

# An interdisciplinary approach to high school curriculum development: Swarming Powered by Neuroscience

Elise Buckley, Joseph D. Monaco, Kevin M. Schultz, Robert W. Chalmers, Armin Hadzic, Kechen Zhang, Grace M. Hwang, and M. Dwight Carr

[Elise.buckley@jhuapl.edu](mailto:Elise.buckley@jhuapl.edu), [jmonaco@jhu.edu](mailto:jmonaco@jhu.edu), [Grace.Hwang@jhuapl.edu](mailto:Grace.Hwang@jhuapl.edu), [Dwight.carr@jhuapl.edu](mailto:Dwight.carr@jhuapl.edu)

**Abstract** - This article discusses how to create an interactive virtual training program at the intersection of neuroscience, robotics, and computer science for high school students with equity of access. A four-day microseminar, titled **Swarming Powered by Neuroscience (SPN)**, was conducted virtually through a combination of presentations and interactive computer game simulations. The SPN microseminar was delivered by subject matter experts in neuroscience, mathematics, multi-agent swarm robotics, and education. The objective of this research was to determine if taking an interdisciplinary approach to high school education would enhance the students learning experiences in fields such as neuroscience, robotics, or computer science. This study found an improvement in student engagement for neuroscience by 16.6%, while interest in robotics and computer science improved respectively by 2.7% and 1.8%. The majority of students (64%) strongly agreed that they enjoyed learning from an interdisciplinary team of experts and 70% strongly agreed that the microseminar emphasized the need to have instruction teams with diverse disciplinary backgrounds. The curriculum materials, developed for the SPN microseminar, can be used by high school teachers to further evaluate interdisciplinary instructions across life and physical sciences and computer science.

*Index Terms* – high school, instructional technology, neuroscience, navigation, swarm robotics

## INTRODUCTION

The development of multi-agent platforms with small-scale robotic vehicles is an exciting target of state-of-the-art autonomous systems engineering: many new applications may emerge from controlling large, distributed groups of inexpensive but agile vehicles. Unmanned robots are rapidly becoming a crucial technology for commercial, military, and scientific endeavors throughout the United States and across the globe. Critical future applications such as disaster relief

and search & rescue will require intelligent spatial coordination among many robots spread over large geographical areas. However, several gaps exist in multi-agent robotic controllers: current communication and control frameworks need to be improved to provide the adaptability, resilience, and computational efficiency required for operating in complex and rapidly changing real-world conditions [1]–[4]. A team of researchers at the Johns Hopkins University Applied Physics Laboratory (JHUAPL) and School of Medicine (SOM) explored whether neuroscience may offer insights to create a new class of multi-agent robotic controllers that could begin to address these aforementioned gaps. The team first secured a grant issued by the United States National Science Foundation (NSF) Integrative Strategies for Understanding Neural and Cognitive Systems Program (NCS) Program, titled “Spatial Intelligence for Swarms Based on Hippocampal Dynamics” [5]. This project brought together principles from theoretical neuroscience (i.e., the analysis and investigation of theories about brain function) and multi-agent autonomous robotic coordination (swarms) to develop smarter controllers based on the concept of the cognitive map (see Related Work).

The first premise of this project was that the world is constantly changing, and mammals have evolved the cognitive ability to plan new paths as needed while avoiding predators and seeking rewards. By contrast, autonomous robots are less robust, and often have difficulty operating in complex environments with changing conditions, such as in uneven terrain and moving obstacles. A second premise is that individual robots in a group are analogous to neurons in an animal's brain, which interact with one another to form dynamic patterns that collectively signal locations in space and time relative to brain rhythms [6]. The distribution of information across space and time has enabled a new paradigm of swarm control, in which swarms can automatically adapt to changes in the world in the same way that a mammal, in this case a rodent, can figure out which detour to take around an unexpected obstacle. Both premises resulted in research that explored the mathematical equivalence between fast time-scale learning in the brain

This author copy of the as-accepted manuscript has been made available in accordance with Section 8.1.9 of the IEEE PSPB Operations Manual.

© 2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

and swarm motion in simulated robots in a framework developed by the research team, coined NeuroSwarms [7], [8]. We implemented the NeuroSwarms controller in a commercially available 3D virtual environment, Unity3D.

There has been limited examples of STEM (science, technology, engineering, and mathematics) educators who collaborate with Ph.D. level researchers to create interdisciplinary high school curriculum and instructions in neuroscience, robotics, and computer sciences. This paper describes such an interdisciplinary approach between researchers and educators. We developed an interdisciplinary four-day microseminar for Maryland high school students, titled Swarming Powered by Neuroscience (SPN), which was offered virtually in January 2021. One of SPN's goals was to determine if student interest in STEM would be enhanced, and if so, would interest be uniform across disciplines or targeted to a specific discipline. Student assessment surveys were administered before and after the SPN microseminar.

### **PEDAGOGICAL FRAMEWORK**

The SPN microseminar was developed to enhance and expand on concepts in the physical and life sciences ordinarily taught in high school in the United States. To do this, STEM educators applied concepts from the United States Next Generation Science Standards (NGSS) [9] which comprises core and component ideas in the life and physical sciences. The Core idea that is most closely aligned to the team's Spatial Intelligence project is LS1.D Information Processing, which describes what students should learn regarding how organisms detect, process, and use information to understand and navigate within their environment. These concepts naturally tie into the formation of a cognitive map and path integration (see Section on Related Work). Furthermore, NGSS LS1.D explains that complex organisms convert information that is sensed from the environment into neural signals that control motor movement and decision making. Students should understand how external and internal stimuli enable an organism to interact with and understand its environment as a function of electromagnetic, mechanical, and chemical signals. More specifically, these interactions with external and internal stimuli can be explained in the context of how an animal is able to achieve path integration within the cognitive map. At the conclusion of lessons that are designed to fulfill the requirements of the NGSS, high school students are expected to understand that the brains of complex animals are divided into distinct regions and neural pathways that enable visual and auditory perception, guide motor movement, interprets perceptual information, and decision making.

The guiding principles behind the SPN microseminar are as follows: (1) Develop developmentally appropriate curricular materials and 3D tasks for high school students; (2) Develop engaging activities; (3) Inform students about careers in neuroscience and engineering; (4) Increase interest in STEM careers and majors; (5) Provide access to

cutting-edge STEM research for high school students from a variety of socioeconomic backgrounds; (6) Facilitate discussions between students and subject matter experts in neuroscience and engineering.

### **RELATED WORK: COGNITIVE MAP AND PATH INTEGRATION**

A sense of direction refers to an individual's ability to know, without explicit guidance, the direction in which they are or should be moving. This sense of direction is necessary in the creation of a cognitive map. The cognitive map is defined in terms of space relative to the external world, i.e., an allocentric reference frame or top-down view of the world. The cognitive map is about allocentric relationships between external objects and oneself. It can be characterized as a neural representation of the external spatial world that represents the distances and direction between places. It allows one to orient oneself within an environment, imagine oneself in different locations of the environment, and construct sequences embedded as paths within that environment. Every location in it produces a prediction to items or landmarks in the environment. This predictive ability is what allows one to do action selection in an environment, e.g., take a right turn after a landmark. To learn a cognitive map, an individual needs to be able to convert a reference frame relative to one's body (i.e., an egocentric reference frame) to an allocentric reference frame. The conversion of reference frames from egocentric to allocentric is essential in navigating the world and in creating detours to get around unexpected obstacles.

A family of specialized spatial neurons in the mammalian brain work together to create a cognitive map. A few of these neurons are summarized in Figure IA. These spatial neurons are characterized by the rate at which neuronal action potentials are released in certain locations within an environment, or more typically referred to as the neuron's location-dependent firing rate. A place field is defined as the area where neurons fire the most in an environment (refer to the red patches in Figure IA). Different types of spatial neurons perform different functions; these spatial neurons are located in a deep region of the brain, referred to as the hippocampal formation. Figure IA uses a 2D environment to illustrate these spatial neurons: place cells typically exhibit elevated firing rate in one restricted region of an environment; border cells exhibit elevated firing rate at environmental boundaries such as vertical surfaces (e.g., cliff or a wall); grid cells exhibit elevated firing rate whenever an animal is located at one of the vertices of a periodic triangular array spread over a region; head direction cells exhibit elevated firing rate whenever an animals' head faces a particular direction relative to the environment; speed cells have a firing rate that correlates with the running speed of the animal. How these spatial neurons achieve sophisticated navigational strategies, such as path integration, is a hot topic of neuroscience research.

As shown in Figure IB, path integration is an egocentric (self-centered) process by which an animal sums the vectors of distance and direction traveled from a start point (e.g., nest) to estimate its current position. Accurate path integration allows an animal to find a direct path back to the start location (Figure IB, path shown in red dashes) versus retracing its steps to return to the start location (Figure IB, path shown if one were to travel by way of the blue arrow). Path integration is an important evolutionary survival function. Animals from ants [10] to rodents [11], among other animals, are known to leave their nest to respectively search for food or for their young and immediately return to their nest by taking the shortest path owing to their ability to navigate by path integration.

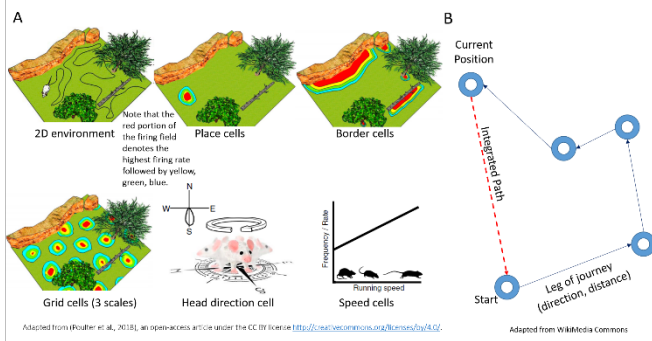


FIGURE I. A. SPATIAL NEURONS THAT CONSTITUTE THE COGNITIVE MAP. ADAPTED FROM [12], AN OPEN ACCESS ARTICLE UNDER THE CC BY LICENSE [HTTP://CREATIVECOMMONS.ORG/LICENSES/BY/4.0/](http://creativecommons.org/licenses/by/4.0/). B. PATH INTEGRATION IS THE PROCESS BY WHICH AN ANIMAL SUMS THE VECTORS OF DISTANCE AND DIRECTION TRAVELED FROM A START POINT TO ESTIMATE ITS CURRENT POSITION. ADAPTED FROM WIKIMEDIA COMMONS.

A problem with path integration as a navigation strategy is that errors may accumulate, and if a large amount of error is accumulated, this may cause the animal to miss its target. Researchers can determine if animals path integrate by experimentally introducing errors to perturb their ability to path integration accurately. In Wittlinger’s 2006 study, the researchers both reduced and extended the animals’ leg lengths to demonstrate that animals would miss their nest proportionally to the amount of leg-length manipulation. More specifically, ants with shortened legs would stop to search for their nest approximately five meters before reaching the actual nest location, while ants with extended legs would travel past their nest by approximately five meters. Path integration operates on self-motion signals which may include (1) proprioception, which is based on information from muscles and joints about limb position; (2) motor efference copy, which is based on information from the motor system that tells the rest of the brain what movements were commanded; (3) vestibular inputs, which is based on information from the vestibular system. For example, the inner ear informs the rest of the brain about motion. Subsequently, deeper parts of the brain – thalamus – integrate all these streams of information to construct a high-level head-direction signal; (4) optic flow, which is based on changes in the visual scene that are projected onto

the retina which are transformed into motion vectors of the external world around the head. Self-motion is integrated over time, but so are errors: thus, path integration must be corrected, or reset, to an absolute, world-centered (allocentric) spatial frame of reference using external cues. These external cues may include visual landmark, odor gradient, or interaural time difference. For additional information about path integration, interested readers are referred to this recent comprehensive review [13].

## LEARNING ENVIRONMENT

### I. Participants

The JHUAPL STEM Program Management Office (PMO) has hosted out-of-school time K–12 STEM programs for over 40 years. All STEM PMO staff have extensive experience making APL research accessible to elementary, middle, and high school students. APL’s core programs include Girl Power, Maryland MESA (Mathematics, Engineering, and Science Achievement), STEM Academy, and ASPIRE, a high school internship program. These programs attract students from the Baltimore and Washington DC Metropolitan areas. JHUAPL also hosts cohort-based learning experiences for undergraduate students in data science and robotics [14].

TABLE I

STUDENT DEMOGRAPHICS

Demographic Category	Percent of Participants
Female	31.4%
Male	65.7%
Not disclosed	2.9%
Asian	37.1%
Black or African American	11.4%
Hispanic or Latino	2.9%
White	22.9%
Two or more races	8.6%
Not disclosed	17.1%
9th grade	42.9%
10th grade	25.7%
11th grade	14.3%
12th grade	17.1%

APL’s STEM Academy is a series of afterschool project-based courses that 8th–12th grade students take to learn about topics ranging from critical thinking to circuit design. Each course is developed in-house by the STEM Academy Specialist and an APL subject matter expert, then taught to students by an APL STEM volunteer working in that field. The STEM Academy enrolls over 600 students per year (84% minority and 53% female). STEM Academy was evaluated by Johns Hopkins University’s Center for Research and Reform in Education in 2018 and found to be effective at increasing interest in STEM careers and the desire to choose a STEM major in college. Students who had completed at least one computer programming course through the STEM Academy and were in 9th–12th grade were recruited for the SPN microseminar. Thirty-five students participated in the SPN microseminar; they were surveyed anonymously before and after the microseminar. Student demographics are summarized in Table I.

## II. Curriculum

The team applied a cross-cutting approach to NGSS LS1.D, resulting in the development of 8 hours of material – 4 hours of presentations and 4 hours of experimentation using the 3D simulation environment Unity3D. These materials were distributed over four 2-hour virtual lessons, which were held daily after school on 11–14 January 2021. Each lesson was structured with a lecture followed by an interactive programming experience. The interactive programming experience was designed to incrementally introduce the students to simulated robotic swarming controllers with increased functionality as the lessons progressed.

Lesson 1 was designed to ensure uniform coverage in neuroscience by all students. The first part of Lesson 1, “Neuroscience Basics: the neuron and nervous system”, provided an overview of the overarching project followed by a general overview of neuroscience. The second part of Lesson 1, “Introduction to Mathematical Swarming”, provided an overview of the mathematics that give rise to collective swarming behaviors in nature. Lesson 2, “How do animal finds their way around living in the wild?”, focused on the concept of spatial navigation including the spatial neurons involved in the formation of a cognitive map. Lesson 2 also explained the methods by which animals transform a sense of motion from external cues (e.g., landmarks, odor gradients) into a sense of location by summing the vector of distances and direction traveled from a start position, a process referred to as path integration or dead reckoning. Lesson 3, “Cognitive Swarming: from oscillations, attractors, to collective spatial behaviors”, focused on a comprehensive review of neuroscience, the hippocampus, and spatial navigation. Lesson 3 also explained the research team’s brain-inspired swarming controller, NeuroSwarms [8]. Lesson 4, “The Evolution of Neuroswarms”, explained the concept of basic research and how that differs from translational research, reviewed prior lecture materials, introduced a Pytorch implementation of the NeuroSwarms controller, and discussed career planning for high school students, followed by an extended question and answer period. All lecture materials including PowerPoint files and recorded lectures are available upon request.

### III. Interactive Programming Experience – Technology Challenges

The SPN microseminar was originally planned to take place in-person with 200 students working in small groups on live programming challenges on laptops with preloaded programs in one weekend in August of 2020. The network would be mapped together in “land parties” so that each small team could explore one region of the island. A culminating activity would include all the teams exploring a new portion of the island simultaneously and seeing which team could maximize their rewards through applying the concepts they learned during the SPN microseminar. However, due to the worsening conditions of the COVID-19

pandemic, we converted this in-person event to a virtual forum which was held on January 11-14, 2021, over two-hour increments after school. The decision to transform to a virtual environment posed technical challenges to the software development team and the educational team. The educational priority was that the students would still be able to work in a hands-on environment where they would be able to manipulate the parameters and directly see the effect on the swarming robots. In planning this virtual version of the microseminar, it was essential that any student who was eligible would be able to participate in the microseminar regardless of the type of computing device they had in their home. Whereas originally the students would be working in-person on laptops with the programs pre-loaded and tested. As a consequence, the software team needed to develop an environment that could be downloaded and provide troubleshooting remotely. Most STEM Academy students attend public schools in Maryland, where many districts provided Chromebooks, or equivalent computing devices, to their students for virtual learning.

To ensure equity of access to the microseminar, the software development team’s new goal was to develop an environment that would be functional within the computing limitations of a Chromebook. This meant that application needed to be distributable on a machine made to stream apps in chrome rather than anything that required too much processing power. There would be limited virtual technical support for the students, so the swarming environment for the students to access needed to be as streamlined as possible.

The software development team focused on coding in WebGL, which allows for interactive graphics on the Chrome web browser. Not having the time or resources to build a new website, which would need to be maintained for longevity, the software team evaluated hosting options and settled on putting the environments live in GitHub. In planning the microseminar via Zoom, time was set aside on the first day for any technology troubleshooting and a Zoom breakout room was staffed by a member of the software development team to address any technical concerns.

### IV. Interactive Programming Experience

Students are challenged to discover all rewards in the simulated environments as quickly as possible by adjusting the parameters presented in the SPN User Interface (UI) during gameplay. The left panel of Figure II contains the SPN UI which is composed of a Main Controller outlined in red (top left), an Allocentric View outlined in blue that presents the simulated environment from above (top right), and an egocentric view, outlined in black, that presents the perspective of each robot (bottom panel). See Table II for a complete list of parameter definitions.

The Main Controller houses large buttons to start or pause the game, as well as to reset parameter values. The SPN UI was designed to allow students to operate a complicated set of equations by using slider bars corresponding to controller parameters to gain an intuition

for how each parameter would affect the overall simulated swarming behavior and elapsed time to reward discovery. At any time during gameplay, students can restart the game or reset all parameter values respectively via the RESTART or RESET VALUES button. Students can view the environment and associated sensing range (i.e., communication between robots which appears as a red line between any two robots) from the perspective of each robot by hitting the PREV BOT or NEXT BOT buttons. The bottom row of the Main Controller, labeled “REWARDS FOUND” visually tallies the number of rewards that are discovered. At the start of each game, eight white boxes are shown; when the reward corresponding to each box is discovered, the white box will turn red.

TABLE II.

SIMULATED ROBOTIC CONTROLLER PARAMETERS.

Controller Parameter [range]	Description	Default
Search Weight [0–1]	The value by which vectors in the controller are weighted by prior to vector summation to affect the overall behaviour of each robot.	1
Search Exponent [-5–1]	Logarithmic control parameter of the physical range of the robots. Lower values make it more likely that robots will spread out over the environment.	-2
Search Decay Exponent [-10–0]	Refers to how quickly a robot forgets what it has seen previously.	-2
Avoid Water Weight [0–1]	Same as Search Weight when a robot enters the ocean.	0.5
Avoid Water Exponent [-10–0]	Same as Search Exponent when a robot enters the ocean.	-4
Swarming Weight [0–1]	Interaction kernel with other robots – specific to NeuroSwarms.	1
Reward Weight [0–1]	Attraction for rewards – specific to NeuroSwarms.	1
Speed [0–3]	The speed of each robot.	1
Sensor [0–3]	Each robot’s sensor range.	1
Comms [0–3]	Each robot’s communication range.	1

The Allocentric View within the SPN UI (box in upper-right corner outlined in blue) conveys important information about the position of each robot (shown in blue) and rewards including the history of the robotic swarm’s search trajectory. Each reward is initially shown in white and upon discovery, the reward turns red. Each robot’s memory of the search space is created by the color of the pixels within this Allocentric View. Black pixels represent areas that the robots have not searched, while different shades of gray represent searched areas. Lighter shades of gray represent areas recently searched, while darker shades of gray represent areas searched long ago. Students can develop swarming strategies based on the search patterns captured in the Allocentric View. Each robot’s memory-based knowledge of the environment is uniquely dependent upon its search trajectory. Thus the Allocentric View presents an

allocentric map of egocentric spatial memory for each robot. Users can access each robot’s memory by hitting the PREV BOT or NEXT BOT buttons.

Representative simulations are illustrated for each lesson (see Figures II–V), which will be described in the remainder of this section. In the first interactive programming experience, eight robots were presented in the simulated world along with eight stationary rewards dispersed within the environment. In Lesson 1, the rewards were initialized as white circles that turn red only upon discovery. Once rewards are discovered by the swarming robots, the reward will remain stationary while each robot will continue to explore the rest of the environment.

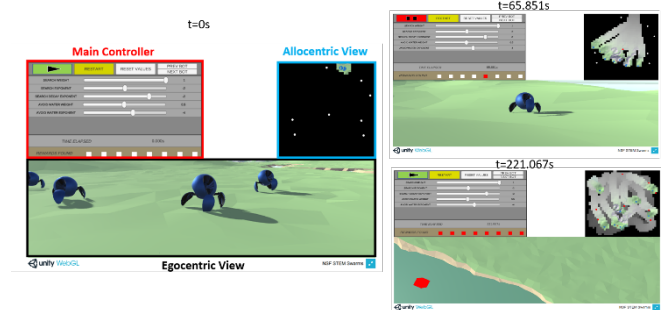


FIGURE II. PROGRAMMING EXPERIENCE IN LESSON 1 – ROBOTS CONTROLLED BY DYNAMIC CO-FIELD CONTROLLER WITH STATIONARY REWARDS. SWARMING POWERED BY NEUROSCIENCE – USER INTERFACE ILLUSTRATED IN LEFT PANEL.

Programming experience in Lesson 1 introduced the students to robotic swarms operated by conventional non-biologically inspired controllers, i.e., dynamic co-fields [15], [16], seeking stationary rewards. As shown in Figure II, at  $t=0$  seconds, robots are still grouped together (see blue squares in Allocentric View, upper-right corner of left panel) and zero rewards have been discovered. At  $t=65.851$  seconds, robots have found one reward (see red square on Main controller in upper-left panel and red circle shown in the Allocentric View in upper-right). At  $t=221.067$  seconds, all eight rewards have been found as shown by both the Main Controller and Allocentric View. The majority of the search area was searched, as exemplified by the different shades of grey in the Allocentric View (upper-right). To access this lesson, go to <https://johnsam2.github.io/DayOne/index.html>.

Programming experience in Lesson 2 introduced the students to conventional swarms operated by dynamic co-fields with mobile rewards that moved randomly. This modification required students to figure out which parameter had to be altered to account for mobile rewards versus the stationary rewards in Lesson 1. More specifically, when adjusting the “Search Decay Exponent” parameter, if the rewards being searched are stationary, it would not make sense to revisit previously searched locations. However, if the rewards are mobile, then there is a clear benefit to adjust the “Search Decay Exponent” variable to ensure that robotic agents revisit old locations over time. As shown in Figure III, at  $t=26.984$  seconds, one reward was found. At  $t=58.325$  seconds, three rewards were found. At  $t=310.575$  seconds,



all eight rewards were found. Notice the differences in reward locations in the Allocentric View (upper-right) across these time points. Discovered rewards (red circles) remain stationary, while undiscovered rewards were mobile until found. To access this lesson, go to <https://johnsam2.github.io/DayTwo/index.html>.

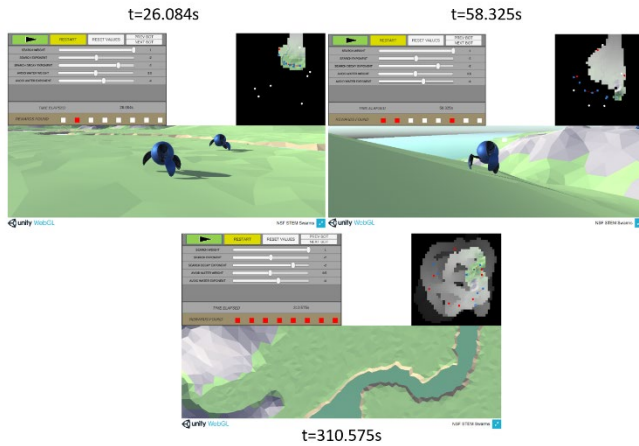


FIGURE III. PROGRAMMING EXPERIENCE IN LESSON 2 – ROBOTS CONTROLLED BY DYNAMIC CO-FIELD CONTROLLER WITH MOBILE REWARDS.

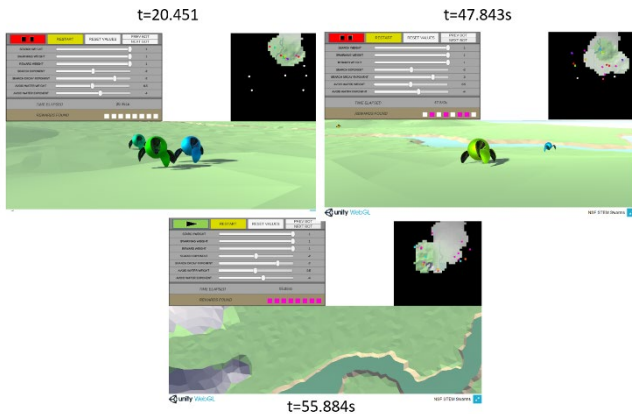


FIGURE IV. PROGRAMMING EXPERIENCE IN LESSON 3 – ROBOTS CONTROLLED BY THE NEUROSWARMS CONTROLLER WITH MOBILE REWARDS.

Programming experience in Lesson 3 introduced robotic swarms that were driven by the NeuroSwarms controller instead of the conventional dynamic co-field method used in Lessons 1 & 2. Importantly, the NeuroSwarms controller features a circularly periodic phase variable that takes values from 0 to  $2\pi$ , corresponding to the angles that span a complete revolution of a circle or, equivalently, a complete cycle (or wave) of an oscillation in time. Thus, each agent maintains an internal phase state, driven by input strength, as a basis for interactive coupling with other nearby agents. This phase-based coupling elicits the sort of spontaneous synchronization, both in-phase (i.e., for interagent attraction) and anti-phase (i.e., for interagent repulsion), observed by Huygens for pendulum clocks anchored to the same wooden board. In our simulations, the phase of each robotic agent was represented by the robot's

color, which was updated based on a periodic HSV colormap at every timestep. Additionally, the NeuroSwarms controller featured two new parameters, Swarming Weight and Reward Weight, which determined the spatial reach of, respectively, swarming and reward-approach behaviors. Specifically, Swarming Weight set the size of the local neighborhood within which agents interacted with each other, via phase-coupled attraction and repulsion as described above. Similarly, Reward Weight set the strength of an interaction that guided agents toward visible rewards in the environment, i.e., within an agent's unobstructed line-of-sight. As shown in Figure IV, the Allocentric View (upper-right) shows the location of each reward and the position of every robot (squares of different colors). At 20.451 seconds, no rewards had been discovered. At 47.843 seconds, four rewards had been discovered. By 55.884 seconds, all rewards had been found. The NeuroSwarms controller resulted in faster discovery of all eight rewards using default settings compared to the dynamic co-field controller from Lessons 1 and 2. To access this lesson, go to <https://johnsam2.github.io/DayThree/index.html>.

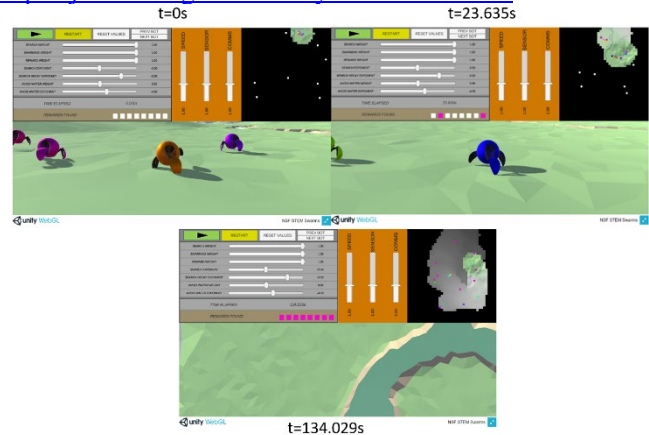


FIGURE V. PROGRAMMING EXPERIENCE IN LESSON 3 – ROBOTS CONTROLLED BY THE NEUROSWARMS CONTROLLER WITH MOBILE REWARDS AND ADJUSTABLE SPEED, SENSORS, AND COMMUNICATION.

Programming experience in Lesson 4 introduced the NeuroSwarms controller with practical parameters such as speed, sensor, and communication range (see Figure V, orange portion between the Main Controller and the Allocentric View). All other control parameters were implemented identically as in Lesson 3. This progression allowed students to experience the intuitive difference between controllers inspired by neuroscience versus those that were not at an increasing level of engineering fidelity. As shown in Figure V, at  $t=0$  second, robots are in starting formation. At  $t=23.636$  seconds, two rewards were found. At  $t=134.029$  seconds, all eight rewards were found. To access this lesson, go to <https://johnsam2.github.io/DayFour/index.html>.

## V. Evaluations

The students were surveyed about their interest in various STEM careers prior to and at the conclusion of the microseminar. They were asked to indicate their interest in

pursuing careers in Neuroscience, Robotics, and Computer Science by selecting a number on a sliding scale from 1-100. Percent change in interest in pursuing a career in STEM was computed based on the difference between the average “% interest: Pre microseminar” and the average “% interest: Post microseminar” normalized by the average “% interest: Pre microseminar” for each discipline. Thirty-five students responded to the pre microseminar survey, while seventeen students responded to the post microseminar survey. Because student identities were protected, it was not possible to compute paired statistics.

## RESULTS

### I. Student Survey Summary

Quantitative results of student interest in STEM topics are summarized in Table III on the basis of pre- and post-SPN microseminar participation. The most notable percent increase in interest was in the field of neuroscience, which had students indicating a 16.6% change in their interest. Modest increases in interest were observed in the fields of robotics and computer science corresponding respectively to 2.7% and 1.9%. This is an encouraging result because many students had little to no familiarity with neuroscience prior to the SPN microseminar. It is also notable that these students were recruited from the STEM Academy, which meant each student had already successfully completed at least one course in a computer programming language and had prior exposure to robotics. Notably, the SPN microseminar substantially elevated their interest in neuroscience.

TABLE III  
STUDENT SURVEY RESULTS

Career Field	% Interest pre-microseminar	% Interest post-microseminar	% Change in interest in pursuing career in STEM
Neuroscience	51.1	59.6	+16.6
Robotics	66.2	68	+2.7
Computer Science	79.9	81.4	+1.9

TABLE IV

DESCRIBE WHAT YOU THINK A “NEUROSARM” IS (DO NOT GOOGLE)

Pre- microseminar	Post-microseminar
<ul style="list-style-type: none"> <li>Controlling a swarm or group of things or robots with the brain.</li> <li>Overwhelming information going into the brain or control center.</li> <li>What I think that “neuroswarm” means is using tiny robots and computer to find and solve neurological problems.</li> <li>A swarm of neuro diseases happening at the same time in your brain.</li> <li>A large group of micro processors</li> </ul>	<ul style="list-style-type: none"> <li>A group of robots that have depend on each other for actions through a neural similar system.</li> <li>Neuroswarm is the network of robots that is based on the concept of neuron connectivity in animals to study how decisions are made. It is very [interesting] bio mimicry concept</li> <li>A neuroswarm is a group of robots that communicate with one other to complete a task</li> <li>A swarm of individual robots</li> </ul>

Pre- microseminar	Post-microseminar
<ul style="list-style-type: none"> <li>that act and solve problems like a real brain.</li> <li>A grouping of neurons in the brain the work as part of a swarm to achieve goals.</li> <li>I think a “neuroswarm” might be what you call the field of robotics related to neuroscience.</li> <li><b>A robotic swarm that works like a brain.</b></li> <li>I think it is improving network or data intelligence by adapting to the bio mimicry mechanisms for real world problems.</li> <li>When many (hundreds of) robots that are programmed, will complete tasks and use machine learning to learn from experience in order to more efficiently complete the task.</li> </ul>	<ul style="list-style-type: none"> <li>that act like the hippocampus or hippocampus-related structures in the brain.</li> <li>It is a swarm that has a system modeled after how neurons work specifically in the hippocampus.</li> <li>I think that a neuroswarm is a group of entities that “think” and act without the input of a human to accomplish a preset goal. They form swarming patterns to accomplish their goal and if implemented in robots, the “neurons” in the swarm can communicate with one another.</li> <li>A neuroswarm is when multiple things, such as robots, or virtually coded things do things together to help the whole.</li> </ul>

Qualitative results of student comprehension regarding the concept of NeuroSwarms are summarized in Table IV on the basis of pre- and post-microseminar participation. Prior to the microseminar, students were asked to define the concept NeuroSwarms without any internet help. Many interesting responses were provided, a sample of them are presented in Table IV. Out of the thirty-five responses, two students admitted that they did not know the answer (not shown in Table IV), while one student provided a correct answer (bold text in Table IV, first column). A few students imagined that NeuroSwarms was a brain-computer interface controller, which was a reasonable but incorrect guess. After the microseminar, thirteen out of seventeen survey respondents provided a range of correct answers. This demonstrates that 76% of the survey respondents understood the lecture on NeuroSwarms.

Quantitative results of student satisfaction by STEM topics and interdisciplinary teaching experiences are summarized in Table V based on post-microseminar participation. The percentage of students who strongly agreed that they learned new knowledge in disciplinary topics varied – i.e., neuroscience: 82%, robotics: 53%, and computer science: 41%. The majority of students (64%) strongly agreed that they enjoyed learning from an interdisciplinary team of experts and 70% strongly agreed that the microseminar emphasized the need to have instruction teams with diverse disciplinary backgrounds.

### II. Interactive Programming Experience

During the actual SPN microseminar, every student was able to access the interactive Unity3D environment virtually. In fact, no student visited the microseminar’s technology support breakout room. The interactive environment worked despite all the students accessing at the same time, allowing for the students to share their insights and top scores via chat in Zoom, thus retaining an element of the original competition-based approach to the NeuroSwarms Unity3D environment.

## DISCUSSION

The SPN microseminar illustrates an effective way to teach neuroscience to high school students who already have a background in robotics and computer science. Our results suggest that the materials developed for the microseminar and the microseminar format could be used as an effective model for developing lesson plans and a strategy to involve STEM professionals in the delivery of instruction to attain the learning objectives of LS1.D. Future microseminars could explore methods to engage robotics and computer science to students who already have a background in neuroscience to determine if reciprocity in interdisciplinary learning experiences is observed.

TABLE V  
STUDENT SATISFACTION SURVEY POST MICROSEMINAR

Question	Disagree	Neither agree or disagree	Agree	Strongly agree
I learned about an application of neuroscience I had not heard of before	0	0	3	14
I learned about an application of robotics I had not heard of before	1	0	7	9
I learned about an application of computer programming I had not heard of before	0	3	7	7
I enjoyed learning from an interdisciplinary team of experts	0	0	6	11
This micro-seminar emphasized the need to have teams with diverse disciplinary backgrounds	0	1	4	12

## ACKNOWLEDGMENT

This work was supported by National Science Foundation Award NCS/FO 1835279. This material is based on work supported by (while serving at) the National Science Foundation. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

- [1] R. M. Murray, "Recent research in cooperative control of multivehicle systems," 2007.
- [2] G.-Z. Yang *et al.*, "The grand challenges of Science Robotics," *Science robotics*, vol. 3, no. 14, pp. 1–14, 2018.
- [3] H. Hamann *et al.*, "Hybrid societies: challenges and perspectives in the design of collective behavior in self-organizing systems," *Frontiers in Robotics and AI*, vol. 3, p. 14, 2016.
- [4] S.-J. Chung, A. A. Paranjape, P. Dames, S. Shen, and V. Kumar, "A survey on aerial swarm robotics," *IEEE Transactions on Robotics*, vol. 34, no. 4, pp. 837–855, 2018.
- [5] K. Whang, "National Science Foundation Award Abstract #1835279 Neural and Cognitive Systems - Foundation (NCS-FO): Spatial Intelligence for Swarms Based on Hippocampal Dynamics. [https://www.nsf.gov/awardsearch/showAward?AWD\\_ID=1835279](https://www.nsf.gov/awardsearch/showAward?AWD_ID=1835279)

- &HistoricalAwards=false." National Science Foundation, Sep. 05, 2018. [Online]. Available: [https://www.nsf.gov/awardsearch/showAward?AWD\\_ID=1835279&HistoricalAwards=false](https://www.nsf.gov/awardsearch/showAward?AWD_ID=1835279&HistoricalAwards=false)
- [6] G. M. Hwang, K. M. Schultz, J. D. Monaco, and K. Zhang, "Neuro-Inspired Dynamic Replanning in Swarms—Theoretical Neuroscience Extends Swarming in Complex Environments.," *Johns Hopkins APL Technical Digest*, vol. 35, no. 4, pp. 443–447, 2021, doi: <https://www.jhuapl.edu/content/techdigest/pdf/V35-N04/35-04-Hwang.pdf>.
  - [7] J. D. Monaco, G. M. Hwang, K. M. Schultz, and K. Zhang, "Cognitive swarming: an approach from the theoretical neuroscience of hippocampal function," in *Proc. SPIE 10982, Micro- and Nanotechnology Sensors, Systems, and Applications XI*, May 2019, vol. 10982, p. 109822D. [Online]. Available: <https://doi.org/10.1117/12.2518966>
  - [8] J. D. Monaco, G. M. Hwang, K. M. Schultz, and K. Zhang, "Cognitive swarming in complex environments with attractor dynamics and oscillatory computing," *Biological Cybernetics*, vol. 114, no. 2, pp. 269–284, Mar. 2020, doi: 10.1007/s00422-020-00823-z.
  - [9] National Research Council, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press, 2012. doi: 10.17226/13165.
  - [10] M. Wittlinger, R. Wehner, and H. Wolf, "The ant odometer: stepping on stilts and stumps.," *Science*, vol. 312, no. 5782, pp. 1965–1967, Jun. 2006, doi: 10.1126/science.1126912.
  - [11] J. Lisman, G. Buzsáki, H. Eichenbaum, L. Nadel, C. Rangananth, and A. D. Redish, "Viewpoints: how the hippocampus contributes to memory, navigation and cognition," *Nature Neuroscience*, vol. 20, no. 11, pp. 1434–1447, Oct. 2017, doi: 10.1038/nn.4661.
  - [12] S. Poulter, T. Hartley, and C. Lever, "The Neurobiology of Mammalian Navigation.," *Curr Biol*, vol. 28, no. 17, pp. R1023–R1042, Sep. 2018, doi: 10.1016/j.cub.2018.05.050.
  - [13] F. Savelli and J. J. Knierim, "Origin and role of path integration in the cognitive representations of the hippocampus: computational insights into open questions.," *J Exp Biol*, vol. 222, no. Pt Suppl 1, Feb. 2019, doi: 10.1242/jeb.188912.
  - [14] M. Villafaña-Delgado, E. C. Johnson, M. Hughes, M. Cervantes, and W. Gray-Roncal, "STEM Leadership and Training for Trailblazing Students in an Immersive Research Environment," in *2020 IEEE Integrated STEM Education Conference (ISEC)*, Aug. 2020, pp. 1–4. doi: 10.1109/ISEC49744.2020.9280735.
  - [15] R. W. Chalmers, "Multi-vehicle collaborative autonomous control under difficult communications condition.," presented at the NDIA, 2005. Accessed: Apr. 14, 2018. [Online]. Available: [https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2005/umv\\_auv/wednesday/chalmers.pdf](https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2005/umv_auv/wednesday/chalmers.pdf)
  - [16] W. M. Spears, D. F. Spears, J. C. Hamann, and R. Heil, "Distributed, Physics-Based Control of Swarms of Vehicles," *Autonomous Robots*, vol. 17, no. 2/3, pp. 137–162, Sep. 2004, doi: 10.1023/B:AURO.0000033970.96785.f2.

## AUTHOR INFORMATION

Ms. Elise Buckley, STEM Program Specialist, Johns Hopkins University (JHU) Applied Physics Laboratory (APL). Dr. Joseph D. Monaco, Research Associate, Department of Biomedical Engineering, School of Medicine, JHU. Dr. Kevin M. Schultz, Senior scientist, JHUAPL. Mr. Robert W. Chalmers, Supervisor, JHUAPL. Mr. Armin Hadzic, Computer Vision Researcher, formerly JHUAPL. Dr. Kechen Zhang, Associate Professor of Biomedical Engineering, School of Medicine, JHU. Dr. Grace M. Hwang, Senior staff engineer, JHUAPL and Johns Hopkins University Kavli Neuroscience Discovery Institute. Mr. M. Dwight Carr, Program Manager, STEM Program Management Office, JHUAPL.