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## Investigating high school students' conceptualizations of the biological basis of learning

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**Fulop RM, Tanner KD.** Investigating high school students' conceptualizations of the biological basis of learning. *Adv Physiol Educ* 36: 131–142, 2012; doi:10.1152/advan.00093.2011.—Students go to school to learn. How much, however, do students understand about the biological basis of this everyday process? Blackwell et al. (1) demonstrated a correlation between education about learning and academic achievement. Yet there are few studies investigating high school students' conceptions of learning. In this mixed-methods research study, written assessments were administered to 339 high school students in an urban school district after they completed their required biology education, and videotaped interviews were conducted with 15 students. The results indicated that the majority of students know little about the biological basis of learning, even with prompting, and they recall having learned little about it in school. Students appear to believe that people control their own ability to learn, and some have developed personal hypotheses to describe the learning process. On written assessments, 75% of participants demonstrated a nonbiological framework for learning, and, during interviews, 67% of participants revealed misconceptions about the biological basis of learning. Sample quotes of these interviews are included in this report, and the implications of these findings are discussed.

assessment; misconceptions; science education; neuroscience

CHILDREN in the United States (U.S.) typically spend >80,000 h in school during the first two decades of their lives with one main purpose: to learn. Scientists have ample evidence that the brain is the organ responsible for this learning, but how much do young students understand about the brain's role in learning? Is it even important that they understand basic information about how the brain works? Research evidence suggests that teaching students to understand the biological basis of learning may indeed help them succeed in academic pursuits. Blackwell et al. (1) conducted a two-part study investigating middle school students' conceptions about intellectual agency, that is, the ability to change one's intellectual capabilities. They found that students' personal theories about intelligence impacted their academic performance and that such conceptions could be changed with education. Students who held an incremental theory of intelligence, a belief that intelligence is malleable with experience and instruction, did better in school than those students who held an entity theory of intelligence, a belief that intelligence is fixed. Furthermore, students who held an entity theory of intelligence who then learned about the biological basis of learning and brain plasticity improved their academic standing.

Although many biological conceptions have been well studied in children of various ages (4, 5, 10, 22), few studies have focused on the conceptions of high school-aged students with respect to the biological basis of learning. One notable exception is a study conducted by Herculano-Houzel (11), in which the author identified a series of alternative conceptions held by the public about neuroscience. Herculano-Houzel collected data from a written survey at the close of the "Decade of the Brain" of over 2,000 Brazilian high school and college students and college graduates. However, only 5 of the 95 survey questions in the study pertained specifically to the biological basis of learning. Furthermore, participants' conceptions were probed only through the use of a multiple-choice survey so that, in the words of the author herself, "rather than hearing what individual respondents 'think' about each issue, only their acceptance, rejection, or acknowledgment of lack of information about each statement is available for analysis."

High school students' conceptions about the biological basis of learning merit study for at least two reasons: 1) high school students are most likely to have taken their last formal biology class more recently than any other study population and 2) they are more likely than younger subjects to be able to articulate their conceptions, particularly about the complexities of learning and the brain. According to the U.S. Census Bureau, as of 2008 only 28% of the U.S. population has attained a bachelor's degree, and even fewer have taken a college-level biology class, so most of the general adult population completed their formal biology education in high school. Finally, high school students are more likely to be able to engage in higher-level thinking and to articulate their ideas verbally than younger students would be.

There have been several efforts to bridge the gap between neuroscientists' laboratory benches and students' experiences in school classrooms. Geake and Cooper (7), Goswami (9), and Cameron and Chudler (2), among others, have advocated the use of cognitive neuroscience to enhance education, and numerous texts have attempted to translate neuroscience for the K–16+ classroom (6, 14, 16, 27, 29). They have described advances in neuroscience, suggested teaching strategies, and highlighted topics of interest. However, these authors do not appear to have generally used methods that capture and use students' preconceptions about learning and the brain. One of the more comprehensive works undertaken to explain advances in neuroscience research to the general public is *Understanding the Brain: the Birth of Learning Science* (14). It describes how the brain learns throughout life, the impact of the environment on the learning brain, the biological basis of literacy and numeracy, the ethics of educational neuroscience, and neuro-myths such as "I'm a 'left-brain,' she's a 'right-brain' person" (14). Even in this wide-ranging report, the authors do not

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provide statistical evidence of the prevalence of such alternative conceptions among the public, nor do they include evidence about the public's actual conceptions, in their own voices. If biology instructors are to teach their students about the biological basis of learning, they must first understand their students' conceptions, frameworks, and beliefs.

In this study, we examined high school students' conceptions about the biological basis of learning, which we share in their own words directly with science educators. We studied high school students' conceptions about the biological basis of learning because of 1) the recent advances in research into the biological basis of learning, 2) the attempts to communicate these findings to the public, and 3) the role that a biological understanding of learning appears to play in students' academic success. This study also has the potential to inform undergraduate educators of entering freshmen on their perceptions of the mechanisms of learning. To gain insight, the present study focused on these two central questions: 1) after their mandatory biology education, how do high school students conceptualize learning? and 2) to what extent do high school students have a biological framework for conceptualizing learning? The design of our study included a mixed-methods research approach including multiple-choice and open-ended written assessments as well as videotaped, one-on-one interviews.

## METHODS

Using a mixed-methods research design to investigate the prevalence of high school students' ideas about the biological basis of learning, we recruited study participants through a stratified random sampling process. To assess ideas about learning and the brain from among a large population of urban students, we collected written assessment data. We then conducted individual interviews with a subset of students drawn from this larger population to more deeply probe the details of how individual students think about learning and the brain.

### *Recruitment for Written Assessments*

We recruited high school students in a large, urban school district. Chemistry classes were targeted so as to reach high school students after they had completed their mandatory year of biology and to capture students' postsecondary biological knowledge. Of the 110 chemistry class periods taught within the district, we selected 15 class periods at random. This study included 339 (8%) of the district's 4,500 high school juniors (chemistry is typically taken during the junior year in this district). The chemistry classes that were randomly selected for the study were taught by 10 different teachers at 7 schools, and class sizes ranged from 20 to 31 students/class. We raffled off two to three office supply gift cards per class for students who participated in the written assessment. Only 1% of the high school students opted out of the study.

### *Administration of Written Assessments*

The written assessment included 1) a multiple-choice assessment with 19 yes/no/don't know assessment prompts (shown in APPENDIX A) and 2) an open-ended assessment consisting of two assessment prompts. All assessment prompts were piloted and refined with high school-aged students who were not participants in the study. Written assessments were conducted at the beginning of each chemistry class period as a warm-up exercise (21) and took 20–25 min. A brief six-question demographic survey was distributed after the written assessments were completed. This survey documented students' prior

experiences in biology as well as their grade level, age, sex, and ethnicity (shown in APPENDIX B).

The following eight multiple-choice assessment prompts were selected from the literature based on their relevance to the biological basis of learning, memory, or intelligence:

- Memory is stored in the brain much like in a computer, that is, each remembrance goes in a tiny piece of the brain.
- To learn how to do something, it is necessary to pay attention to it.
- Memory is stored in a net of many cells scattered throughout the brain.
- Learning is due to the addition of new cells to the brain.
- Communication between different parts of the brain happens through electrical impulses and chemical substances.
- The mind is a product of the working of the brain.
- Any brain region can perform any function.
- All our actions are conscious and decided consciously.

The next eight multiple-choice assessment prompts were modified from the literature for a high school reading level (11):

- Learning is due to changes in the brain.
- Connections between cells in your brain change when you learn something.
- It is with the brain that we learn.
- It is with the heart that we learn.
- Knowing about the brain can help you understand how you learn.
- Normal development involves the birth and death of brain cells.
- The bigger your brain, the more intelligent you are.
- Intelligence is something you inherit from your parents and cannot be changed by your experiences.

The following three additional multiple-choice assessment prompts were developed by the authors:

- I am a student in the (name of) school district.
- I think it is important to know how my brain works.
- The brain can change itself.

Eleven of the sixteen multiple-choice assessment prompts that were taken or adapted from the literature had been previously demonstrated to elicit agreement on the most appropriate answer by >90% of neuroscientists surveyed.

On the open-ended written assessment, the prompt "Changes happen inside of you when you learn something" was designed to reveal the extent to which high school students possessed a biological framework for conceptualizing learning without prompting. While it allowed high school students to bring their own frameworks to bear, the prompt "What changes, if any, happen inside your brain when you learn something?" was designed specifically to elicit responses of a biological nature. The multiple-choice assessment was administered first, followed by each of the open-ended assessment prompts, in the order described above.

### *Recruitment for Interviews*

High school students were invited to participate in the interviews directly after the administration of the written assessment, and 90 students volunteered to participate. We attempted to schedule interviews with all of these volunteers; however, due to scheduling conflicts and concerns from parents and students about being videotaped along with the sensitivity of the topic, 15 high school students completed the interview. The interview subjects represented nine chemistry classes from six schools. Interviews were one on one, semistructured, videotaped, conducted after school, and lasted 40–50 min. All participants were compensated with a school supply gift card.

### Administration of Interviews

Although psychologists have used videotaped interview methods for many years, this technique is somewhat novel in biology education research (26). Such interviews can be time consuming, costly, non-random, and nonanonymous compared with written assessments. However, they provide the best means possible to deeply probe participants' conceptions and to portray those conceptions accurately in participants' own words. The interview protocol (Table 1) was developed through two rounds of pilot testing to establish face validity of the questions. To put the high school student participants at ease and encourage them to think about how they use their brains during learning, the interview began with a brainteaser, an oblong toy with two balls inside. Participants had to figure out how to move the two balls to opposite sides simultaneously. Three hint cards were revealed in succession and were increasingly more obvious in moving subjects toward the solution, which required spinning the toy like a top. Thirteen followup interview questions were designed to elicit participants' conceptions about the biological basis of learning and connections to the classroom. Three of the questions were taken directly from the written assessment.

### Data Analysis

All written responses were assigned codes to protect anonymity and were scored blind with respect to sex, race, chemistry class, and school.

Systematic, post hoc quantitative analysis was performed on each multiple-choice assessment question to determine the prevalent themes.

Analysis of the open-ended written assessments included three analyses, as described below:

1. In the first analysis, we counted the number of times that participants used "mind" and "brain" in their responses so that we could quantify the extent to which they included biological language related to the brain and the nervous system.

2. In the second analysis, we developed a conceptual rubric to characterize the extent to which participants' responses were biologically based (e.g., nonbiological, minimally biological, or primarily biological; see Table 2).

3. In the third analysis, we developed a second, multidimensional conceptual rubric to more specifically measure the nature of participants' biologically oriented explanations for learning (see Table 3).

Both the second and third analyses described above were rescored with a second observer to develop interrater reliability (IRR). To calculate IRR for each of these analyses, a randomly selected 5% of the responses were scored by two observers using a conceptual rubric. Cohen's  $\kappa$  coefficient, a statistical measure of IRR, was calculated. In cases where IRR was low, the observers discussed and refined the rubric.

For the videotaped interviews, students were assigned pseudonyms, and transcripts of the videotapes were developed and coded. Interview data analysis was guided by qualitative grounded theory. Grounded theory is the analysis of qualitative data such as transcripts, written reflections, or interviews to look for emergent themes and code the qualitative data according to these themes (8). Emergent themes were identified, and transcripts were systematically analyzed. Finally, interview transcripts were scored using the conceptual rubric described above to characterize the extent to which participants' responses were biologically based (e.g., nonbiological, minimally biological, or primarily biological).

This study was reviewed and approved by both the Committee for the Protection of Human Subjects of the Institutional Review Board of San Francisco State University (approval no. H7-049) and the Research Office of the San Francisco Unified School District.

## RESULTS

### Study Population

Eight percent (339 students) of the school district's 4,237 high school juniors participated in the written assessments. The participation rate was 99% (339 of 348 students) for the written assessments and 4% (15 of 339 students) for the videotaped interviews. All of the participants indicated on their demographic surveys that they had completed their mandatory year of high school biology.

The design of the present study is a model that could be replicated with other populations, in other geographical areas.

Table 1. *The interview protocol*

Interview Protocol
<i>Brainteaser</i>
Show the brainteaser: "Have you seen this before?"
1. What ideas do you have about how to get the two balls to opposite ends at the same time?
Instruct the participant to view the hint cards, one at a time.
<i>Reflection</i>
2. Do you think you have learned this well enough to be able to show it to . . . your family tonight? your friends next week at school? a teacher next year? friends in college?
3. What exactly do you think you've just learned?
4. What changes do you think have taken place inside of you, if any, as a result of learning how to solve this puzzle?
5. What would you say to someone who told you that learning is a result of changes in the brain?
6. What changes do you think have taken place inside your brain from learning this puzzle?
7. Do you think learning is a physical process that involves molecules moving around somehow? Why do you think that?
8. Do you think learning involves . . . changes in connections between cells or neurons? the addition of new cells or neurons? Please explain your answer.
9. What would you say to someone who told you that your brain is always changing?
10. Where did you learn about the things we've been talking about? How much of what you know about learning and the brain came from your high school biology class?
<i>Teaching and Learning</i>
11. What would you say to someone who told you that your ability to learn is something you inherit from your parents and cannot be changed by your experiences?
Rephrase: How much control do you think you have over your ability to learn?
12. Do you think knowing about your brain and nerves can help you in school?

Table 2. *Conceptual rubric used to score responses of high school students to the prompt "Changes happen inside of you when you learn something" along with descriptions and sample quotes from each category*

Category	Description	Sample Quote(s)
Primarily biological	Mentions neural structures and proposes a biological mechanism for learning	"I believe it's not physical nor emotional but neurological. As we learn new information everyday our brain takes in these information and stores them at a specific site in the brain . . ." (sic)
Minimally biological	Either mentions neural structures or proposes a biological mechanism for learning	"When you learn something there is bound to be some chemical reaction going on inside of you."
Nonbiological	Neither mentions neural structures nor proposes a biological mechanism for learning	"I totally agree because when I learn something, I think about the subject differently than how I used to." "I think you/your body becomes more mature as you learn more and more." "It makes you feel better about yourself." "You correct yourselves. You improve on what you have learned and apply it to situations that you have learned about." (sic) "Physically? No, I don't think when one learns something change happens. Mentally & emotionally? Yes, I think when one learns something change happens . . ." (sic) "Change doesn't literally happen . . . Learning is just an abstract idea."

To that end, an attempt was made to select high school students for participation in the study as randomly as possible. However, due to segregation of the students and resources within the school district, the ethnic composition of the study participants was not reflective of the district as a whole. Seventy-one percent of participants in the written study and 67% of participants in the interviews self-identified as Asian, Pacific Islander, or Filipino compared with 44% district wide, and 20% of participants in the interviews self-identified as White compared with 10% district wide. All other ethnicities were lower than district averages (written assessments: 4% African-American, 7% Latino, 5% White, 3% other; interviews: 6.5% African-American and 6.5% declined to state) (25). Forty-six percent of all study participants were female compared with 48% district wide, 52% were male compared with 52% district wide, and 2% declined to state (25). The average participant age in the written study was 15.5 yr old and in the interviews was 16 yr old. The small sample sizes of participant subgroups prohibited additional demographic analysis.

*Multiple-Choice Written Assessments*

Participants' responses to the 19 multiple-choice written assessment prompts are shown in Table 4. Assessment *prompt 1* was intended to orient students to the response scale. As-

essment *prompts 2–4* revealed students' attitudes about learning and the brain, and assessment *prompts 5–10* revealed alternative conceptions about the biological basis of learning. Assessment *prompts 11–19* pertained to other areas of neuroscience, including communication within the brain, the mind-brain connection, and brain function, development, and size.

As a reminder, multiple-choice assessment *prompts 7–10* and *14–17* were selected from the literature based on their relevance to the biological basis of learning, memory, or intelligence, and assessment *prompts 3–6, 11, 12, 18, and 19* were modified for a high school reading level (11). Thirteen of the sixteen multiple-choice assessment prompts that were taken or modified from the Herculano-Houzel study (11) elicited agreement on the most appropriate answer by >90% of neuroscientists surveyed.

Less than 70% of the student population agreed with neuroscientists on the majority of the multiple-choice assessment prompts. Seven of the thirteen (54%) assessment prompts eliciting 90% agreement from neuroscientists elicited the same responses from <70% of the high school student population. These were assessment *prompts 5–7, 14, and 16–18*.

*Attitudes about learning and the brain.* Responses to multiple-choice assessment *prompts 2–4* revealed that most high school students appeared to have positive attitudes about learn-

Table 3. *Conceptual rubric developed to score responses of high school students to the open-ended written assessment prompt "What changes, if any, happen inside your brain when you learn something?"*

Score	Structures (Level of Neural Structures)	Mechanism (Biological Mechanism for Learning)	Plasticity (Plasticity of the Nervous System)
0	Does not address nervous system structure	Does not address biological mechanisms	Does not address the nervous system as plastic or static
1	Mentions the nervous system or brain	Mentions a macroscopic change in the brain, i.e., that the brain grows or develops more wrinkles	Describes the nervous system as a storage or processing unit, i.e., "the brain changes because the knowledge is filling up the spaces"
2	Mentions neurons, brain cells, synapses, or nerves	Mentions chemical or electrical activity or signals	Describes the nervous system as plastic, i.e., "new associations in your brain allow you to associate certain things with others"
3	Describes the structure of the brain, brain cells, neurons, or nerves	Describes cellular or molecular mechanisms for learning, i.e., the addition of brain cells or more connections between brain cells	Give examples of the plasticity of the nervous system, i.e., "your brain automatically responds to the situation according to past experience. For example, if a baby touches the stove, they learn that it is hot"

Table 4. Responses of high school student participants to the multiple-choice written assessment

Prompt	Yes		No		Don't Know	
	%	n	%	n	%	n
Orientation to the response scale						
1. I am a student in the _____ school district.	100*	337	0	0	0	0
Attitudes about learning and the brain						
2. I think it is important to know how my brain works.	80*	270	7	24	13	42
3. Knowing about the brain can help you understand how you learn.	75*†	254	10	35	13	45
4. Intelligence is something you inherit from your parents and cannot be changed by experience.	5	18	85*†	285	10	32
Alternative conceptions about the biological basis of learning						
5. Learning is due to changes in the brain.	59*†	199	8	28	32	108
6. Connections between cells in your brain change when you learn something.	41†	139	12	40	47*	157
7. Learning is due to the addition of new cells to the brain.	28	94	22†	75	49*	165
8. Memory is stored in the brain much like in a computer, that is, each remembrance goes in a tiny piece of the brain.‡	73*	246	10†	35	17	56
9. To learn how to do something, it is necessary to pay attention to it.‡	86*†	290	10	33	4	12
10. Memory is stored in a net of many cells scattered throughout the brain.‡	45†	150	5	18	49*	165
Additional ideas about neuroscience						
11. It is with the brain that we learn.	83*	279	5	17	12	40
12. It is with the heart that we learn.	33	111	46*	156	21	69
13. The brain can change itself.	33	112	25	85	41*	138
14. Communication between different parts of the brain happens through electrical impulses and chemical substances.	58*†	196	6	21	35	117
15. The mind is a product of the working of the brain.	76*†	257	2	7	21	71
16. Any brain region can perform any function.	18	61	52*†	175	29	98
17. All our actions are conscious and decided consciously.	29	98	46*†	156	24	81
18. Normal development involves the birth and death of brain cells.	52*†	176	10	34	37	125
19. The bigger your brain, the more intelligent you are.	10	33	72*†	241	18	60

*n* = 337 students total. Assessment prompts 7–10 and 14–17 were taken directly from the literature, and assessment prompts 3–6, 11, 12, 18, and 19 were modified from the literature (10). \*Responses to the assessment prompt chosen by the largest number of students. †Responses to assessment prompts with agreement by >90% of neuroscientists surveyed. Less than 70% of the student population agreed with neuroscientists on the responses to the majority of multiple-choice assessment prompts. ‡Responses to these assessment prompts elicited agreement by 50–90% of neuroscientists.

ing and the brain. The responses to *prompt 2* (“I think it is important to know how my brain works”; 80% yes) and to *prompt 3* (“Knowing about the brain can help you understand how you learn”; 75% yes) revealed that, like most neuroscientists, most high school students believed that learning about the biological underpinnings of learning is valuable. The responses to *prompt 4* (“Intelligence is something you inherit from your parents and cannot be changed by your experiences”) revealed that most participants (85% yes) correctly believed that a person can influence his or her own ability to learn and that such an ability is not controlled entirely by one’s genes.

*Conceptions about the biological basis of learning.* A majority (59%) of high school students responded “yes” to *prompt 5* (“Learning is due to changes in the brain”). However, less than half of the high school students (41%) correctly agreed with *prompt 6* (“Connections between cells in your brain change when you learn something”). In fact, more high school students replied “don’t know” (47%) than “yes” (41%). Only 22% of participants correctly replied “no” to *prompt 7* (“Learning is due to the addition of new cells to the brain”). Almost three-quarters (73%) of high school students incorrectly agreed with *prompt 8* (“Memory is stored in the brain much like in a computer, that is, each remembrance goes in a tiny piece of the brain”). However, >86% of high school students correctly agreed with *prompt 9* (“To learn how to do something, it is necessary to pay attention to it”). Finally, almost half (49%) of high school students did not know whether “Memory is stored in a net of many cells scattered throughout the brain,” and fewer than half (45%) correctly agreed with the statement (*prompt 10*).

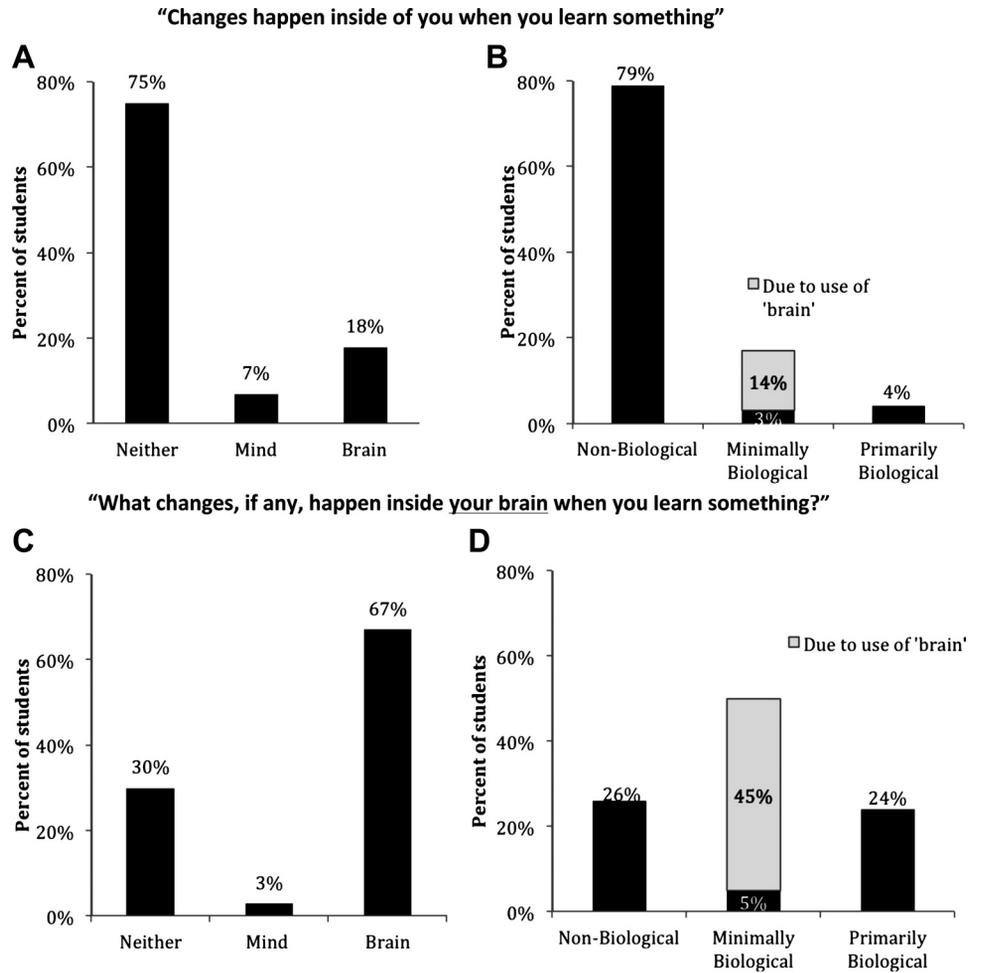
*Additional ideas about neuroscience.* More than 83% of high school students correctly agreed with *prompt 11* (“It is with the brain that we learn”), whereas almost half (46%) correctly disagreed with *prompt 12* (“It is with the heart that we learn”). In response to *prompt 13* (“The brain can change itself”), the largest number of students indicated that they did not know the correct answer (41%). Well over half (58%) of the high school students correctly agreed with *prompt 14* (“Communication between different parts of the brain happens through electrical impulses and chemical substances”), and the majority (76%) also agreed with *prompt 15* (“The mind is a product of the working of the brain”). *Prompt 16* (“Any brain region can perform any function”), *prompt 17* (“All our actions are conscious and decided consciously”), and *prompt 18* (“Normal development involves birth and death of brain cells”) each elicited correct responses from approximately half the high school students (52% no, 46% no, and 52% yes, respectively), and *prompt 19* (“The bigger your brain, the more intelligent you are”) elicited a correct response from the majority (72% no) of high school students.

#### Open-Ended Written Assessments

“Changes happen inside of you when you learn something.” Analysis of how often students used “mind” or “brain” in response to the prompt “Changes happen inside of you when you learn something” revealed that only 25% of high school students used either “brain” or “mind” in their responses and 75% of high school students used neither (Fig. 1A).

Similarly, analysis of responses using the first conceptual rubric revealed that 79% of high school students hold a

Fig. 1. Written responses of high school students to the assessment prompts “Changes happen inside of you when you learn something” (A and B) and “What changes, if any, happen inside your brain when you learn something?” (C and D). Data in A and C were scored by counting the use of the terms “mind” and “brain” to quantify the extent to which students included biological language related to the brain and nervous system. Data in B and D were scored using the conceptual rubric with the categories of nonbiological, minimally biological, and primarily biological to characterize the extent to which participants’ responses were biologically based.  $n = 339$  students.



nonbiological and 22% hold a minimally biological framework for learning. Only 4% of participants appeared to possess a primarily biological framework for learning (Fig. 1B). Cohen’s  $\kappa$  coefficient for calculating IRR with the first conceptual rubric was 1.0 (perfect agreement).

“What changes, if any, happen inside your brain when you learn something?” Analysis of how students used “mind” or “brain” revealed that one-third of high school students (30%) used neither the words “mind” nor “brain” in their response, even though the term “brain” was used in the assessment prompt (Fig. 1C).

Similarly, analysis using the first conceptual rubric revealed that 26% of high school students gave a nonbiological response. Fifty percent of the responses were scored as minimally biological. Of those, 45% were due to the use of the word “brain,” which was included in the prompt (Fig. 1D). While students had been unprompted to think biologically by the assertion “Changes happen inside of you when you learn something,” 4% had responded biologically. However, 24% responded biologically to the prompt “What changes, if any, happen inside your brain when you learn something?” (Fig. 1D).

To investigate the extent to which students showed evidence of understanding the neural structures and mechanisms involved in learning and the role of plasticity in learning, we also scored these responses using the second, multidimensional conceptual rubric. As shown in Fig. 2, at least 10% scored a 2

or above in each category. Cohen’s  $\kappa$  coefficient to rate IRR was 0.93 (almost perfect agreement) for structures and 0.73 (substantial agreement) each for mechanism and plasticity.

Finally, 5% of participants (16 of 337 students) on the open-ended written assessment described personal hypotheses about learning and the brain using similes, metaphors, or other literary devices. We grouped these personal hypotheses into five categories: the brain as a processing unit, the brain as a storage unit, the brain as an organizer, benefits of learning, and difficulties of learning (Table 5).

Interviews

Analysis of the 45-min one-on-one interviews revealed participants’ more deeply rooted ideas including a variety of alternative conceptions about the biological basis of learning. In response to the interview question “What changes do you think have taken place inside of you, if any, as a result of learning how to solve this puzzle?,” 80% (12 of 15) of the high school students’ initial answers were nonbiological (Fig. 3). Seven of the interviewed students who were asked whether they believed that learning was a “physical process that involves molecules moving around” initially disagreed. Instead, they either disagreed with the concept that learning involved any changes in the brain (“... I don’t recall learning about how there’s changes in the brain ...”), they discussed changes in other parts of the body aside from the brain (“For playing

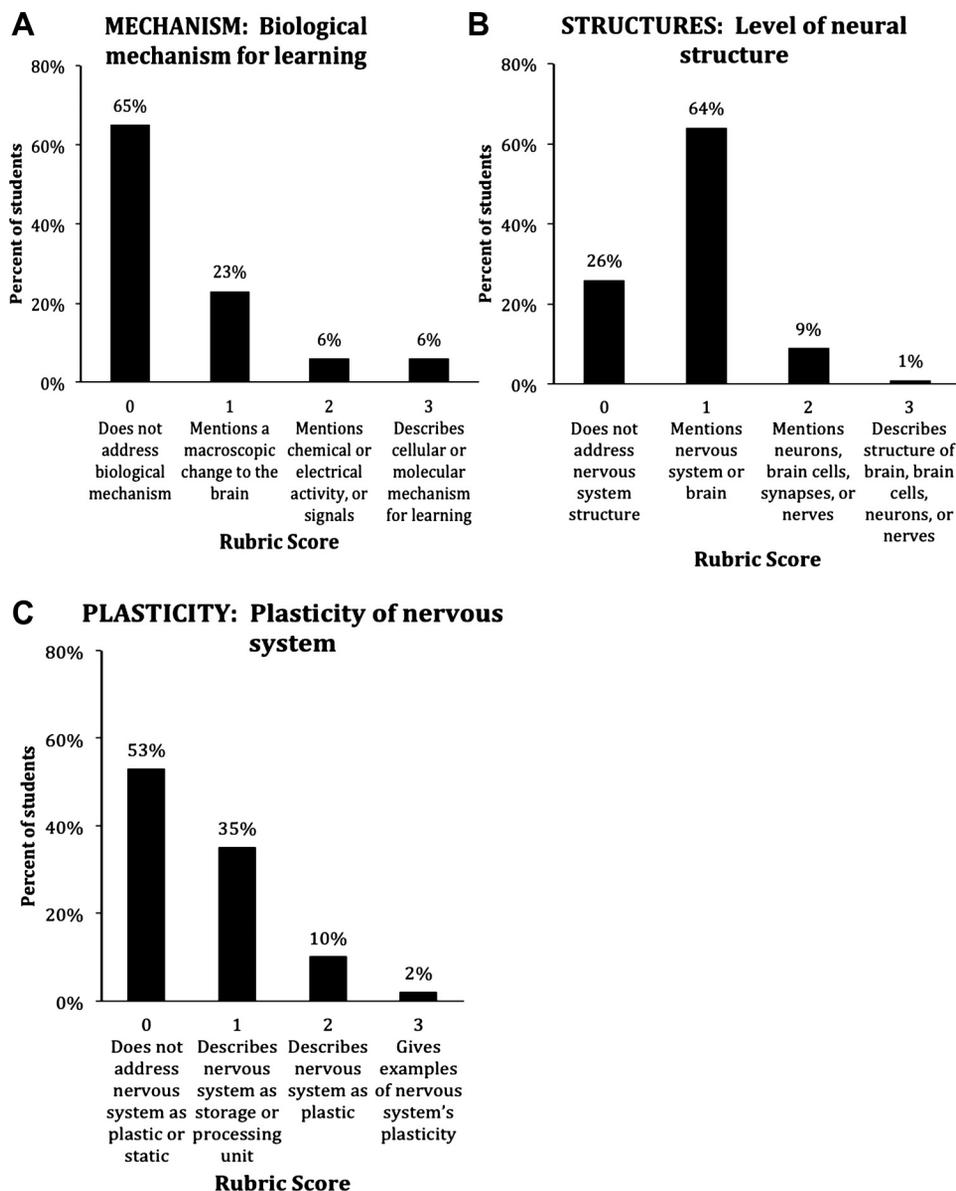


Fig. 2. More than two-thirds of high school students' responses to the open-ended written assessment prompt "What changes, if any, happen inside your brain when you learn something?" scored a 0 or 1 in all three categories of the conceptual rubric.  $n = 339$  students.

violin my fingers might be more in the shape of the flat surface"), or they discussed a "mental" instead of a physical change ("I think learning is more of a mental process, not much physical").

Students revealed a variety of interpretations of the word "physical," which, in some cases, confounded their responses. While two students believed the word "physical" to mean any sort of change on a cellular level or smaller, three others interpreted it as learning how to do tasks involving physical activity (such as swimming) as opposed to learning in such a way that required no movement (such as a math formula). Two students believed it to mean anything that caused an anatomic change (including the development of wrinkles in the brain), and one student believed it described a change in affect (such as a person appearing to be depressed or angry).

Students held the conception that cells were round but nerves were long and, therefore, that one could not be composed of the other. One conception was that cells were "squishy," "circles," or "ovals," whereas nerves were "wires"

or "long and skinny." Sharon reconciled this difference by explaining that cells "act as bricks to a wall" and that together they "make up the walls of the nerves." Alternatively, David explained that "the nerves and cells work together to help the brain." Ten of the fifteen (67%) participants expressed confusion or lack of knowledge about the relationship between cells and nerves and their roles in learning. The remaining five participants simply did not discuss the relationship between nerves and cells (Table 6).

Four of the fifteen interviewed high school students struggled to explain how and why brain cells were rearranged during learning (Table 7). They either believed that new cells were created or entire cells changed location during the learning process. Trevor, for example, hypothesized that when learning the brainteaser, "some neurons rearranged themselves or were created."

During the interviews, discussions of participants' conceptions about the biological basis of learning revealed that they recalled learning very little about the nervous system in high

Table 5. *Personal hypotheses about the biological basis of learning articulated by 5% of high school student (16 of 337) to the open-ended written assessment prompt "What changes, if any, happen inside your brain when you learn something?"*

Descriptive Term	Sample Quote(s)
<i>The brain as a processing unit</i>	
Train track	"Sometimes, when one is trying to understand a participant, your train of thought is incomplete and stops short. When you actually learn something, that is when the train's tracks are all set up and lead to the final destination."
Domino effect	"When you get a new piece of information it affects all other information you already have stored, so anything new affects everything to some degree. It's kind of like a domino effect."
Bridge	"It's like my mind is connecting the pieces of information together with bridges and I attempt to apply the idea to a similar problem."
Puzzle	"[Learning] is almost like putting the whole pieces of [a] puzzle together." "When I learn something, it's like a new piece to the puzzle, and this piece connects to old pieces and opens areas for new pieces."
Computer hard drive	"I believe our brain is like this internal hard drive that has a virus that blocks off some files once in a while. Our brain is like a hard drive that has folders that leads to more folders that opens when we try to relate things."
<i>The brain as a storage unit</i>	
Library	"The thing you learned is inscribed in to the 'library' of your brain . . ."
Vault	"Our brain is like our vault, vault that contains information. If we learn something new, it's like putting another file into the vault . . ."
Snapshot	"I don't know, but maybe what you learn turns into a memory like a snapshot in a picture which stays in your brain."
<i>The brain as an organizer</i>	
Defrag	"My brain gets disorganized, need to file up the new things I've learned. Basically need to defrag my brain, so when I need the next time, won't take a second to think about it, it will just be Boom! on my thoughts and ready to speak." (sic)
<i>Benefits of learning</i>	
Locked door	"I feel that my brain was born with many locked doors and they are waiting for me to unlock them. Every time I learn something, it unlocks a door, so I must keep learning to unlock the rest of them."
Exercise	"I think learning is like exercise for the brain." "The more you learn the stronger your brain because using it is exercising it." "If I learn new stuff it exercises my brain and gets more 'in shape.'"
Vaccination	"[Learning is] like having a vaccination. If brain don't change, that mean you don't understand and you won't improve." (sic)
<i>Difficulties of learning</i>	
Small space	"Sometimes when you try to learn something new and you don't understand it, it feels as if your brain was a jar and someone screwed on the lid too tight and shook it around. Sometimes it feels like someone put a wall around your brain and you can't think clearly. It feels like being trapped in a small room where the window is too small to see anything."

school—and even less about the biological basis of learning. Only seven of the fifteen participants reported spending any time studying the nervous system in high school biology class, and all but one of these responses were similar to Lance's, who said "We kinda covered a little bit [about learning and the brain] at the end of the year last year" and only specifically recalled having learned that drugs destroyed brain cells. The remaining nine interviewed students recalled spending no time studying the nervous system in high school biology class. For example, Tara remarked: "Biology teaches about the body? We didn't learn about the body in biology [class]."

In the interviews, some participants devised personal hypotheses to explain the mechanism of learning, causes of memory loss and disease states, and differences between various types of learning. Such personal hypotheses about the learning process (similes, metaphors, and other descriptive explanations) are shown in Table 8. Links to videos of participants sharing their personal hypotheses are also included in the Supplemental Material.<sup>1</sup> We classified these hypotheses into four categories; the first two were the same as those of the written assessment data set. The four categories were 1) the brain as a processing unit, 2) the brain as a storage unit, 3) the

function of brain cells in learning, and 4) macroscopic brain changes during learning. Data analysis revealed that a higher percentage of participants articulated personal hypotheses during the interviews than on the written assessments (64% and 5%, respectively). The most prevalent was the brain as a storage unit, which was described by almost 20% of the interviewed participants. Participants incorporated elements from what they reported having learned from school, magazines, their families, television shows, movies, and the internet as well as elements from their own imaginations.

Almost all interviewed high school students believed that a person can influence his or her own ability to learn and that such an ability is not controlled entirely by one's genes. All but one student said they would strongly disagree with someone who told them that one's ability to learn is something you inherit from your parents and could not be changed by your experiences. The one student who didn't completely disagree, Xandra, said "I agree and disagree because usually families are inclined to a certain field but also children can be different from their parents."

Some students experienced a cognitive shift during the interview. The interview process seemed to allow participants to rethink their conceptions about learning and the brain. Two students verbalized their awareness of this shift; James, for example, declared "Honestly, I'm reconsidering things I've

Supplemental Material for this article is available at the *Advances in Physiology Education* website.

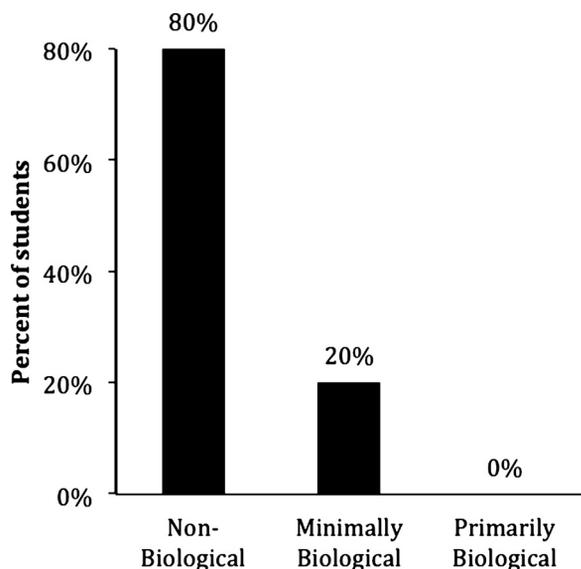


Fig. 3. Eighty percent of interviewed high school student responses to the question “What changes do you think have taken place inside of you, if any, as a result of learning how to solve this puzzle?” were scored as nonbiological on the conceptual rubric.  $n = 15$  students.

said earlier in this interview. Now I’m feeling like learning is due to changes in the brain.”

## DISCUSSION

More than 10 yr after the end of the “Decade of the Brain,” five findings emerged from the present study, indicating that there may be a lack of neuroscience knowledge, but not a lack of interest in the topic, among high school students, the majority of whom have completed their required biology education. Each of these five findings is articulated below.

### Principal Findings

Without prompting, the majority of high school students did not appear to have a biological framework for learning. As indicated by evidence from the open-ended written assessment and interviews, less than one-quarter of the students conceived of learning in biological terms or brought a biological framework to bear on the question of how one changes as a result of learning.

Less than 70% of the student population agreed with neuroscientists’ responses on the majority of multiple-choice assessment prompts. In previous studies, neuroscientists agreed that learning is due to changes in connections between cells the brain (and not to the addition of new cells) and that memory is scattered throughout the brain (and not stored in discrete areas). However, <70% of high school students’ responses to the multiple-choice written assessment prompts indicated agreement with neuroscientists’ answers on each of these topics.

Even with prompting, only a minority of high school students appeared to have specific knowledge about the biological underpinnings of learning. On the multiple-choice written assessment, only a slight majority of high school students indicated that learning is accompanied by changes in the brain. In videotaped interviews, few students indicated that changes due to learning involve the rearrangement of synapses and that

they do not typically involve the addition of new cells. On the open-ended written assessments and during interviews, students appeared to be confused about how cells are rearranged during the learning process; the relationship between cells, nerves, and neurons; and the meaning of related vocabulary words such as “physical” and “mental.”

Few students reported learning much about the nervous system, the brain, or the biological basis of learning in school. The nervous system appears in the Life Science National Science Education Standards (“Behavior of Organisms”); however, only 7 of the 15 interviewed high school students reported having received instruction on the nervous system during their formal schooling, and 6 of these students reported that their instruction was minimal.

Most students indicated that understanding how their brains worked could help them to become better learners, and they attempted to make sense of the learning process by developing their own personal hypotheses about how learning works. On the multiple-choice written assessment and during interviews, students indicated that they held an incremental theory of intelligence, that is, the belief that intelligence was not “fixed” at birth, and they believed that they could influence their own ability to learn. Interviewed students’ personal hypotheses about the learning process included similes (“Brain cells are like pixels”), metaphors (“The thing you learned is inscribed in to the ‘library’ of your brain”), and other descriptions (“Cells give the nerves energy”). Students reported that they developed these hypotheses based on what they saw on television, read on the internet or in books, heard from other people, or made up themselves.

### Further Implications

Implications for increasing the amount and relevance of neuroscience education. Eric Kandel (17) predicted that “the biology of mind will be to the twenty-first century what the biology of the gene was to the twentieth century.” In that case, a baseline level of awareness about scientific advances about neurobiology and the biological basis of learning will be critical for the general public. The findings from Blackwell et al. (1) also indicate that having knowledge about their brains may improve students’ self-confidence and academic performance in all areas of study. Students appear to be ready, willing, and able to learn about their own brains, yet may not be learning about them in school. If students are not learning about the biological basis of learning in biology classes, it is unlikely that they are learning it in other parts of the high school curriculum. In California, teaching students about the learning process itself is not included in the English, mathematics, social studies, or health curricular standards. In the words of James, one of the interviewed high school students, “It’s like . . . a carpenter who doesn’t know what tools he has until his boss teaches him.”

This is not the first study to call on science educators to increase public knowledge of neuroscience (2, 11, 17; E. Chudler, private correspondence), but we propose that educators change the way they teach about neuroscience: that they shift their focus from topics such as action potentials, neural anatomy, and lobes of the brain to topics more directly relevant to students’ personal and academic lives, including the biological basis of learning. Currently, neuroscience is not promi-

Table 6. *During interviews, 67% of high school students (10 of 15) expressed alternative conceptions about the relationship between cells and nerves*

Interviews
<i>Claire</i>
“In your brain and throughout your body there’s nerves and cells. In the brain they have a different purpose. Nerves transmit information from one part of your brain to another. Every time you learn it rewires to connect to the things you’ve learned before . . . The cells give the nerves energy.”
<i>David</i>
“Nerves—are they connected to the brain? I think there is cells in the brain, there is nerves in the brain. Something happens to the nerve, or the brain—like it goes through the nerves, or the other way around—the body affects the nerves which affects the brains . . . I guess the nerves and the cells work together to help the brain.”
<i>Frank</i>
“Physically I don’t think the cells in my brain merge but they’re connected through nerves or just thoughts. You take one memory from one cell and put another memory from another cell and put them together in a third cell.”
<i>Harry</i>
“Cells make up nerves? I think cells make up tissue and then it goes up and then organ, system, and stuff.”
<i>John</i>
“I learned molecules bounce around and cause pressure, so maybe the electrons are causing pressing. Electron clouds. What are they called—neurons—something like the signals? I’m not sure . . . I watched a video. Something about how the brain works . . . it sends signals. They had a diagram of electrons bouncing in between. I remember the picture but not the words.”
<i>Lance</i>
Interviewer: “How many [nerve] cells connect our fingertip to our brain?” Lance: “Since cells are kind of small, I guess—one billion? They’re probably connected side to side, one following another one.”
<i>Sharon</i>
“When I think of nerves I think of . . . a wire connecting parts of our bodies . . . So for nerves it would just be like cells together in a cylinder. So it’s kind of like a brick wall. For the walls of the nerves, I think the cells act as bricks to a wall, like they stack up on one another and they make up the walls of the nerves.”
<i>Steven</i>
“The brain sends the message to your cells and then the cell does the work.”
<i>Tara</i>
Interviewer: “Is a nerve a cell?” Tara: “Not a cell . . . I think a bunch of cells.” Interviewer: “What’s the shape of cells?” Tara: “Oval.” Interviewer: “What’s the shape of a nerve?” Tara: “Like a string.” Interviewer: “What’s the relationship between cells and nerves?” Tara: “I think cells are grouped together, like atoms are grouped together to form matter.”
<i>Xandra</i>
“A nerve is made up of billions of cells. Cells are microscopic, so big things in your body are made up of billions of cells.”

nently considered in many K–12 science education programs. In general, there are few neuroscience educational materials available to K–12 educators, and those available curricula tend to emphasize neuroanatomy and basic neural mechanisms, often without connecting neuroscience concepts to real-world phenomena. In addition, these curricula do not appear to address alternative conceptions in neuroscience. For example, the Society for Neuroscience publishes *Brain Facts*, “a primer on the brain and nervous system” designed for the general public (24). While the primer provides basic information in accessible language, the two-page section on “Learning, Memory, and Language” explains learning primarily in the context of language acquisition. To foster conceptual change among students, neuroscience education could be better served by targeting identified misconceptions and develop curricula with this goal in mind.

*Implications for more research into students’ conceptions about neuroscience.* With this study, we have attempted to create a model that could be replicated with other populations to uncover some high school students’ conceptions about the biological basis of learning; however, more research is warranted to generalize this list, that is, to develop a list of widespread misconceptions among the public about this topic. To that end, an attempt was made to select high school students for participation in the study as randomly as possible, and the data on student characteristics were collected primarily to demonstrate that the results came from a diverse high school student population. However, due to segregation of students and resources within the school district, the ethnic composition of study participants was not reflective of the district as a whole. Nonetheless, along with the Herculano-Houzel study (11), we hope that this is among the first of many to reveal students’ voices about the nervous system

Table 7. During interviews, 27% of high school students (4 of 15) expressed alternative conceptions about how and why cells are rearranged during learning

Interviews	
<i>Jennifer</i>	
"I was thinking that branches would be added. So it would still be new cells but then it would just be connected to . . . It would be like from the same branch if it's something you've done a lot, like reading or playing a game of soccer and then you practice a lot and then you do better kicking or dribbling. And then if you try something new then you would have a new branch and then it'll be . . . for different topics the development will be different . . . you'll learn differently."	
<i>Lance</i>	
Interviewer: "Do you think learning involves . . . changes in connections between cells in your brain?"	Lance: "Probably. Probably one cell's data goes to another cell, in some respect."
Interviewer: "If you had to guess, how do you think it would happen?"	Lance: "When it divides. Since it divides it creates a copy of itself, so more and more of itself."
<i>Sharon</i>	
"So I think when I learn something cells in my brain move around like . . . before I learn something they would be clustered together in some way. And then when I learn something they would move around and spread out and then when I would learn something they would move around and be in a different order."	
<i>Trevor</i>	
Interviewer: "What changes do you think have taken place inside your brain from learning this puzzle?"	Trevor: "Some neurons rearranged themselves or were created."
Interviewer: "Were some neurons created just now?"	Trevor: "I guess so, based on what I just said. I don't know how long it takes but I would say fairly quickly."

and, specifically, about the biological basis of learning. In addition to this topic, further research into students' conceptions about other areas of neuroscience (consciousness, sleep, injury, disease, memory, personality, etc.) could reveal a variety of conceptions and misconceptions that could guide neuroscience education for years to come.

Table 8. Personal hypotheses about the biological basis of learning articulated by 60% of participants (9 of 15 students) during interviews

Descriptive Term	Sample Quote
<i>The brain as a processing unit</i>	
Telephone	"The brain is almost like a telephone, if I could put it like that. So if I was to call you and I'm telling you some new information, it somehow has to get through you and usually a telephone you need electricity to make it run, right? So I suppose the brain would need some sort of energy to make all the information go into the brain." (Tara)
<i>The brain as a storage unit</i>	
Computer storage	"I guess sectors like different areas of the brain—just really general—because I don't know how the brain really works so I just use sectors as, for instance, computers or other storage things like USB flash drives or those things that have sectors for storing information." (Frank)
Computer code	"You have a hard drive in your brain and then when you learn something then you just write your data into your hard drive." (Harry)
Photograph	"I think a memory would be like a lot of photos or documents in your brain that aren't really complete . . ." (Jennifer)
<i>The function of brain cells in learning</i>	
Pixel model	"I think, like a picture—it'll have different pixels to capture that image and to expand that image; it depends how much pixels it is. So I guess it's almost like brain cells; it depends how much effort of your brain cells you put into a certain thing in order for you to memorize it or capture it." (Charles)
Cells as food	"I think that the cells in there don't have anything to do with learning. I think that they're there to help feed the nerves what they need to be able to rewire . . ." (Claire)
Light switch	". . . each brain cell is like a like switch or has a light switch and it's connected in different ways, and every time you learn something a light switch is shifted." (James)
Swimming in a pool	"I think when I learn something cells in my brain move around, like before I learn something they would be clustered together in some way and when I learn something then they would move around and spread out and then they would go back to that place but they would be in a different order . . . I guess you can think about, like, a swimming pool . . . objects floating in the water, like tubes. When it's peaceful, or when nothing's happening then they're just all stuck in a corner; they're right against each other. When something happens then they all float away from the spot but then they come back and float side by side but in a different place." (Sharon)
<i>Macroscopic brain changes during learning</i>	
Crumpled newspaper	". . . like in a giant ball of newspaper, but still crumpling . . . I think if we learn something it's just more crumply but as we're turning older, I thought our brain expands so I thought as we're turning older we're just adding more paper but when we learn something we're crumpling it." (David)

Links to videos of participants sharing their personal hypotheses are included in the Supplemental Material.

Table A1. Multiple-choice written assessment with prompts in the order they appeared on the original assessment

Please circle Yes, No, or Don't Know for each of the statements below			
I am a student in (name of) School District.	Yes	No	Don't Know
I think it is important to know how my brain works.	Yes	No	Don't Know
Memory is stored in the brain much like in a computer, that is, each remembrance goes in a tiny piece of the brain.	Yes	No	Don't Know
Learning is due to changes in the brain.	Yes	No	Don't Know
To learn how to do something, it is necessary to pay attention to it.	Yes	No	Don't Know
Memory is stored in a net of many cells scattered throughout the brain.	Yes	No	Don't Know
Learning is due to the addition of new cells to the brain.	Yes	No	Don't Know
Connections between cells in your brain change when you learn something.	Yes	No	Don't Know
Communication between different parts of the brain happens through electrical impulses and chemical substances.	Yes	No	Don't Know
The brain can change itself.	Yes	No	Don't Know
It is with the brain that we learn.	Yes	No	Don't Know
It is with the heart that we learn.	Yes	No	Don't Know
The mind is a product of the working of the brain.	Yes	No	Don't Know
Knowing about the brain can help you understand how you learn.	Yes	No	Don't Know
Any brain region can perform any function.	Yes	No	Don't Know
All our actions are conscious and decided consciously.	Yes	No	Don't Know
Normal development involves birth and death of brain cells.	Yes	No	Don't Know
The bigger your brain, the more intelligent you are.	Yes	No	Don't Know
Intelligence is something you inherit from your parents and cannot be changed by your experiences.	Yes	No	Don't Know

APPENDIX A: MULTIPLE-CHOICE WRITTEN ASSESSMENT

The table below shows the multiple-choice written assessment with prompts in the order in which they appeared on the original assessment.

APPENDIX B: DEMOGRAPHIC SURVEY

The following demographic survey was administered after the written assessment.

Demographics (Optional)

Please provide the appropriate answer to the following questions.

- Question 1. What is your grade level?
- Question 2. What is your age?
- Question 3. What is your sex?
- Question 4. What is your ethnicity?
- Question 5. When did you take biology?
- Question 6. What letter grade(s) did you receive in biology?

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

R.M.F. and K.D.T. conception and design of research; R.M.F. performed experiments; R.M.F. and K.D.T. analyzed data; R.M.F. and K.D.T. interpreted results of experiments; R.M.F. prepared figures; R.M.F. drafted manuscript; R.M.F. and K.D.T. edited and revised manuscript; R.M.F. and K.D.T. approved final version of manuscript.

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