break-in (*p*-value 0.001). Students showed a similar trend, with an average time reduction from 6 min on their first break-in to 1.8 min on their final break-in (*p*-value 0.01).

To achieve the first successful break-in, experts were significantly faster than novices (*p*-value 0.01), taking an average of only 1.6 min, compared to novices' 3.1 min despite being under the same conditions. We assert that this inherent proficiency stems from the similarity of the software to their lived experience patch-clamping. However, the difference between the groups closed as the number of break-ins increased, and by the fifth and final break-in, experts were no longer significantly faster than novices (*p*-value 0.6). In fact, almost all users—including students—were achieving break-in in approximately 1 min.

Pipette handling, measured as number of pipette breaks per break-in, also improved with experience (Fig. 5b). While experts rarely broke the pipette and therefore showed minimal change with successive break-ins, novices exhibited a 60% reduction in pipette breaks between their first and final break-in (*p*-value 0.08) suggesting improvement in fine motor control. The student data was too varied to determine significance, but converged from an average of 1.5 pipettes broken before the first break-in to 0 recorded pipette breaks on the final break-in. Even though pipette break reduction within each group did not reach significance, the overall

Fig. 5 **a** Average time between successful break-ins in minutes over five successful break-in attempts for Student ($n = 10$, blue), Novice ($n = 5$, red), and Expert ($n = 5$, green) groups. **b** Mean number of pipette breaks per successful break-in attempt for Student, Novice, and Expert groups. Error bars represent standard deviation



population averaged across all groups (experts, novices, students combined) showed a significant decrease in pipette breaks per break-in, from 0.87 pipettes broken per user on the first attempt to 0.03 on the fifth (p-value 0.003).

Discussion

Results indicate that the simulation software is effective in enhancing hands-on learning for both novices and trainees while mirroring the experiences of expert users. By providing a realistic, interactive virtual environment, the simulation software offers a cost-effective alternative to physical training, which can significantly reduce the barriers to acquiring these skills and understanding. The simulation is easily integrated as an activity into a classroom setting. For broader instructional design, the activity can be introduced in a flipped classroom format, with pre-lab tutorials followed by simulation practice during class or lab time. In our classroom implementation, students successfully achieved whole-cell at least five times each, enabling both repetition and reflection.

Initial feedback from expert users was that the "simulation closely mirrored the patching experience" and that "after the initial attempt [the simulation] was easy to use." A Patch-clamp Technician for 20+ years tried the simulation and remarked: "It's pretty good!... [The simulation] has every control [we use] when we patch, and the current and resistance graphs are exactly like what we see… It's deeper than just a game, it really mimics most situations and events of a typical patch-clamp experiment." These comments suggest that the tool is authentic enough in both visual and mechanical fidelity to elicit recognition from experienced users. Further, a doctoral student who conducts patch-clamping experiments for his thesis stated that "[Once] you use that [simulation], you clearly understand what patch-clamping is."

The qualitative feedback received from the students was also overwhelmingly positive. Students appreciated the hands-on learning experience the simulation provided. One student stated "[The simulation] deepened my understanding of the patch-clamping technique and … [was] easy to use and extremely educational." Many students highlighted that the virtual environment allowed them to practice and understand the intricacies of patch-clamping, and thus do better in their course, without the stress, cost, and time associated with learning on real equipment in a lab setting.

Instructors should ensure students carefully read all instructions prior to attempting the simulation and should set realistic expectations about performance. For example, "students should not expect to be successful on their first attempt, but each student should be able to reach the conservative goal of achieving five whole-cells within a 20-min session". Supplementary materials, such as instructional videos, user manuals, and guided exercises, could be provided to enhance the learning experience if desired. Finally, instructors should encourage students to explore failure modes and consider the added difficulty these failures would add outside the simulation. Through such classroom integration, the patch-clamping simulation can broaden exposure to and understanding of this Nobel Prize-winning technique.

Positive feedback from students further highlights the potential for integrating this software into neuroscience and medical curricula. Students not only found the software helpful for learning the technical aspects of patch-clamping, but also appreciated the opportunity to experiment and make mistakes without the consequences associated with real equipment. This aligns with educational theories that emphasize the importance of experiential learning and the role of simulation in providing a safe space for skill development. Future studies will include a side-by-side training of novice patch-clamp researchers with and without the simulation to assess real training outcomes.

Future developments of this software could include other patch-clamping modes and failure modes, such as cell-attached patching or outside-out patching, and cell-to-cell patch-ability or seal degradation, respectively. We may also incorporate advanced features such as machine learning algorithms to provide personalized feedback and adaptive learning paths for users. This could further enhance the training experience by identifying individual strengths and weaknesses and offering targeted practice scenarios. Moreover, in the future, integrating the simulation software with actual laboratory equipment could provide a hybrid training model where students begin with virtual practice and gradually transition to real-world experiments, guided by the software's feedback mechanisms. This blended approach could close the loop for research trainees, providing the best of both worlds by combining the accessibility and safety of virtual training with the practical experience of working with real equipment.

The patch-clamping simulation software represents an advancement in the field of neuroscience education, offering an effective, accessible, and scalable solution for training both novices and experienced users. The positive outcomes observed in user trials and student feedback underscore its potential to enhance hands-on learning and skill acquisition. Future developments and broader applications could further extend its impact, making advanced scientific training for patch-clamping even more widely available and effective.

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Author Contributions ADV was responsible for co-conceiving the simulation, introducing the study to students, analyzing the data, determining experimental design, creating figures and drafting the manuscript and performing revisions. NM was responsible for co-conceiving and coding the simulation as well as designing and packaging the GUI. KS performed statistical analysis and revisions. VG and EA were each responsible for creation of the database and creation of the corresponding educational study figures. MR was responsible for high level oversight of the ideation, as well as study participant recruitment. TF contributed to the writing of revisions and restructuring of the manuscript. CRF co-conceived the study, participated in designing of the simulation and experiments, and contributed to the text and content of the manuscript including revisions and edits. All authors approve the content of the manuscript.

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Data availability All relevant materials and data are included in the manuscript. Code for the Graphical User Interface is available as a release in the following GitHub repository. https://github.com/FlipFloop/holypipette-game/releases/tag/exe-release

Declarations

Competing Interests None to declare.

Ethical Approval All human subject surveys were done under IRB H24078 approved by Georgia Institute of Technology IRB.

Consent for Publication The authors consent to publication of this work in the journal Biomedical Engineering Education.

References

1. Sakmann B, Neher E. Single-channel recording. In: Sakmann B, Neher E, editors. Single-channel recording. New York: Springer; 1995.
2. Kolb I, Ananthakrishnan A, Husain N, et al. PatcherBot: a single-cell electrophysiology robot for adherent cells and brain slices. J Neural Eng. 2019;16(4): 046003.
3. Stimberg M, Brette R. holypipette: a python package for automated patch-clamp experiments. Version v0.2.1. 2023
4. Yip MC, et al. Patch-Walking: coordinated multi-pipette patch-clamp for efficiently finding synaptic connections. Elife. 2024. https://doi.org/10.7554/elife.97399.2.
5. Chuong AS, Miri ML, Busskamp V, Matthews GA, Acker LC, Sørensen AT, et al. Noninvasive optical inhibition with a red-shifted microbial rhodopsin. Nat Neurosci. 2014;17(8):1123–9. https://doi.org/10.1038/nn.3752.
6. Holst GL, Liu Y, Rajendran PS, et al. Autonomous patch-clamp robot for functional characterization of neurons in vivo: development and application to mouse visual cortex. J Neurophysiol. 2019;121(6):2341–57. https://doi.org/10.1152/jn.00738.2018.
7. Hamill OP, Marty A, Neher E, Sakmann B, Sigworth FJ. Improved patch-clamp techniques for high-resolution current recording from cells and cell-free membrane patches. Pflugers Arch. 1981;391(2):85–100. https://doi.org/10.1007/BF00656997.
8. Annecchino LA, Schultz SR. Progress in automating patch-clamp cellular physiology. Brain Neurosci Adv. 2018;2: 2398212818776561. https://doi.org/10.1177/2398212818776561.
9. Cold Spring Harbor Laboratory. Ion channels in synaptic & neural circuit physiology. 2024. https://meetings.cshl.edu/courses.aspx?course=C-ION
10. Kolb AY, Kolb DA. Learning styles and learning spaces: enhancing experiential learning in higher education. Acad Manage Learn Educ. 2005;4(2):193–212. https://doi.org/10.5465/AMLE.2005.17268566.
11. Kolb DA. Experiential learning: experience as the source of learning and development. Englewood Cliffs: Prentice Hall; 1984.
12. Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, et al. Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci U S A. 2014;111(23):8410–5. https://doi.org/10.1073/pnas.1319030111.
13. Kozma RB. Technology and classroom practices: an international study. J Res Technol Educ. 2003;36(1):1–14. https://doi.org/10.1080/15391523.2003.10782399.
14. Rosser JC Jr, Lynch PJ, Cuddihy L, Gentile DA, Klonsky J, Merrell R. The impact of video games on training surgeons in the 21st century. Arch Surg. 2007;142(2):181–6. https://doi.org/10.1001/archsurg.142.2.181.