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HOW WE TEACH | *Generalizable Education Research*

Drawing on student knowledge of neuroanatomy and neurophysiology

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Slominski TN, Momsen JL, Montplaisir LM. Drawing on student knowledge of neuroanatomy and neurophysiology. *Adv Physiol Educ* 41: 212–221, 2017; doi:10.1152/advan.00129.2016.—Drawings are an underutilized assessment format in Human Anatomy and Physiology (HA&P), despite their potential to reveal student content understanding and alternative conceptions. This study used student-generated drawings to explore student knowledge in a HA&P course. The drawing tasks in this study focused on chemical synapses between neurons, an abstract concept in HA&P. Using two preinstruction drawing tasks, students were asked to depict synaptic transmission and summation. In response to the first drawing task, 20% of students ($n = 352$) created accurate representations of neuron anatomy. The remaining students created drawings suggesting an inaccurate or incomplete understanding of synaptic transmission. Of the 208 inaccurate student-generated drawings, 21% depicted the neurons as touching. When asked to illustrate summation, only 10 students (roughly 4%) were able to produce an accurate drawing. Overall, students were more successful at drawing anatomy (synapse) than physiology (summation) before formal instruction. The common errors observed in student-generated drawings indicate students do not enter the classroom as blank slates. The error of "touching" neurons in a chemical synapse suggests that students may be using intuitive or experiential knowledge when reasoning about physiological concepts. These results *1*) support the utility of drawing tasks as a tool to reveal student content knowledge about neuroanatomy and neurophysiology; and *2*) suggest students enter the classroom with better knowledge of anatomy than physiology. Collectively, the findings from this study inform both practitioners and researchers about the prevalence and nature of student difficulties in HA&P, while also demonstrating the utility of drawing in revealing student knowledge.

neuron; neurophysiology; intuitive knowledge and P-prims; drawing; assessment

IN THE UNITED STATES, Human Anatomy and Physiology (HA&P) has a reputation as one of the most difficult courses a student will take as a part of his or her pre-health professional major (7, 40). That difficulty is often attributed to physiology, widely perceived as harder to learn than anatomy (22, 40). The challenges of learning physiology have been documented in many systems, including cardiovascular (23, 28), respiratory (23, 24), and digestive (27). However, little research has explored the learning challenges of neuroanatomy and physiology, especially at the introductory level.

Research on student understanding of neuroanatomy is largely absent, whereas research on student understanding of neurophysiology has focused almost exclusively on advanced undergraduate and postgraduate students. In general, despite their advanced level, these students struggle with neurophysiology. For example, students have trouble reasoning about the variables of membrane potential (37) and the events occurring during synaptic transmission (25). Even medical students (19) and practicing physicians (13) struggle to reason appropriately about neurophysiology.

This small body of research is informative but cannot predict novice student reasoning in HA&P. Research on student understanding of neuroanatomy and physiology at the introductory level is quite limited (33). This research identified students' alternative conceptions regarding both the central and peripheral nervous systems at various organizational levels and found students struggled to articulate simple neuron anatomy and could not reason about more complex concepts like reflex arcs. These results are a first step in exploring student understanding of neuroanatomy and physiology and underscore a need for additional research at the introductory level. We cannot assume that the challenges experienced by students in upper-division and postgraduate courses are the same as those faced by introductory students.

The importance of prior knowledge. A critical first step in improving student understanding of physiology is to identify the knowledge and resources students bring to the HA&P classroom. Students are not blank slates: they have a broad range of personal experiences with many of the common physiological phenomenon covered in a typical HA&P curriculum (e.g., thermoregulation, digestion, motility). Therefore, they enter the classroom with unique ideas and understandings, even about abstract concepts like neurophysiology. However, students' everyday experiences with HA&P may lead to intuitive ideas about physiology that are limited or simply wrong.

As an example, through personal experiences, students may know that exercise results in a stronger heartbeat. However, their explanations of why the heartbeat is stronger demonstrate shallow or inaccurate reasoning. Students may intuit that "the strength of the heartbeat increases because tissues need more blood" (23). This reasoning does not reflect an awareness of physiological principles; rather, it reflects intuitive ideas students have developed through their own experiences. Students' use of intuition to reason about exercise is not uncommon in the HA&P classroom, and this reasoning approach may extend to all biological systems. The use of intuition is problematic, because these ideas are often scientifically inaccurate and may result in faulty conceptions that students are not readily able to abandon (20, 38).

Students' prior knowledge can have a profound impact on their subsequent learning. Ausubel's Meaningful Learning Framework articulates a relationship between prior knowledge and learning new material (4). In this framework, meaningful

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learning occurs when a learner can connect new information with existing knowledge. If new information cannot be linked to existing knowledge, meaningful learning is difficult and may not occur. Instead, rote learning may take place (3, 4). Using the Meaningful Learning Framework, we might predict that student challenges in learning physiology result from students' inability to connect and align new material with existing knowledge constructs. This could arise because the existing constructs may not exist, or, if they do, are limited or faulty in some way.

Ausubel's Meaningful Learning framework also posits that, to best support students in building meaningful connections, we must first identify students' existing knowledge structures. Failing to reveal student's existing knowledge will limit the impact of instruction: an instructor is unlikely to introduce a concept in a way that aligns with and builds from students' preexisting knowledge structures. However, developing assessments that reveal students' preexisting knowledge about HA&P is not always an easy task.

Drawing to reveal authentic ideas. HA&P education literature has identified many instances where, even after instruction, students continue to struggle with physiology concepts (e.g., fat metabolism, chemical equilibrium, glomerular filtration; Refs. 8, 9, 26). However, there is far less evidence examining how students reason about physiology before instruction.

To better support incoming students, the HA&P community can begin developing instruction that meets the needs of the learners as they enter our classrooms. This is especially necessary for challenging content areas like neurophysiology. Assessing what students know at the start of the course is critical to developing effective instruction. However, creating assessments that capture student thinking before instruction is a time-consuming and nontrivial task. Traditional assessment techniques, like multiple choice or true/false questions, do not always reveal the diversity in students' reasoning (29). Rather, these assessments often reflect instructor ideas about students' reasoning and misconceptions and are rarely validated empirically. These limitations can be addressed, in part, through validation procedures, yielding more widely operational and reliable instruments (1). While efforts to generate validated concept inventories in biology and physiology are increasing, there are few published instruments at present (10, 21). If educators hope to characterize student thinking across topics for which a validated concept inventory does not yet exist, they will need to look to other assessment options.

Student-generated drawings are a type of free-response assessment where students construct an answer rather than selecting a provided answer. As students draw, they actively decide what concepts and structures they will include (and exclude) and how they will depict anatomical relationships to show physiology. As a result, when drawing tasks are used before instruction, they have the potential to reveal the diversity of student ideas and reasoning rather than that of an instructor. By extension, instructors gain a more robust picture of student thinking, which can directly inform instruction.

Drawing assessment tasks are particularly powerful when the extent of student knowledge in a given course varies tremendously (17). For example, previous research using student-generated drawings asked students about their own awareness of internal body structures (34, 35, 41). Specifically, students were asked to draw "what they thought" was inside themselves or other animals. These open-ended questions resulted in diverse drawings containing varying representations of isolated organs and incomplete systems. These students had diverse perceptions of body systems and tissues. Such extensive variation could have been masked with a multiple choice item where students would have selected one response that best matched their own ideas.

Drawing tasks can also reveal student understanding of more specific HA&P concepts. In their research in introductory HA&P courses, Ranaweera and Montplaisir (33) asked students to draw a series of neural structures (e.g., lateral view of the brain, multipolar neuron, cross-section of a nerve) both before and after formal instruction. Through analysis of what students chose to draw, researchers were able to identify a number of common alternative conceptions. For example, instead of drawing a reflex arc as an organized neuron chain, many students drew a literal "arc" or semicircle. Researchers observed a similar type of error when students were asked to draw unipolar, bipolar, and multipolar neurons. Students included positive and negative signs into the cell body.

Hay and colleagues (16) also used student-generated drawings as a means to reveal how students think about neuron anatomy. Researchers used these drawing tasks to reveal how an individual's idea of a neuron may be impacted by the extent of their research experiences. Study participants represented a continuum of research experience from very little (upper-level undergraduates) to extensive (PhD students, postdoctoral research associates, laboratory principal investigators). When asked to draw a neuron, upper-level undergraduate students almost always drew a standard, textbook representation of a neuron. Interestingly, student depictions were similar. After a significant involvement in neuroscience research, PhD students, postdocs, and principle investigators in the field communicated ideas dissimilar to the typical textbook figure. PhD students and postdocs drew more authentic and natural representations of neurons, including features one might see in real tissue. Principle investigators, however, communicated a more abstract idea of a neuron, and their representations seemed to reflect their own research endeavors. Like the Ranaweera and Montplaisir study (33), the work done by Hay and colleagues (13) exemplifies the affordances of asking learners to draw. Even a relatively simple drawing task can accommodate and reflect a great deal of variation in student ideas that may be masked by more traditional means of assessment.

Research questions. The studies conducted by Silverthorn (37), Montagna et al. (25), and Hay et al. (16) offer valuable insight into upper-level and postgraduate student knowledge of neurophysiology. We build from this research to capture introductory HA&P students' preexisting ideas about neuron anatomy and physiology. To do so, we used a series of drawing tasks to capture a variety of student ideas about neuron anatomy and physiology. Specifically, we ask:

1. What knowledge of neuron anatomy and physiology do students bring to the introductory HA&P classroom?
2. Before classroom instruction, are students better able to depict neuroanatomy or neurophysiology?
3. How do students' depiction of neuroanatomy change over time in an introductory HA&P course?

METHODOLOGY

Course context. Data for this study were collected from the first course in a two-semester HA&P sequence taught at a large, public, Midwestern university. This course spanned the integumentary, nervous, muscular, skeletal, and endocrine systems. There were 519 students enrolled across two sections and a single instructor and graduate teaching assistant (GTA, author TS) taught both sections. There are no prerequisites for the course, and there was an accompanying laboratory course that most students enroll in simultaneously. The student population of this course was largely freshman or sophomore and diverse in major (Table 1). All participants in the study were 18 yr of age or older, in compliance with approved Internal Review Board protocol no. SM14224.

Instruction. Course instruction was primarily traditional lecture that included occasional small-group and whole-class discussions. The auditorium housed two large projectors: one was primarily used by the course instructor to display pertinent images from the course textbook, while the second projector was used by the GTA to simultaneously diagram course content. The primary role of the GTA was to create and annotate lecture drawings. These lecture drawings were developed by the GTA and course instructor before class and included abstract representations or modified box-and-arrow models to illustrate structural organization and complex physiological processes (for example GTA drawings, see Supplemental Fig. S1; Supplemental Material for this article is available online at the Journal website).

Table 1. *Demographic data for the full class compared with those students who completed drawing task 1*

	Full Class	*Drawing Task 1*
Total students	519	352
Major		
Nursing	118 (22.7)	85 (24.1)
Health and Wellness	112 (21.6)	66 (18.8)
Pharmacy	105 (20.2)	80 (22.7)
Allied Sciences	78 (15)	60 (17)
Life Sciences + other STEM	59 (11.4)	36 (10)
Non-STEM (e.g., Art, History, Education, University Studies)	46 (8.9)	25 (7.1)
Did not report	1 (0.2)	0
Class		
Freshman	126 (24.3)	72 (20.5)
Sophomore	255 (49.1)	193 (54.8)
Junior	69 (13.3)	42 (11.9)
Senior	67 (12.9)	44 (12.5)
Graduate	1 (0.2)	1 (0.3)
Did not report	1 (0.2)	0
Sex		
Male	187 (36)	123 (35)
Did not report	1 (0.2)	0
First-generation college student		
Yes	110 (21.2)	79 (22.4)
Did not report	63 (12.15)	39 (11.1)
Incoming GPA		
3.5–4	147 (28.3)	128 (36.4)
3–3.49	67 (12.9)	37 (10.5)
2.5–2.99	71 (13.7)	43 (12.2)
2–2.49	38 (7.3)	27 (7.7)
1.5–1.99	25 (4.8)	11 (3.1)
<1.5	12 (2.3)	3 (0.9)
No GPA (e.g., first semester freshman, did not report)	159 (30.6)	103 (29.3)
Final course grade		
A	112 (21.6)	97 (27.6)
B	91 (17.5)	72 (20.5)
C	75 (14.5)	62 (17.6)
DFW	241 (46.4)	121 (34.4)

Values are no. of students (n) (with % in parentheses).

Table 2. *Drawing tasks used to elicit student thinking about neuroanatomy and neurophysiology*

Drawing	Focus	Drawing Task
1	Neuroanatomy	Draw a diagram of 2 typical neurons in a linear pathway. Label the significant regions. Using arrows, show the direction of information flow along the neurons.
2	Neuroanatomy + Neurophysiology	Draw a neuron and illustrate how signals arriving at the receiving end could be varied in strength and complexity. On the same neuron, illustrate how signals could be varied in strength and complexity at the output end.

Student learning in the course was evaluated through individual performance on summative multiple-choice exams, short writing assignments completed in class, formative online quizzes, and online LearnSmart modules composed of knowledge-level questions to assess factual recall. At the start of some classes, students were also asked to generate drawings depicting anatomy or anatomy and physiology as a form of formative assessment. Students who had completed the assigned textbook readings could have adequately completed these drawing tasks. However, there were no reading checks or quizzes to verify whether students had completed the readings before class. After the drawings were collected, the GTA created an accurate response to the prompt. Students wrote their names on their drawings; however, drawings were not graded and were completed on a voluntary basis. These formative assessment drawing tasks comprise the data streams for this study.

Data. Throughout the course, students created and submitted in-class drawings and were familiar with the format of these tasks. Two formative assessment drawing tasks (Table 2), written by the research team in consultation with the course instructor and predetermined course learning goals, were the focus of this research. These drawing tasks were presented via two large projection screens in the front of the classroom.

Drawing task 1 was presented to students after an assigned textbook reading but before any formal in-class discussion about neurons or the nervous system (Fig. 1). This task asked students to depict a concept that was primarily anatomical (Table 3). Neuroanatomy had not yet been discussed in the classroom in any form, including motoneurons. Students who completed the assigned reading could have adequately answered the drawing task. However, as noted previously, there were no reading assessments, so we were unable to determine whether students had read about neuroanatomy and neurophysiology before they were asked to draw these concepts in class.

Drawing task 2 asked students to depict neuron anatomy and to overlay neurophysiology in the form of summation (Table 3). *Drawing task 2* was presented to students after an assigned textbook reading, formal instruction about neuron structure, and formal instruction about basic synapse physiology (see Supplemental Fig. S1). Specifically, instruction between *drawing task 1* and *drawing task 2* covered neuron anatomy, the role of ions and membrane potentials,

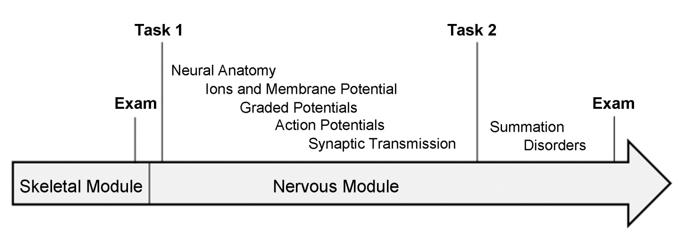

Fig. 1. Timing of drawing tasks in nervous system module.

Table 3. *Structural accuracy rubric for drawing 1, structural accuracy rubric for drawing 2, and functional accuracy rubric for drawing 2*

	Accurate	Inaccurate
Structural accuracy *drawing 1*	• Two complete neurons • Labels were used accurately • Projections that were distinctly different • Contains synaptic cleft	• Missing or incomplete neurons • Projections were not distinctly different • Inaccurate labels • Other erroneous depictions
Structural accuracy *drawing 2*	• One complete neuron • Labels were used accurately • Projections that were distinctly different	• Missing or incomplete neurons • Projections were not distinctly different • Inaccurate labels
Functional accuracy *drawing 2*	• Correctly depict at least one type of summation (temporal or spatial)	• No attempt to draw summation • Inaccurate depiction of summation (temporal or spatial)

graded potentials, action potentials, and basic synaptic transmission. Students had not yet received formal instruction on summation, and the GTA's depiction of summation had not yet been presented in the classroom. Students were not asked to complete any drawings between *drawing task 1* and *drawing task 2*; however, students were encouraged to draw in their notes.

Each drawing task was presented at the same point in instruction across both sections of the course. After ~5–8 min, the course instructor ended the activity and collected the drawings. There were no course points associated with participation or completion of these drawings. Students could choose not to participate without any negative impact on their course grade.

Rubric and coding. Our research goal was to explore how HA&P students depict neuroanatomy and neruophysiology in representational drawings, which resulted in a broad coding approach to accommodate the range of ideas students depicted. To accomplish this, we used emergent coding (36, 39) to develop three rubrics (Table 3): Structural Accuracy for *drawing 1*, Structural Accuracy for *drawing 2*, and Functional Accuracy for *drawing 2*. In general, each rubric categorized student drawings as accurate or inaccurate. An accurate drawing was one in which no major errors were evident to the coders; however, the drawing might not have been complete. We chose to code for accuracy rather than completeness because students were limited by time. Completeness of a drawing relies on the number of structures or labels a student depicted; a time-pressed student may inadvertently omit critical labels or structures, which does not necessarily reflect a lack of knowledge. In addition, coding drawings for completeness would have focused on the presence or absence of specific structures and would, as a result, reflect instructor (or researcher) ideas rather than student ideas.

While coding *drawing 1* for structural accuracy, common features among the inaccurate drawings were documented. Upon review, it became apparent that most of these commonalities occurred at the level of the synapse (e.g., incorrect structures in the synapse, incorrect orientation of the structures in the synapse, incorrect depiction of the synaptic cleft). After coding for structural accuracy, we did an additional coding of *drawing 1* to identify inaccurate features of the synapse.

While reviewing student responses to *drawing task 2*, it became evident that most of the structural inaccuracies at the synapse that were observed in *drawing 1* were no longer present. Because of this improvement, we did not code for the predetermined, structural synapse errors (i.e., touching, dendrite-dendrite, etc.) like we did for *drawing 1*. We only coded *drawing 2* for the overall structural accuracy of the synapse.

For the functional component of *drawing 2*, most errors resulted from attempts to alter "standard" synaptic transmission. A majority of drawings recreated the GTA's depiction of summation (Fig. 1) or a variation of that drawing (see example in Fig. 4*B*). Because the inaccurate responses to *drawing 2* showed much less variation and largely reflected the instructional materials, we did not do any finer coding.

We specifically crafted the rubrics for *drawing 2* to treat all major errors the same. If a drawing contained at least one major error (as described in Table 3), we classified it as inaccurate. We acknowledge that some drawings contained varying numbers of major errors. However, the number of major errors identified in a students' drawing did not change the effect on the function communicated, namely that signal propagation failed to result. For example, using the Structural Accuracy for *drawing 1* rubric, if a student did not include an arrow extending from the axon-terminal to dendrite at the synapse, it was unclear to coders if the student knew where neurotransmitters are released, the location of neurotransmitter receptors, or even the function of the axon or dendrites. While it may be that a student simply forgot to include an arrow, we did not feel justified in assuming the student knew anything more than they communicated through their drawing. Furthermore, drawings that contained more than one major error often intertwined the errors, compounding the effect and making it difficult to parse just how many errors were present.

Instead of trying to quantify the number of distinct errors, we saw more value in *1*) assessing the overall quality (i.e., ability to function as drawn); and *2*) identifying the most common major errors (i.e., inaccurate ideas) across the population. We wanted to be able to characterize and describe the way students think about neurons before instruction, not necessarily how inaccurate their ideas were.

Analysis. After generating the coding rubric for *drawing 1*, two biology education researchers (authors TS and LM) individually coded 30 random drawings from *drawing 1*. Initial agreement was 83%. Any dissimilarity was discussed until agreement was reached. Two additional subsets of 40 student drawings were coded, and final agreement was 92%. One author coded the remaining drawings independently. The same researchers also generated the structure and function rubrics for *drawing 2*. Final agreement on the structure rubric for *drawing 2* was 88%, and the function rubric was 86%.

We used McNemar's test to determine whether the accuracy of students' depictions of neuroanatomy changed from *drawing 1* to *drawing 2*. We also used Pearson's χ^2 test to compare the accuracy of anatomy depicted in *drawing 1* to the accuracy of physiology depicted in *drawing 2*. This allowed us to determine whether students, before instruction, were able to more accurately draw neuroanatomy than neurophysiology. All statistical analyses were conducted in the R statistical environment (32).

RESULTS

Of the 519 students enrolled in the two sections of the course, 355 (68%) submitted drawings in response to the first drawing task; however, three student drawings lacked any recognizable anatomical structures or terms and were removed from the study, leaving 352 codable drawings. The 352 students who completed the drawing task were comparable to the overall population of the course in terms of demographics;

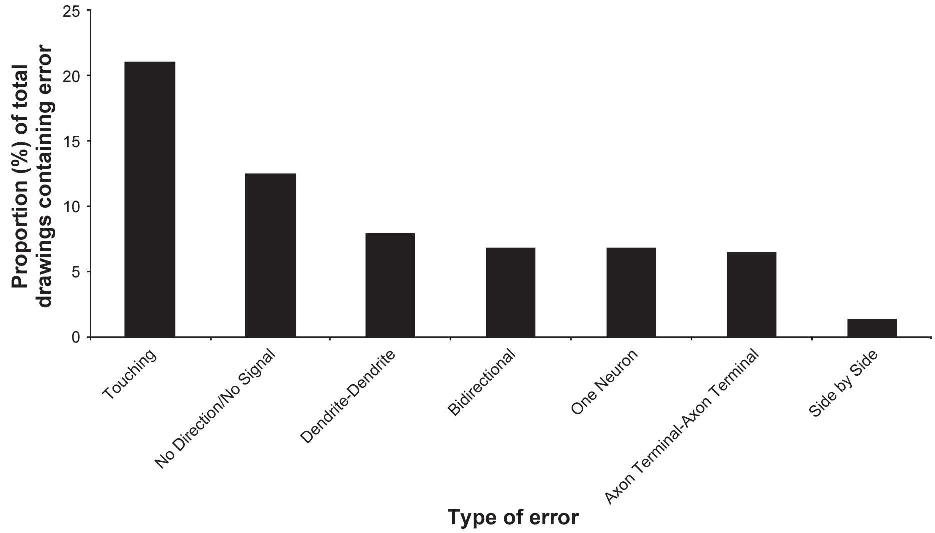

Fig. 2. Errors observed in *drawing task 1*. Drawings could exhibit more than one error, resulting in proportions adding to >100%.

however, fewer students who earned a C or DFW completed the drawing task (Table 1).

Student ideas about neuron anatomy and physiology are diverse before instruction. Of the 352 codable drawings submitted in response to *drawing task 1*, 69 were coded as accurate representations of neuroanatomy (19.4%). The remaining 283 drawings were coded as inaccurate. Further coding of inaccurate drawings revealed a variety of student ideas. Using emergent coding, we identified seven common errors made by students, many of which related to the synapse (Figs. 2 and 3).

The most prevalent error we observed was "touching" (the first neuron depicted as physically touching the second neuron, Fig. 2). This error was observed in 21% of drawings, either in isolation (8.5% of all drawings) or in conjunction with other errors (12.5% of all drawings).

The second most common error was "no direction/no signal"; these drawings did not include an arrow or other mechanism to represent signal movement. We observed this error in 12.5% of drawings. This category was not explored further because any ideas about synaptic transmission students may have had were obscured by the missing indication of direction.

The five remaining error types (i.e., dendrite-dendrite connections, bidirectional signals, one neuron, axon terminal-axon terminal, and side-by-side connections) were observed at low levels (e.g., <10%) in student-generated drawings.

Before instruction, students depict neuroanatomy more accurately than neurophysiology. In response to *drawing task 2*, which occurred after formal instruction on neuroanatomy, but before formal instruction on neurophysiology, most students were unable to accurately depict summation. More than 95% of students incorrectly depicted summation (Table 4), through failing to clearly show signal movement and/or drawing only one neuron (see student drawing in Fig. 4*B*).

As depicted in Table 4, 20% of students were able to create accurate responses to *drawing task 1* (neuroanatomy), and only 4% were able to create accurate responses to *drawing task 2* (neurophysiology). Students were significantly better at depict-

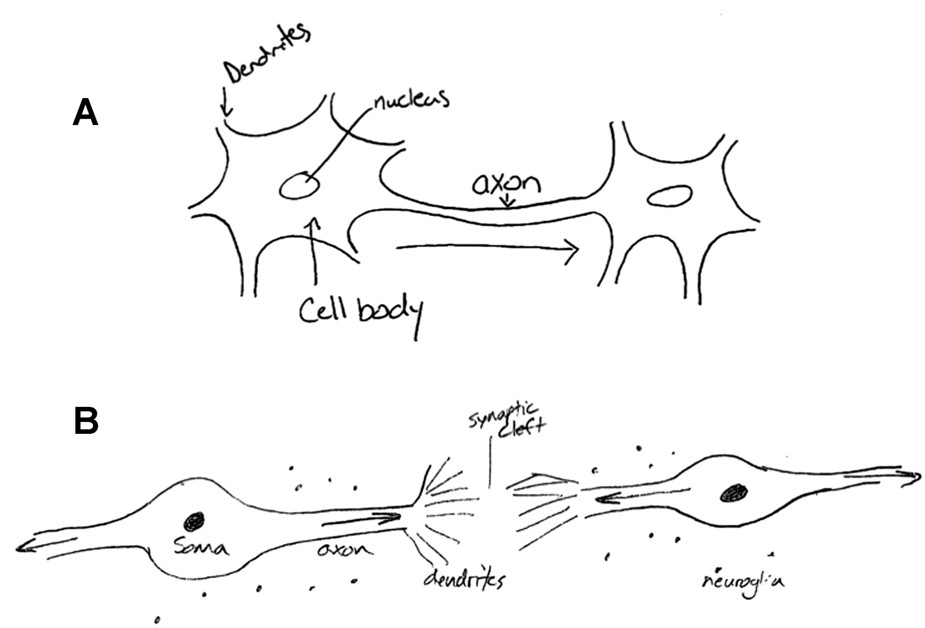

Fig. 3. Examples of errors observed in *drawing task 1*. *A*: an example of a drawing coded as "touching." *B*: an example of a drawing coded as "dendrite-dendrite" and "bidirectional."

Table 4. *Proportion of students creating accurate drawings in response to drawing tasks 1 and 2*

Accuracy	*Drawing 1*, Structure (Preinstruction)	*Drawing 2*, Structure (Postinstruction)	*Drawing 2*, Function (Preinstruction)
Accurate	20.3 (53)	87.7 (229)	3.8 (10)
Inaccurate	79.7 (208)	12.3 (32)	96.2 (251)

Values are in % [with no. of students (n), in parentheses]; n = 261 total, which only includes students who completed both drawing tasks.

ing neuroanatomy before instruction (*drawing 1*) than they were at depicting neurophysiology before instruction (*drawing 2*; $X^2 = 31.84$, degrees of freedom = 1, $P < 0.001$; Table 4).

Instruction improves student depiction of neuron anatomy. When comparing structural accuracy from *drawing task 1* to *drawing task 2*, student depiction of neuroanatomy significantly improved after receiving instruction ($X^2 = 170.14$, degrees of freedom = 1, $P < 0.001$; Tables 4 and 5). Errors in *drawing task 2* were minimal and did not deviate from those observed in *drawing task 1* (*i.e.*, "touching," "dendrite-dendrite," etc.; Fig. 4).

DISCUSSION

We collected over 600 student-generated drawings from an undergraduate HA&P course to explore students' prior knowledge about neuroanatomy and physiology. Analyses of these drawings revealed *1*) before instruction, students have many different conceptions of neuroanatomy and neurophysiology; *2*) student depiction of neuroanatomy improved after instruction; *3*) students' preinstruction ideas of neuroanatomy are more accurate than neurophysiology; and *4*) drawing can serve as an informative formative assessment in undergraduate HA&P.

Students' prior knowledge is diverse. Student ideas about neuroanatomy and physiology, as depicted in their drawings, were highly variable. To our knowledge, most of these ideas (e.g., touching, dendrite-dendrite) are not yet documented in the HA&P literature. In addition, student drawings showed evidence of inconsistent ideas, often containing both correct and incorrect pieces of information within a single drawing. For example, in response to *drawing task 1*, 21% of students depicted two neurons in a linear pathway that were directly touching across the synapse (see Fig. 2; 21% includes all drawings containing the "touching" error). In these drawings, the neurons were oriented correctly but are drawn such that there is direct contact between the pre- and postsynaptic neuron. Another common theme we observed was the "dendrite-dendrite" depiction (Fig. 3). In these drawings, students did depict a synaptic cleft, but the neurons were not oriented correctly. These drawings are evidence that student ideas are not simply right or wrong. Rather, our data suggest that novice learners simultaneously possess both accurate and inaccurate ideas about neuroanatomy and neurophysiology.

Student responses to *drawing task 2* (the summation task) showed significant improvement in neuron anatomy and revealed a substantial lack of knowledge of neuron physiology (Table 4). Most students seemed to recreate pieces of their response to *drawing task 1*, perhaps indicating they had no intuitions or prior knowledge to inform their drawing of neuron physiology. This observation may reflect the dynamic nature of a physiology concept like summation: it is difficult to observe the additive effects of multiple stimuli. Using Ausubel's Meaningful Learning Framework (4), if students lack prior knowledge about neurophysiology, they could experience added difficulty when learning about summation, because students have little to which to connect this new concept. Although students may have some familiarity with the concept of summation through math and may draw on this idea when creating drawings in response to *task 2*, our drawing tasks asked students to transfer this idea of summation to both a new content domain and into a visual representation (vs. numerical). Research has demonstrated how difficult transfer is (5, 6), and we posit that students in A&P may struggle to transfer ideas about mathematical summation to neurophysiology. As a result, students may resort to memorizing, which is a difficult task, prone to inaccuracies, that can impede meaningful learning. If instructors are made aware of this absence of prior knowledge, instruction can use a scaffolding approach that explicitly links what knowledge students do have with the physiological foundations of summation. By deliberately revealing and connecting information absent from student constructs, instruction will favor meaningful learning, as opposed to memorization.

Possible origins of student ideas. Students were able to depict a number of ideas about neural communication before formal instruction on the nervous system (Fig. 2). Most of these ideas were incorrect, but they do suggest students had some knowledge of neuron structure and physiology. Where would students have gained this knowledge? Neurons are not like skin, bones, or muscle, structures students experience and observe in their everyday lives. Students can touch their own skin, for example, and could easily form ideas about the skin before receiving formal instruction. By extension, drawing tasks asking about the differences between thick and thin skin could tap into a substantial degree of prior knowledge gained informally throughout students' everyday experiences. However, the nervous system may be much more abstract to students: students cannot rely on direct observation, and, by extension, they cannot rely on everyday experiences with the nervous system to reason about the anatomy or physiology.

As we wonder how student ideas about neuron anatomy and physiology develop, two ideas emerge. First, students may gain some ideas through textbook readings. However, given the propensity of errors in student drawings before classroom instruction, it seems likely that students are either not reading the textbook, or are reading it in a very cursory manner such that they retain little of what they read. A second possibility is that students implicitly apply knowledge about other physical phenomena to explain events in a different context: in this case, how neurons communicate with one another.

Students may use experiential knowledge to frame their thinking about the flow of neurotransmitters. For example, students may tap into common examples of flow, such as water moving through pipes or electricity moving along a wire. If students are using these experiences to guide their thinking about neurotransmitters, their reasoning could mandate that, in order for a signal, or neurotransmitter, to move from one neuron to the next, neurons need to touch, even in a chemical synapse. This way of thinking (applying preexisting pieces of intuitive knowledge to new contexts) has been observed and

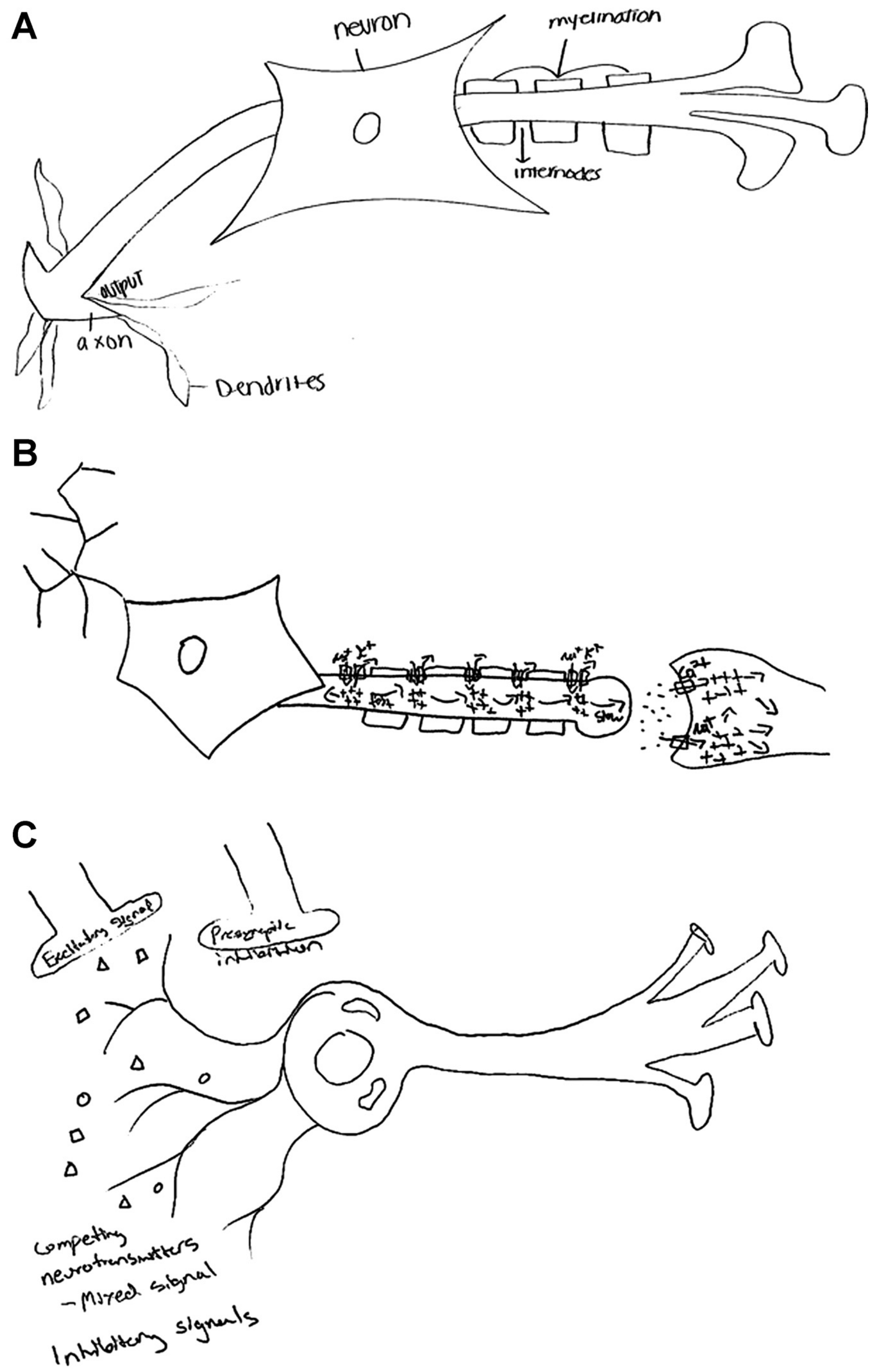

Fig. 4. Examples of student drawings in response to *drawing task 2*. *A*: an example of a drawing coded as structurally inaccurate. *B*: an example of a drawing coded as functionally inaccurate. While this drawing does contain accurate pieces of information regarding synaptic transmission, it does not depict spatial or temporal summation. *C*: an example of a drawing coded as functionally accurate.

well studied in physics education literature through the lens of phenomenological primitives or "p-prims" (11–13). It is possible that p-prims may be driving some of the ideas students include in their drawings. By extension, p-prims may contribute to a broad range of difficulties students experience in HA&P. Identifying possible p-prims or experiential resources students use to reason in HA&P is a critical step toward developing effective curriculum.

The importance of revealing prior knowledge. The results of our drawing tasks demonstrate that students have some preexisting ideas of neuron structure and function. However, students' drawings of neuroanatomy and neurophysiology suggest that many think neurons must touch to propagate a signal. By uncovering this way of thinking, instructors can create instruction that aligns with Ausubel's Meaningful Learning Theory. Instructors can explicitly address the idea of neurons "touching," while simultaneously teaching accurate neuron anatomy and physiology. As a result, the accurate components of a student's preexisting idea can be connected to new information. By grounding this new information in their cognitive structure, students will be more likely to develop a deeper understanding of neuron anatomy and physiology (3, 4).

In other disciplines, instructors can look to validated concept inventories to expose and quantify student's prior knowledge. Concept inventories are a tool that can both evaluate the depth of knowledge an individual has regarding a specific topic or

Table 5. *Proportion of students creating accurate drawings in response to drawing task 1 and the structure portion of drawing task 2*

	Drawing 2 (Structure) Accurate	*Drawing 2* (Structure) Inaccurate
Drawing 1 accurate	19.5 (51)	0.8 (2)
Drawing 1 inaccurate	68.2 (178)	11.5 (30)

Values are in % [with no. of students (n), in parentheses]; n = 261 total, which only includes students who completed both drawing tasks.

discipline and identify alternative conceptions. The Osmosis and Diffusion Conceptual Assessment (ODCA), for example, is one such tool (14). The ODCA is an 18-item multiple-choice assessment designed to evaluate a student's understanding of osmosis and diffusion, while also revealing alternative conceptions. Unfortunately, there are very few tools like this available for use in HA&P, in part because we have limited evidence of student understanding of specific HA&P concepts. Thus tasks that require students to construct responses are exceptionally useful to elicit student thinking in HA&P and represent a necessary first step toward developing more validated and reliable assessments like concept inventories.

Implications. Undergraduate science curricula rarely ask students to communicate their content understanding through pictorial representation (42). However, student-generated drawings can be a useful tool to elicit student thinking while also giving students practice at communicating scientific ideas (2, 18). Drawing tasks require students to identify relevant pieces of information and then construct a mental model to satisfy the task at hand. That mental model is materialized through a drawing, providing the instructor with a constructed response that directly reflects student thinking (31, 42).

In this study, we used student-generated drawings as informal, formative assessments in an introductory HA&P classroom. Our analysis suggests incoming introductory HA&P students struggle to comprehend the structural characteristics of synapses, and we advocate that instructors use this information to modify their instruction of neuroanatomy and neurophysiology. We suggest HA&P instructors incorporate instructional tools, activities, or assessments that draw student attention to the presence and utility of a synaptic cleft in neuron signaling.

Student drawings of neuroanatomy and neurophysiology were diverse and, taken as a whole, emphasized how varied student thinking is in HA&P. Because of this variation, we advocate for assessing student thinking before instruction. Once an instructor is aware of his or her students' preexisting ideas, he or she can adapt instruction to better support student understanding of HA&P. Furthermore, had we assessed student thinking through a multiple-choice item, it is unlikely that we would have had the foresight to include ideas like "dendrite-dendrite" and "no direction" as distractors. Therefore, we urge instructors to utilize multiple assessment formats when gathering evidence of student thinking. The work presented here supports the use of student-generated drawings as one effective option for preinstruction assessment.

In some cases, drawings can be assessed rather quickly, making them useful in high enrollment classrooms. In this instance, we used student-generated drawings as informal, formative assessments in a large introductory HA&P classroom. Although drawing tasks were not part of summative assessments, they still provided invaluable information to the instructional team. The GTA and course instructor reviewed drawings immediately following collection. Through this review process, the instructional team identified a propensity for students to draw neurons as connected (touching) and modified instruction for the next lecture to specifically address this idea. Formative assessment opportunities, like the drawing tasks used in this study, provide a tool to engage students in active reflection on what they know and can communicate in their drawing, and conversely, what they do not know. However, because drawings are an open-response assessment, instructors need be sure the task is focused and narrowly defined. Our tasks were highly specific, and, as a result, we were able to code student drawings for their ideas about synaptic transmission.

More students were able to accurately communicate neuroanatomy after receiving formal instruction. During class, students listened as the instructor explained course material and watched as the GTA (author TS) constructed diagrams (see Supplemental Fig. S1). Students were encouraged to recreate these diagrams in their own notes, but they were not required to complete any drawings for formative assessment credit. Our work, in concert with emerging literature on the utility of drawing (2, 30, 31), underscores the potential of drawings to promote student learning in HA&P.

Limitations. We recognize that several factors limit the claims we can make. First, it is possible that students in this study gained their knowledge about neuron anatomy and physiology from textbook readings. However, the drawing tasks were designed so students had to create images not found in the textbook. At a minimum, students had to synthesize textbook ideas to create novel representations. Given that there were no reading checks built into the curriculum, it is unclear if the accurate drawings were a product of reading the assigned text or an experience occurring elsewhere, perhaps a high school biology course. Future studies could incorporate reading quizzes into the curriculum or probe student knowledge at the start of the semester rather than the start of a unit.

Second, it is possible that students felt impeded by their drawing skills, and, as a result, their drawings might not truly reflect their understanding of the content being assessed. However, we would argue that, if prompts are focused, some basic ideas or ways of thinking would still emerge from students' drawings. Our study consisted of more than 600 drawings, and, while drawings rarely contained an expert-like depiction (Fig. 3), very few were not codable, and ideas about student neuroanatomy and synaptic transmission still emerged from their drawings. Our evidence supports the claim that even poor drawings provide new and meaningful insight into student thinking.

Conclusions. The results of this research extend prior research on student understanding of HA&P to the introductory classroom. The variation we observed in student-generated drawings confirm that *1*) students enter HA&P classrooms with preexisting ideas about neuroanatomy and physiology; and *2*) these ideas vary tremendously across individuals. In addition, our study is one of the first to systematically document novice learner ideas of neuroanatomy and physiology. Our research extends the work of Hay et al. (16) to the introductory HA&P classroom and provides a baseline of student ideas about neuroanatomy and physiology.

Student generated drawings provide new insight into student ideas and reasoning about neuroanatomy and neurophysiology. To our knowledge, this research represents one of the first studies to explicitly characterize student ideas about neuroanatomy and physiology before instruction. As such, these results are informative to both instruction and subsequent research. In addition, we recommend development of instruction that integrates drawing into formative and summative assessment practices and in-class learning activities. To improve HA&P instruction at a national scale, we suggest additional research that characterizes student ideas about other HA&P concepts using student-generated drawings. The perspectives gained by this research will more authentically reflect student ideas and will support evidence-based instructional practices that foster student learning in introductory HA&P classrooms.

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AUTHOR CONTRIBUTIONS

T.N.S. conceived and designed research; T.N.S. performed experiments; T.N.S., J.M., and L.M. analyzed data; T.N.S., J.M., and L.M. interpreted results of experiments; T.N.S. prepared figures; T.N.S. drafted manuscript; T.N.S., J.M., and L.M. edited and revised manuscript; T.N.S., J.M., and L.M. approved final version of manuscript.

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