EVERYTHING YOU AND YOUR TEACHERS NEED TO KNOW ABOUT THE LEARNING BRAIN

EDITED BY: Sabine Peters, Nienke van Atteveldt, Jessica Massonnié and Stephan E. Vogel
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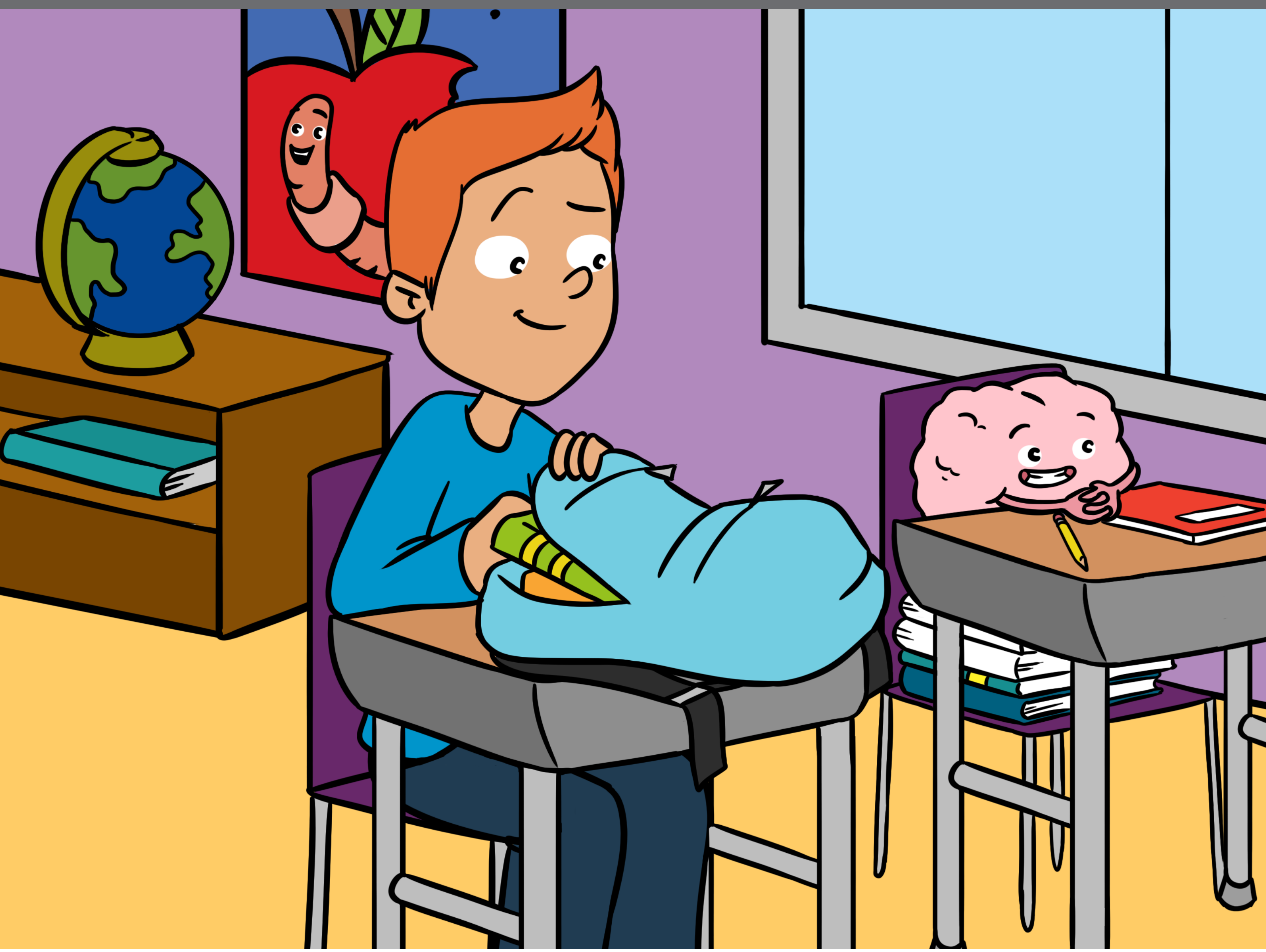

frontiers FOR YOUNG MINDS

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EVERYTHING YOU AND YOUR TEACHERS NEED TO KNOW ABOUT THE LEARNING BRAIN

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Children go to school to learn, and learning takes place in the brain. In the age period of formal schooling, a child's brain is still undergoing major developmental changes. For these reasons, neuroscience (the study of the brain) and education are closely connected. Learning is possible because the brain is plastic: plasticity refers to the capacity of the brain to reorganize its structure and thereby change function and behavior.

But what exactly changes in the brain when we learn something new? What are optimal conditions for the brain to learn? Why do we also forget things? What developmental changes occur in the brain during childhood and adolescence, and how are these processes different or similar to the neural mechanisms of learning and memory?

Neuro-imaging research, or 'brain scanning', has accelerated our current understanding of brain development, learning, memory and other school-related skills such as reading and math but also creativity, metacognition and learning-related emotions and anxieties. But what do these brain scanning techniques actually measure? What kind of questions can we address with neuro-imaging, and what are the limitations?

In this Collection, we will provide an accessible overview of the current state-of-the-art insights into the mechanisms of brain development, learning and memory. The collection will help children understand how their brains learn and develop, and how these processes are shaped by their environment and their own efforts. Moreover, we will discuss why it is important that their teachers and other educational practitioners know about the brain and neuroscience methods. Finally, we will also explain what happens if wrong ideas about the brain circulate, or the correct knowledge is misinterpreted. Neuromyths such as 'we only use 10 percent of our brain' are persistent, but important to counter with explaining why they are false, and what is true instead.

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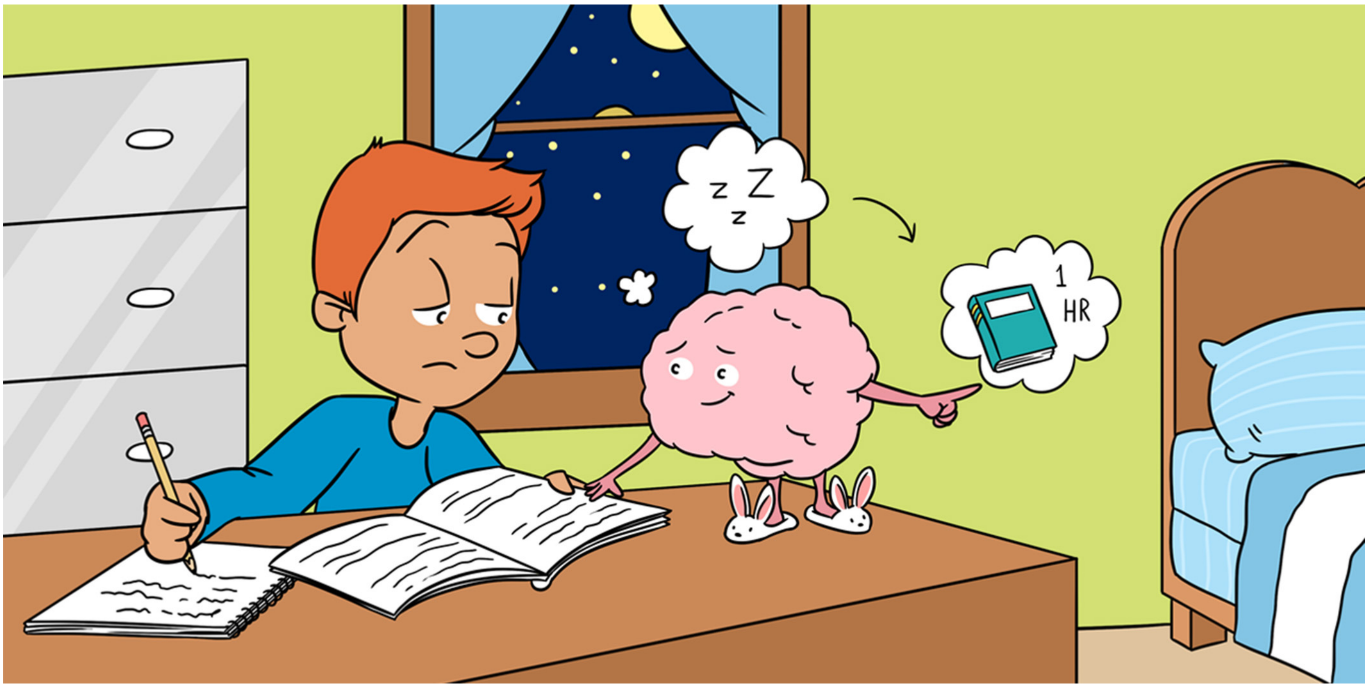

UNDERSTANDING YOUR BRAIN TO HELP YOU LEARN BETTER

Jérémie Blanchette Sarrasin [1,2*], ***Lorie-Marlène Brault Foisy*** [1,2], ***Geneviève Allaire-Duquette*** [3] **and** ***Steve Masson*** [1,2]

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YOUNG REVIEWERS:

DR. H. BAVINCK SCHOOL
AGES: 8–12

LOCARNO HIGH SCHOOL
AGES: 17–18

The past few years have been marked by a large number of discoveries about the learning brain. Those insights have the potential to support teachers in designing even better classroom environments to help you learn better. While understanding the brain can be helpful for teachers, this knowledge can also be beneficial for you as a student. For instance, it can encourage you to believe in your capacity to improve your own skills. Such beliefs make it more likely for you to make an effort and to make better use of supportive learning strategies [1]. In this article, we briefly present some core principles of the learning brain and suggest learning strategies inspired by neuroscience for you to try at school or at home.

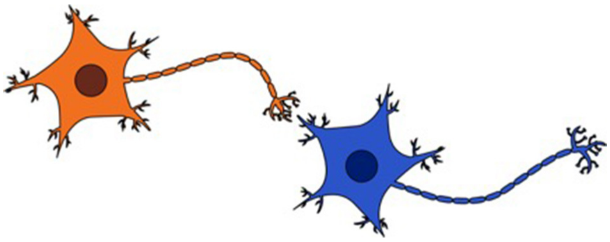

Figure 1

Figure 1

Figure illustrating two neurons that are connected.

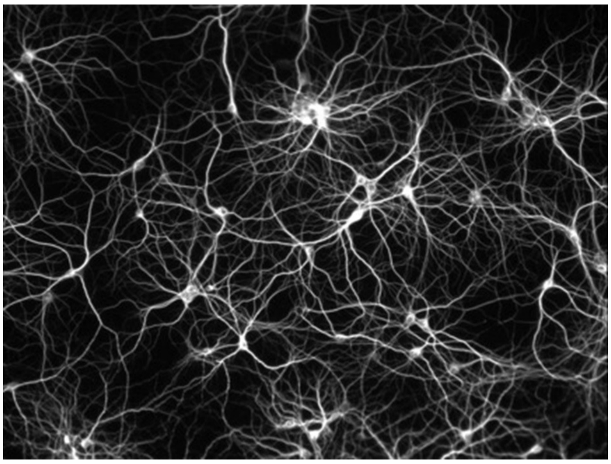

Figure 2

Figure 2

Figure illustrating the very large number of connections between neurons.

WHAT HAPPENS IN MY BRAIN WHEN I AM LEARNING?

Your brain is primarily composed of about 85 billion neurons, which is more than the number of stars you can see with the naked eye in the night sky. A neuron is a cell which acts as a messenger, sending information in the form of nerve impulses (like electrical signals) to other neurons (see Figure 1). For example, when you are writing, some neurons in your brain send the "move fingers" message to other neurons and this message then travels through the nerves (like cables) all the way to your fingers. The electrical signals that are communicated from one neuron to another are therefore what allows you to do everything you do: write, think, see, jump, talk, compute, and so on. Each neuron can be connected with up to 10,000 other neurons, leading to a large number of connections in your brain [2], which looks like a very dense spider web (see Figure 2).

When you are learning, important changes take place in your brain, including the creation of new connections between your neurons. This phenomenon is called **neuroplasticity**. The more you practice, the stronger these connections become. As your connections strengthen, the messages (nerve impulses) are transmitted increasingly faster, making them more efficient [3]. That is how you become better at anything you learn whether it is playing football, reading, drawing, etc. We can compare the connections between your neurons to trails in a

NEUROPLASTICITY

The ability of your brain to change, that is to create, strengthen, weaken or dismantle connections between your neurons.

Figure 3

Figure 3

Figure illustrating the analogy of the trail in the forest.

forest (see Figure 3). Walking through a forest without a trail is difficult, because you have to compact and push the vegetation and branches out of the way to carve your way through. But the more you use the same trail, the easier and more practicable it becomes. Conversely, when you stop using the trail, the vegetation grows back, and the trail slowly disappears. This is very similar to what happens in your brain—when you stop practicing something, the connections between your neurons weaken and can ultimately be dismantled or pruned. That is why it may seem so difficult to start reading again when school starts if you have not read all summer. However, it is possible for some neural networks to become so strong that the trails or connections never completely disappear.

The fact that learning rewires your neurons shows how dynamic (plastic) your brain is—that the brain changes and does not remain fixed. Practicing or rehearsing repeatedly activates your neurons and makes you learn. These changes happen as early as when a baby is in their mother's womb and continues throughout a person's life. So, the question is, how can you help your neurons to create and strengthen their connections? Here, we present two strategies that appear to be more compatible with how your brain works and could help you learn better.

WHICH LEARNING STRATEGIES ARE MORE COMPATIBLE WITH YOUR BRAIN?

Strategy 1: Repeatedly Activating Your Neurons

REPEATEDLY ACTIVATING YOUR NEURONS

Practicing a lot, trying to retrieve information from your memory, for example by explaining a concept to a friend or answering quiz questions.

Because the connections between your neurons need to be activated multiple times to become stronger and more efficient, a first and crucial strategy is to repeatedly activate them. This means that to learn arithmetic tables for instance, you have to practice it repeatedly, to establish the "trail" between your neurons. As a baby, you were not able to speak and walk within 1 day: you practiced a lot. However, it is important to note that only reading or glancing at your arithmetic tables will not be that helpful in connecting your neurons. You might also find it quite disengaging and boring. To create the connections between your neurons, you need to retrieve the arithmetic tables from your memory. In other words, you have to try recall the answer yourself to activate your connections. We are not saying that this is easy to do! However, scientists think that this "struggle" improves learning because the challenge is an indication that you are building new connections. Remember, learning something new is like hiking in a bush with no designated trail, you will probably walk slowly at first, but if you keep hiking, trails will start forming and eventually you will be walking on well-beaten tracks. Besides, when you do try to recall what you have learned and make a mistake, it can help you identify gaps in your learning and give you an indication of which trail still needs to be worked on.

Scientists have also noted that performing tests or exams can help you remember information better than studying alone [4]. For example, if you study your arithmetic tables interspersed with test periods, you will probably perform better on your final test than if you had only studied. Why? The tests require that you retrieve the information from the neurons in which the information is stored, thus activating your connections and contributing to their strengthening. The point is thus to practice retrieval in an engaging way. There are different strategies that you could try at home, for example answering practice questions or using flashcards. These should improve learning more than re-reading or listening to lectures (as long as you do not flip the flashcard over before recalling the answer!). Other strategies include preparing questions to ask to a classmate or a parent as well as redoing tests or exercises. Use your imagination! What you need to remember is that first, for your neurons to strengthen their connections, you need to retrieve the information and avoid just reading or listening to the answer. Second, you should plan a way to get feedback to know whether you got something correct or incorrect. Do not be discouraged if you face challenges, this is a natural step of the learning process taking place in your brain!

SPACING THE ACTIVATION OF NEURONS

Practicing more often but for a shorter period. For example, instead of studying for 2 h in a row, studying 4 periods of 30 min over a few days allows your brain to take breaks and sleep which helps you remember better in the long run.

Strategy 2: Spacing the Activation of Neurons

Now that you know that neurons need to be activated repeatedly for learning to occur (and that it means retrieving information), you probably wonder how often you should practice. Scientists who study the learning brain observed that breaks and sleep between learning periods enhance learning and minimize forgetting [5]. It therefore seems better to retrieve often within spaced practice sessions, as opposed to a massed practice (practicing a task continuously without rest). For instance, instead of studying or doing homework for 3 h, after which you would probably feel exhausted anyway, you could separate this learning period into three 1-h periods or even into six half-an-hour periods. In short, when spacing your retrieval practice, you allow your brain to make the connections that you strengthened during your practice sessions more efficient. When you take a quick break from practicing, let us say a 20 min recess, you allow for the maintenance or replacement of the receptors on the surface of the neurons. The receptors are like electric outlets that receive the nerve impulse (electrical signals) from other neurons. Taking a break helps them work better: your neurons can thus transmit their nerve impulses more easily to other neurons. Finally, when you get a night of sleep between practice sessions, you actually benefit from a free retrieval practice session because while you sleep, your brain reactivates the connections between the neurons that you activated during the day. You could also get similar benefits from a nap. Next time you find yourself sleepy in class, you could tell your teacher that you are in fact trying to do retrieval practice! In brief, when spacing out learning, and especially retrieval practice, your brain is more activated than when you mass learn in one long session.

At this point, you are probably asking yourself how to space out learning in your day-to-day life. The good news is that there are a number of ways to do it and it can be easily adapted to different skills, such as solving mathematical problems or memorizing definitions. The most obvious change you can make to your study schedule is to break up sessions into smaller sessions. You could also ask your teacher to set daily or weekly review quizzes and other assignments. Finally, spacing can be done by doing interleaved practice. This consists of a set of problems arranged so that consecutive problems cannot be solved by the same strategy. For example, you could mix your math problems so that geometry questions, algebra, or inequality problems are randomly sequenced. The added benefit of interleaving is that you engage in different activities in-between two sessions, making good use of your time. In brief, one thing to keep in mind is that information that was previously learned will require less effort to re-learn because the spacing gives your brain time to consolidate—meaning your brain produces the building blocks required for the connections between your neurons.

CONCLUSION

Your brain is where learning occurs and you therefore need to keep your neurons active to optimize the use of class or study time. The two learning strategies proposed in this article have the potential to help you learn better by creating optimal conditions to strengthen and consolidate the connections between your neurons. You now know that you can get better by repeatedly using the "trails" in your brain and by spacing out your practice. This greater understanding of how your brain learns and the use of supportive learning strategies can now allow you to help your brain learn better!

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We would like to wholeheartedly thank those who assisted in the translation of the articles in this Collection to make them more accessible to kids outside English-speaking countries, and for the Jacobs Foundation for providing the funds necessary to translate the articles. For this article, we would especially like to thank Nienke van Atteveldt and Sabine Peters for the Dutch translation.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

DR. H. BAVINCKSCHOOL, AGES: 8–12

We are Spectrum classes 5–6 and 7–8 of the Bavinckschool in Haarlem, the Netherlands. This is a group of 40 kids (19 in group 5–6 and 21 in group 7–8) who are eager to learn a bit more than the regular school program. They had a lot of fun reviewing for FYM, and went through the articles with great focus and enthusiasm, and made a critical evaluation. They really enjoyed contributing to science and helping out!

LOCARNO HIGH SCHOOL, AGES: 17–18

HI! We are two classes of Locarno High School in Switzerland. We study chemistry and biology. We are in the last year of high school, and we are preparing for our final exams, which will begin in 2 months. It was a great experience analyzing the article, and we thank you for the activity you have given us. Thanks to you, we were able to give feedback on a scientific text in English (which is not our mother tongue). We really felt empowered!

AUTHORS

JÉRÉMIE BLANCHETTE SARRASIN

I am a Ph.D. student at Université du Québec à Montréal. I study how the brain learns and how it is possible to benefit from this knowledge to foster teaching practices that are more compatible with the learning brain. My research actually focuses on teaching students how their brain learns to help them learn better! *blanchette_sarrasin.jeremie@uqam.ca

LORIE-MARLÈNE BRAULT FOISY

I am a professor at the University of Quebec in Montreal (UQAM). After studying to become a teacher in elementary school, I decided that I wanted to know more about how children learn. This is why I am doing research in education. I believe that it is important to understand better what happens in the brain of children when they learn different things (e.g., reading, science). If we understand better how their brain learn, it will give us clues to teach better!

GENEVIÈVE ALLAIRE-DUQUETTE

I am a post-doctoral fellow at the Constantiner School of Education, Tel Aviv University. My research and teaching focus on the interdisciplinary study of human learning, development, and teaching, namely Mind, Brain, and Education (MBE). My current work attempts to better understand the mechanisms of reasoning in science and mathematics using cognitive neuroscience methods.

STEVE MASSON
I am a professor at Université du Québec à Montréal. Using a tool called magnetic resonance imaging, I look inside the brain to see what changes when students learn in school. Sometimes, I even look if the way teachers teach influences what change in students' brain when they learn. Pretty cool!

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NEUROSCIENCE
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WHY YOUR MIND IS LIKE A SHARK: TESTING THE IDEA OF MUTUALISM

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YOUNG REVIEWERS:

AIDAN
AGE: 9

DANIELA
AGE: 10

LEIMINA
AGE: 11

LUCIE
AGE: 11

We want to understand how children get so much better at certain cognitive abilities like reading, writing, and problem solving as they get older. To better understand this, we followed hundreds of children across a period of years, to see how abilities like problem solving and vocabulary changed over time. We found that having good vocabulary to start with made children's problem solving develop more quickly. It also worked the other way around: being better at problem solving meant children were quicker to learn new words. In other words, each cognitive ability may help other abilities develop. This idea is called mutualism. We were very excited by this discovery, because it can help us understand how children get better at things they never practice directly, and how teachers can better help children who find certain school topics more challenging.

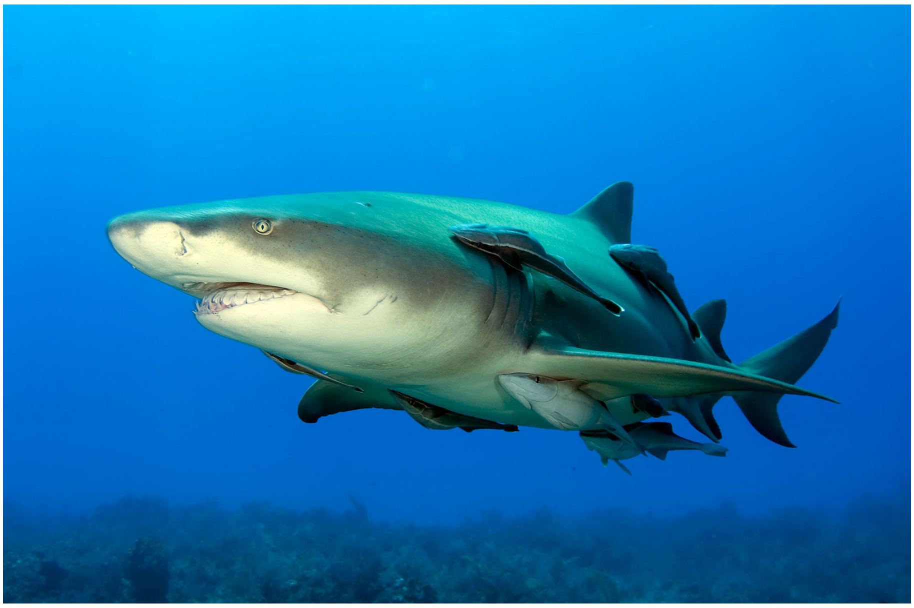

Figure 1

Figure 1

A suckerfish hitching a ride on a lemon shark (source: Albert Kok, wikimedia).

WHAT ANIMALS CAN TEACH US ABOUT OUR MINDS

One of nature's strangest sights can be found off the coast of Australia: small fish, called suckerfish, or remoras, attach themselves to sharks using a suction cup on their heads (Figure 1—the picture with the shark). Why doesn't the shark just eat the suckerfish? Why does the suckerfish even go near the shark? As it turns out, both animals benefit from this arrangement. The suckerfish eats parasites and dead skin off the shark, helping the shark stay clean and healthy. In return, the suckerfish gets a free ride through the oceans, eats the scraps left over after the shark's meal and is protected from other predators who would not go near the shark—everybody wins! This phenomenon, where both species benefit, is called **mutualism**. Recently, scientists have used the idea of mutualism to understand something that seems, at first glance, entirely different: human learning.

MUTUALISM

The idea that different cognitive abilities (such as how many words you know, and how well you can solve problems) actually help each other develop over time.

WHAT IS MUTUALISM?

Whenever you try to solve a problem—at school or elsewhere—you use what psychologists call your **cognitive** abilities. Cognitive abilities are things like memory (how well you can remember things from the past), **vocabulary** (how many words you know) and reasoning (how good you are at solving problems). Many things you do and learn in school rely on cognitive abilities. Vocabulary, for instance, is a really important building block of language, as well as other skills. For example, you use your vocabulary when you apply for a job, tell a story, or write a message to a friend.

COGNITIVE

"Cognitive" is a term scientists use to refer to mental processes like thinking, reasoning, remembering, and problem solving.

VOCABULARY

This means how many words you know the meanings of.

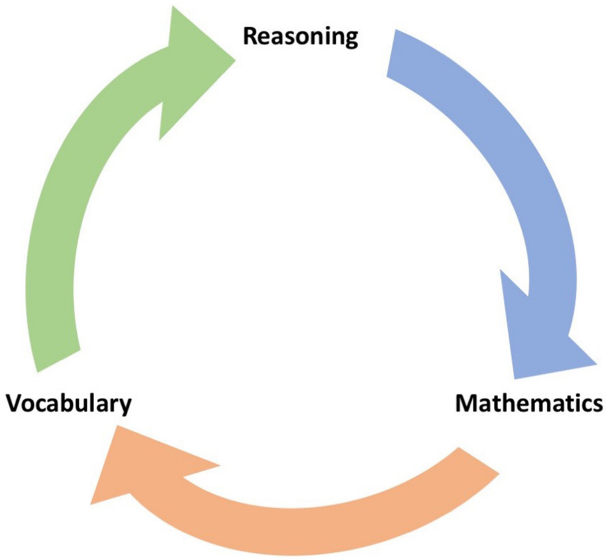

Figure 2

The idea of mutualism: different cognitive skills help each other grow over time.

Normally, scientists study different cognitive abilities separately, just like you study lots of different subjects in school. However, in some recent studies, scientists have discovered exciting connections *between* cognitive abilities. As it turns out, rather than being entirely separate skills, your cognitive abilities behave a bit like sharks and suckerfish—they help each other grow over time. As you can see in Figure 2 (see the picture with the arrows arranged in a circle), your vocabulary is not just useful for improving language skills, it may also help your reasoning, which, in turn, may help your maths skills, which may help your vocabulary. This idea is called mutualism of cognitive abilities [1].

How Can We Test the Idea of Mutualism?

To test the idea of mutualism, we followed 800 young people (aged 14–24 years) over time and measured their vocabulary and reasoning skills) [2]. In Figure 3, you can see what the vocabulary and reasoning tests looked like. In the vocabulary test, we asked our young people to point out a cone (among other shapes), or explain what a word like "enthusiastic" means. For the reasoning task, we asked young people to fill in the missing puzzle piece (hint: count the shapes from left to right in each row). In our study, the children and adolescents took these tests twice, about 1.5 years apart.

We found that the children and adolescents got a bit better at vocabulary and reasoning over time—just like you get better at most things as you get older. Most importantly, though, we discovered evidence for mutualism of cognitive abilities. It turns out that having a good vocabulary to begin with makes it more likely reasoning improves, and having good reasoning skills to begin with helped with learning more words more quickly. Just like having good balance or

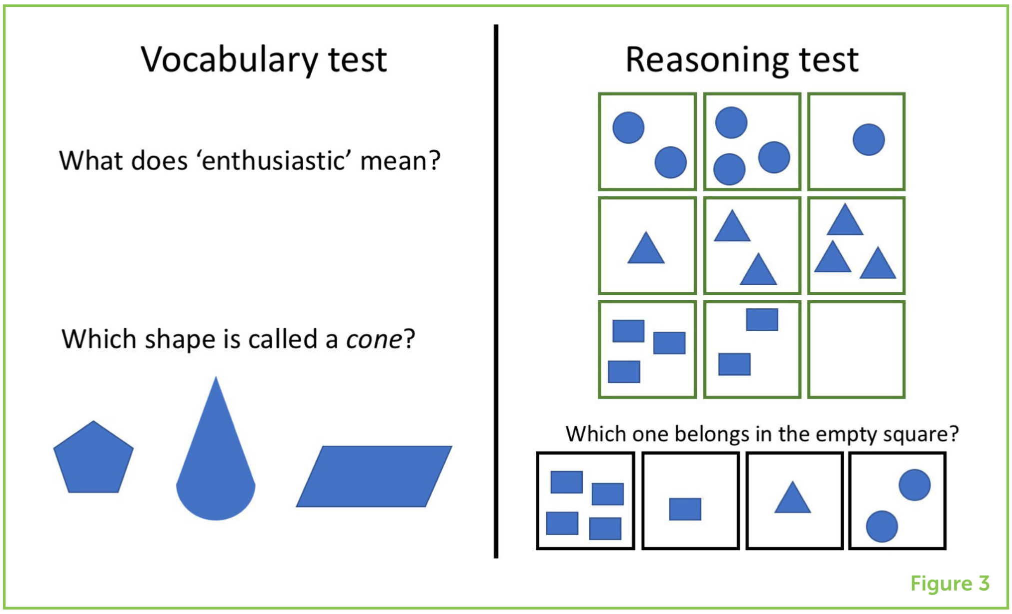

Figure 3

An example of a vocabulary test (left) and a reasoning test (right) used to study mutualism of cognitive abilities.

being able to run quickly might help you improve in sports like football or tennis, having good vocabulary and reasoning can help you to develop other cognitive skills as well. To find out whether this finding was reliable, we tested the idea of mutualism in a separate group of young people—this time much younger (6–8 years old). Sure enough, again we found that children with better reasoning abilities made faster improvements in vocabulary, and vice versa [3].

HOW CAN MUTUALISM HELP YOU IN SCHOOL?

Why could understanding the idea of cognitive mutualism help you? Well, there are several reasons. For example, it may help understand what happens when you learn in school. Two scientists, Stuart Ritchie and Elliot Tucker-Drob, used data from over 600,000 people [4] and found that going to school makes you better at cognitive tests, like IQ tests. This is pretty impressive, given that most of these tests were never taught directly in school. Their findings suggest that going to school actually makes you smarter, even at things you do not directly learn. This is similar to mutualism: having good "building blocks" may allow a range of cognitive abilities develop more quickly.

Understanding mutualism is also useful when you are having a hard time at school. Say you are struggling with maths and you are not sure how to get better. According to mutualism, it might be that getting better at one cognitive ability (like vocabulary) could help you get better at other cognitive abilities, including the one you find harder (like mathematics), even if they seem unrelated. So, do not give up on maths just yet. Working on something else, such as reading, might help boost your maths grades down the line, which in turn could help boost your English grades, which could boost your maths grades, and so on.

There is even a new study that shows just this: being a little bit better at reading helped kids improve their multiplication skills over time [5]. Therefore, being good at a particular school subject is not just good in and of itself—being good at any subject might help you gain a whole bunch of other skills more easily.

WHAT DID WE LEARN ABOUT OUR MINDS?

What our research on mutualism shows is that your mind is a bit like the shark and suckerfish: different abilities, like vocabulary and problem solving, actually help each other grow over time. You can think of mutualism as a rule of thumb for learning, both inside and outside the classroom. Mutualism shows the importance of making connections. Both you and your teachers may find it helpful to connect different topics and subjects—what are the links between them, and how can you use what you learned in maths to understand biology? Thinking about, and forming, these connections between topics may help you make the most out of your time at school. Maybe learning about mutualism may even make you think a bit differently about topics at school. It is important not only to study hard, but also as widely as you can. You never know what potential benefits learning one skill will have on the others!

Mutualism is a very new and exciting research field, and there is much left to learn. We are still working hard to understand how it happens in real-life classrooms. We do not know, for instance, whether other cognitive abilities like memory also show the effects of mutualism, whether some children show mutualism more than others, how the brain supports mutualism, or how long you may have to train in reading before you see any benefits in your mathematics. We are working on it though, so stay tuned!

ACKNOWLEDGMENTS

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ORIGINAL SOURCE ARTICLE

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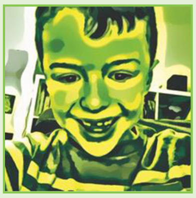
YOUNG REVIEWERS



AIDAN, AGE: 9

Aidan is 9 years old, he likes coding and science. He likes to read a lot as well. He likes to read book series like "Wings of Fire," "How to Train Your Dragon," "The Three Doors Trilogy," "Deltora Quest," "His Dark Materials Trilogy," "Mr. Gum," "Harry Potter," and "Weir Do."

DANIELA, AGE: 10

Hi, my name is Daniela. I am 10 years old. I live in Australia. My favorite hobby is to play tennis, and my favorite subject is science. When I grow up I would like to study science and be a doctor.

LEIMINA, AGE: 11

Hi, I love sport especially netball, but I also love other sports as well. I would say that I am a pretty good artist. I just love reading and learning new things.

LUCIE, AGE: 11

Lucie loves science and maths. She is quite interested in biology and chemistry. In her spare time, Lucie likes to read. Her favorite book genres are non-fiction, action, fantasy, and romance.

AUTHORS

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Rogier is a psychologist who wants to understand why children learn skills so quickly, and why older people tend to get a bit worse at things when they grow (really) old. He looks at large groups of children and adults to figure out how their brains change over time, and what those changes do to how they think, reason, and remember. He loves sharks and was very happy he could use a picture of one in this paper. *rogier.kievit@mrc-cbu.cam.ac.uk; www.rogierkievit.com

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Ivan is a Ph.D. student at the MRC Cognition and Brain Sciences Unit at the University of Cambridge. His research attempts to understand how the brain and behavior interact with each other during childhood and adolescence to produce intelligence. He hopes to apply insights from his research to help guide education policy, especially for disadvantaged youth struggling to learn in school.

DELIA FUHRMANN

Delia is a psychologist who is fascinated by how the mind and brain develop. She works at the University of Cambridge and King's College London. She wants to understand how the environment impacts us at different ages. Outside the lab, she likes playing with her kids, reading books, and dancing.

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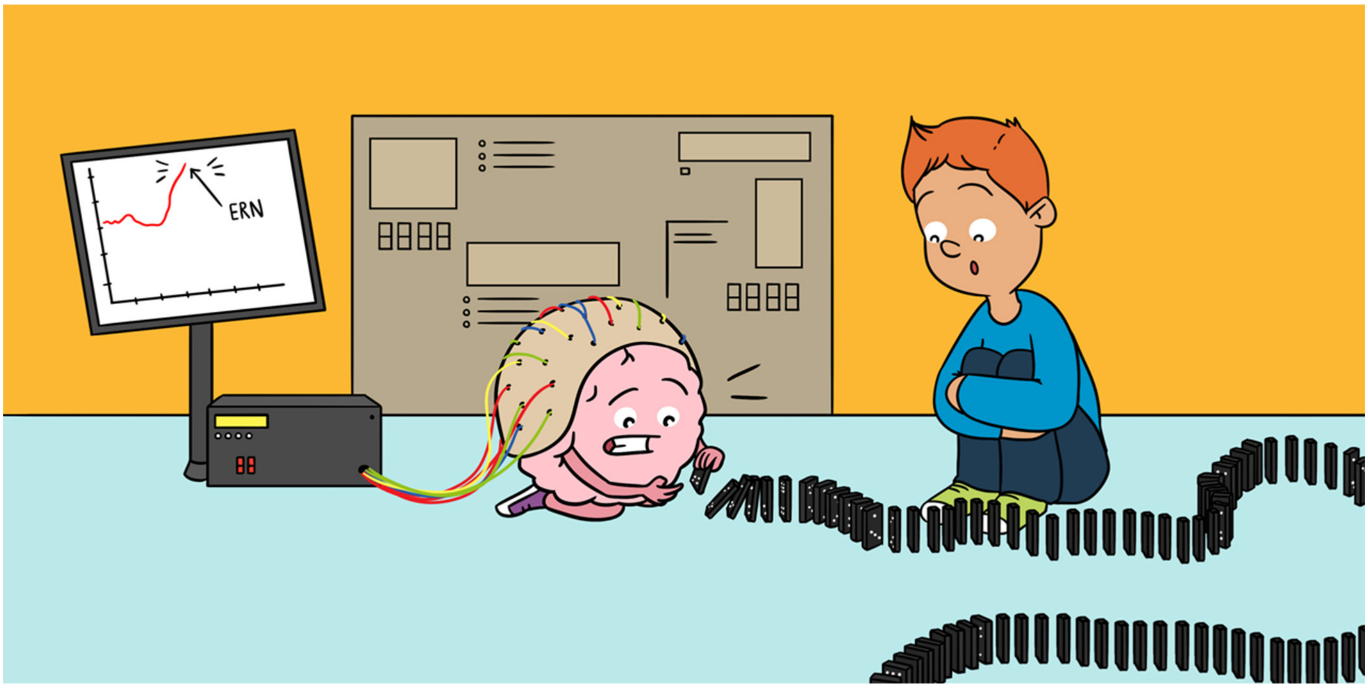

LEARNING FROM MISTAKES: HOW DOES THE BRAIN HANDLE ERRORS?

***Knut Overbye*[1], *Rune Bøen*[2], *Rene J. Huster*[3] and *Christian K. Tamnes*[2,4,5*]**

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YOUNG REVIEWERS:


ASHLEY
AGE: 12


JULIA
AGE: 14


SAMANTHA
AGE: 15

We all make mistakes—and when we do, it is a great opportunity for the brain to adjust what it is doing and to learn. To study how the brain detects and deals with errors, researchers have used caps equipped with sensors that can measure brain activity. One thing researchers have found using this method is that the brain creates a specific kind of brain activity when a person makes a mistake. This activity, called the error-related negativity or ERN, happens almost at the same time that the error is made. It is as if the brain already knows we are making a mistake within fractions of a second, before we are even aware of it. Where in the brain does this ERN come from? How does it help us learn? And how does it change as we develop from children to adults?

MAKING MISTAKES

Making a mistake feels bad. That sudden annoying jolt you feel when the dart misses the dartboard or the sinking feeling you get when you get an F on a test. These feelings can be annoying or painful, but they are part of what your brain does to make you succeed in the future.

Making a mistake could have meant injury or death for our distant ancestors who lived in the wild, hunting game and avoiding predators. The brains of our ancestors had to help them learn from their mistakes, so that the human race could survive. An important function of the brain is to try to predict the future. This includes how we can change our actions in the future, to avoid making the same mistakes. Understanding how the brain detects and copes with mistakes is therefore important for understanding how the brain works and how we learn.

We can think of a mistake like this: you start out with a goal you want to achieve. Perhaps you are playing soccer and you are about to make a free kick. Your goal is literally to score a goal. You assess the situation and choose a plan of action. Say the opposing team has set up a wall, so you decide to curve the ball around the players and into the goal. But you put too little spin on the ball, and it hits a goal post and deflects.

In this example, the mistake was caused by an incorrect prediction. You predicted that the way you kicked the ball would result in you scoring a goal but, to your surprise, it hit the goal post instead! In other words, what you thought would happen did not actually happen. Although you might be disappointed for not scoring a goal, this event tells you something very important. It tells you that your ideas about how the world works and how you can affect it are not completely correct. Now you know that, next time, you will need to kick the ball with more spin. Thanks to such learning experiences, you will fine-tune your kicking until you ultimately score.

HOW DOES THE BRAIN DEAL WITH ERRORS?

Brain cells communicate with each other using electricity. Some of this electrical activity travels away from the brain cells to the outside of the head. It passes through brain tissue, the skull, and your skin along the way. By using caps with special sensors called electrodes, we can record this activity; this method is called **electroencephalography (EEG)**. EEG allows us to study brain activity while people perform different tasks. The brain never stops working, even when you sleep, and thus constantly produces this electrical activity. By looking at patterns in these electrical "brain waves," it is possible to see a lot about what is going on in the brain. We can see if people are awake

ELECTRO ENCEPHALOGRAPHY (EEG)

A method to record electrical activity of the brain.

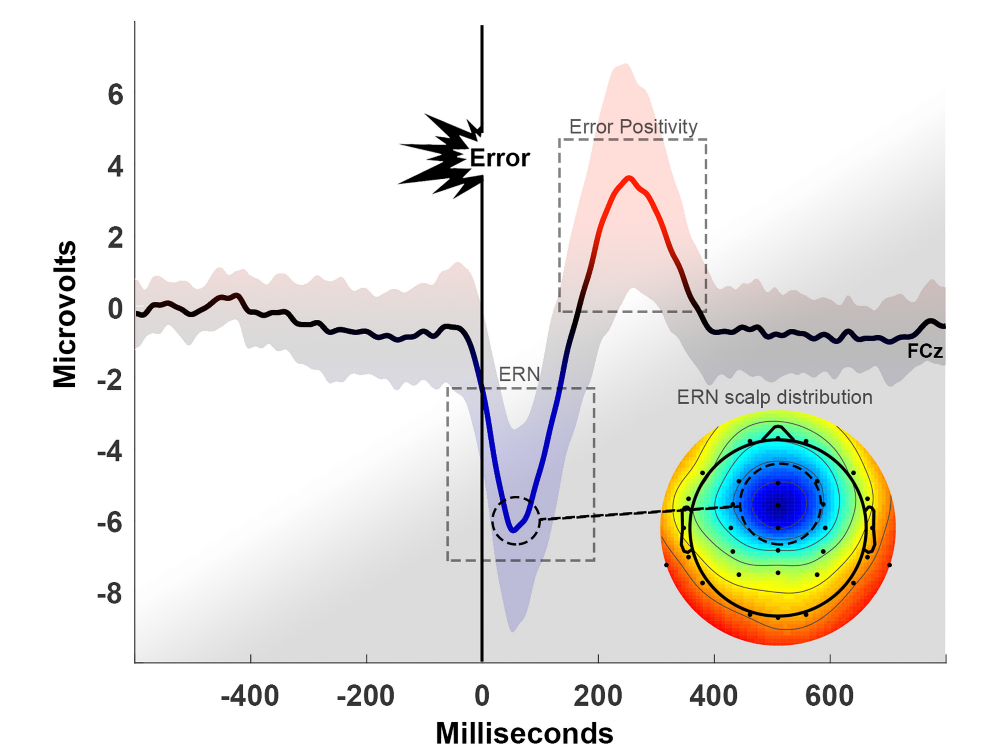

Figure 1

The error-related negativity (ERN) and the error positivity. A specific pattern of brain activity can be observed when we make an error. In the graph, the wavy line shows the brain activity over time. The vertical line represents the time at which the error was made. You can see that the ERN (blue), happens almost immediately after the error is made and is strongest at the top of the head, while the error positivity (red), comes a bit later.

ERROR RELATED NEGATIVITY (ERN)

Negatively charged electrical brain activity which happens very quickly after an error and which signals detection and processing of the error.

CINGULATE CORTEX

A part of the brain deep inside in the middle of the brain.

CINGULUM BUNDLE

A nerve tract containing a collection of fibers that connect many different parts of the brain.

or sleeping, if they are relaxed or focused, or if they just made an error.

In the laboratory, we study brain activity related to errors by giving someone a very difficult task, in which he or she is bound to make a lot of errors. For example, the person might be asked to quickly press a certain key on a keyboard when a left or right arrow is shown at the center of the screen, but the arrow is surrounded by many distracting arrows pointing in the other direction. Whenever the person makes an error, a special pattern of brain activity shows up: a sharp, negative electrical activity that is strongest at the top of the head. Since this electrical activity is negatively charged and associated with making errors, it is called the **error-related negativity**, or ERN [1] (Figure 1).

The ERN is thought to come from a brain region deep inside the front part of the brain called the **cingulate cortex** [2] (Figure 2). The ERN is likely the result of the cingulate cortex detecting an error and sending an alert signal to other parts of the brain, through connections called the **cingulum bundle**, focusing the person's attention to decrease the likelihood of making new mistakes.

A curious thing about the ERN is how quickly it happens after you make an error. So quickly, in fact, that it happens before you are aware of your mistake. The ERN usually occurs no later than 100 ms (1/1,000 of a second) after an error has been made. The ERN can even occur at

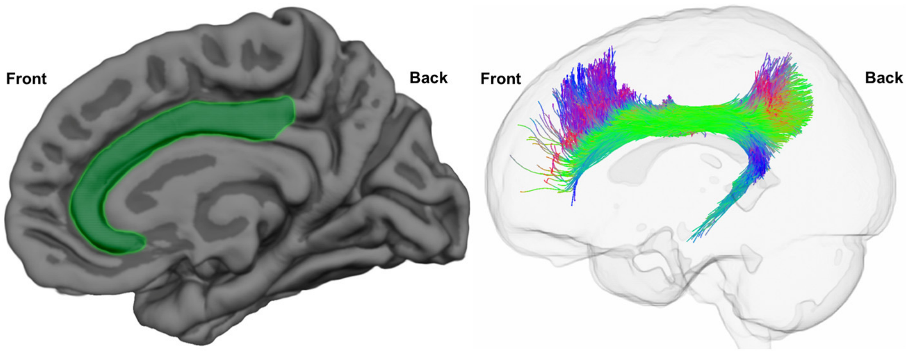

Figure 2

Figure 2

The cingulate cortex and the cingulum bundle. **Left:** The cingulate cortex, shown in green, is a region deep inside in the middle of the brain, and is the source of the ERN. **Right:** The cingulum bundle, the fiber connections that lie underneath the cingulum cortex, connects different brain regions (made by Sila Genc).

almost the exact same time as the error itself. In contrast, you will not have a feeling of making an error until at least 200 ms later. It is like your brain knows you have made a mistake before "you" do! And indeed, scientists think that this is exactly what happens. The cingulate cortex compares our actual actions to what we would like to do or should achieve, and the ERN then signals to our conscious self that the actual action and the outcome we expected do not match. The ERN thus brings this error or mismatch to our attention. The actual awareness of making an error happens at the same time as a later brain signal, called the **error positivity**, which is an electrical signal that scientists believe to be involved in our awareness of making an error.

ERROR POSITIVITY (PE)

Positively charged electrical brain activity which happens from 200 ms after an error and is involved in our awareness of making the error.

HOW DO ERRORS HELP US ADJUST OUR BEHAVIOR AND LEARN?

Many scientific studies have found that, after making a mistake, we respond more slowly in the next round. This might be because the brain is trying to give itself more time, to avoid making the same mistake again. The stronger the ERN is after an error, the slower the response in the next round tends to be [3].

Some people have a larger ERN than others. Does this mean that these people are more sensitive to making errors and learn more from their mistakes? Some studies seem to support this idea. For instance, Hirsh and Inzlicht [4] found that a stronger ERN was associated with better school performance. In their study, the researchers measured the brain activity of university students and found that the students who had a larger ERN also tended to have better grades.

Having a strong ERN is not necessarily always a good thing, however. People who are more anxious tend to have stronger ERNs [5], and very strong brain responses to errors are associated with increased distractibility rather than improved focus. If the ERN shows the brain reacting and responding to errors, then a really strong ERN might be the brain overreacting, being more upset and alarmed by making a mistake than is necessary.

HOW DO ERROR SIGNALS CHANGE AS WE GROW UP?

In childhood and adolescence, the body goes through many physical changes, but there are also many changes in how we think, feel, and behave, and in our motivations. These changes, along with the ever-greater responsibilities and expectations we face in life, require repeated trial-and-error in order for us to learn the social and academic skills we need to thrive as adults.

Studies show that the ERN changes with age, with adults and older teenagers having stronger ERN signals compared to children [3]. That the ERN increases in strength through childhood and adolescence is probably related to the way the brain develops. Different parts of the brain develop at different speeds. Some brain regions are fully mature by late childhood, while others continue to develop into adulthood [6]. The cingulate cortex, which produces the ERN, does not stop developing until the late 20s. In other words, a part of the brain that is important for learning from our mistakes takes a really long time to develop compared to many other parts of the brain.

CONCLUSION

Making mistakes can be annoying and frustrating at times. However, it is also very important for us to learn from our mistakes, so we can correct our responses and do things differently the next time we are in the same situation. The brain is very sensitive to mistakes and it produces a specific type of electrical activity when we make errors, called the ERN. This error signal: (1) occurs before we are aware of our mistake; (2) becomes more powerful as we get older; and (3) can predict how well we perform at school or university. There is still much we do not know about how the brain reacts to mistakes. Doing more research on the ERN might help us solve some of these mysteries.

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YOUNG REVIEWERS

ASHLEY, AGE: 12
Hi I am Ashley!! I like to dance flamenco everyday because it is fun and is a great physical activity. Flamenco and acting class are my favorite classes this year. I go to

a school that focuses not just on normal classes, but on performing arts as well. In my spare time I like making jokes and playing card games with my family.

JULIA, AGE: 14

My name is Julia and I am a ninth grader from Berlin. I am a student who is very interested in math, chemistry, and sciences, especially neuro- and space sciences or quantum mechanics, but I enjoy learning languages too. At home I am talking with my parents in Ukrainian because originally we come from Ukraine and in addition I am studying German, English, and French at school. In my free time I really like playing the piano, dancing, and reading books.

SAMANTHA, AGE: 15

Hi my name is Samantha! I like to read and write, and I am working on writing a long story right now. My favorite classes are Chemistry and English. In my free time I enjoy contemplating the mysteries of the universe, staring off into space, and writing stories.

AUTHORS

KNUT OVERBYE

Knut is a psychologist and cognitive neuroscientist. He has studied how adolescent brains react to errors and surprises. He is currently studying how the brain changes physically when we practice something for a long time. Both at work and at home, Knut enjoys programming and finding new uses for virtual reality.

RUNE BØEN

Rune is a research assistant and helps other researchers to perform experiments. He is interested in the brain and how it works, and wants to become a cognitive neuroscientist in the future. He enjoys science and learning new things. When he is off work, he likes to read books, listen to podcasts, and watch soccer games.

RENE J. HUSTER

René is a cognitive neuroscientist who studies how the brain helps us to adapt to changes in the environment, and how we can function under challenging conditions, for example, how can you resist eating a cookie now, when you might get three more if you wait another 30 min? When he is not working, he likes to practice Jiu Jitsu or the bass guitar.

CHRISTIAN K. TAMNES

Christian is a psychologist and a developmental cognitive neuroscientist. He studies how the brain develops through childhood and adolescence. He is also interested in how the development of the brain makes us who we are. In his research, he tries to figure out if the shape and function of the developing brain can tell us something about why some people are very outgoing or smart, or even why some people get mentally ill. In his free time, he mostly hangs out with his two kids. *c.k.tamnes@psykologi.uio.no

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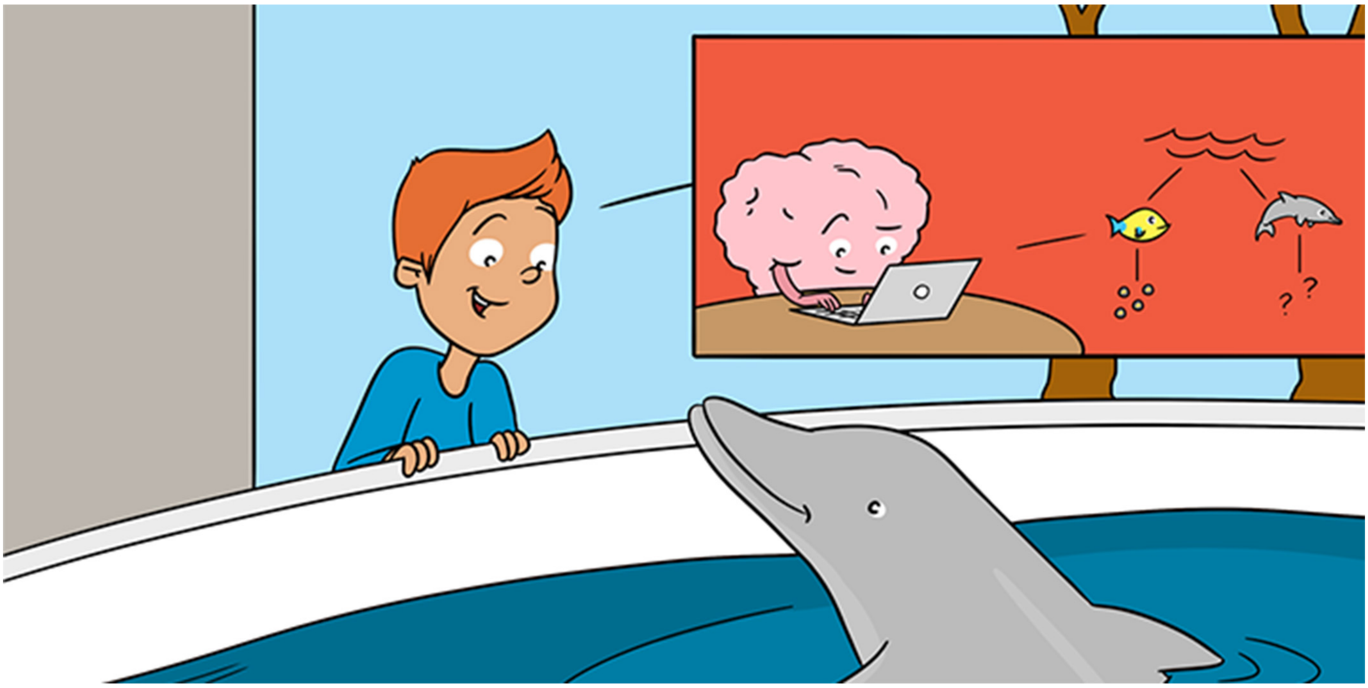

HOW TO USE YOUR MEMORIES TO HELP YOURSELF LEARN NEW THINGS

Marlieke van Kesteren** and Martijn Meeter

Department of Education Sciences, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

YOUNG REVIEWERS:

DR. H. BAVINCK SCHOOL
AGES: 8–12

ELIZA
AGE: 10

MALLETS BAY SCHOOL
AGES: 9–10

Remembering is an essential brain function. Think about it—what would happen if you did not remember anything? You would not be able to recall the things you learn at school. Actually, you would not even know that you had to go to school, or where your school is! Many people think that memory can be compared to a closet, where you put something and later retrieve it the same way you put it in. But this is not really how it works. In fact, memory works more like news websites on the internet that keep changing content depending on what happens in the world. A good website also includes links to other websites where you can look up related information. Whether you remember something well depends on many things that happen in your brain during and after learning. One factor that is very important for learning is the knowledge that is already stored in your brain. When you already know a lot, it is easier to add new information. We will also show you how you can use this knowledge about how memories are formed to help you remember new things you learn at school.

YOUR PREVIOUS KNOWLEDGE MAKES IT EASIER TO LEARN

Take a moment to think about everything you already know. Consider life events, the people you know, books you have read, games you have played, stuff you have learned at school, et cetera... It is a lot, right? Well, it is very useful to have all this knowledge stored in your brain. This knowledge helps you to understand the world around you, but it also makes learning new information easier, since you can link the new information with what you already know. For example, when you already know some things about the brain because you have read Frontiers Young Minds Neuroscience articles before, it will probably be easier for you to remember what we are about to tell you. The neuroscience knowledge in your brain makes it more likely for new memories to "stick." We call such a knowledge structure a **schema** [1].

SCHEMA

Prior knowledge in your brain.

HIPPOCAMPUS

A brain region that helps you to remember by linking different parts of a memory together.

HOW MEMORY WORKS IN YOUR BRAIN

In the brain, there are many regions that help to store memories. The most important one is called the **hippocampus** (which means seahorse, because it is shaped like a seahorse). Without your hippocampus you could not learn new information [2]. Scientists think that the hippocampus links different parts of a memory together. For example, when you learn that fish lay eggs, the hippocampus makes a connection between "fish" and "eggs" (see Figure 1). This means that the memory itself is not in the hippocampus, but without the help of the hippocampus, you could not link the different parts of the memory together. This happens when forget something: the different parts of the memory are still there, but they cannot be connected anymore.

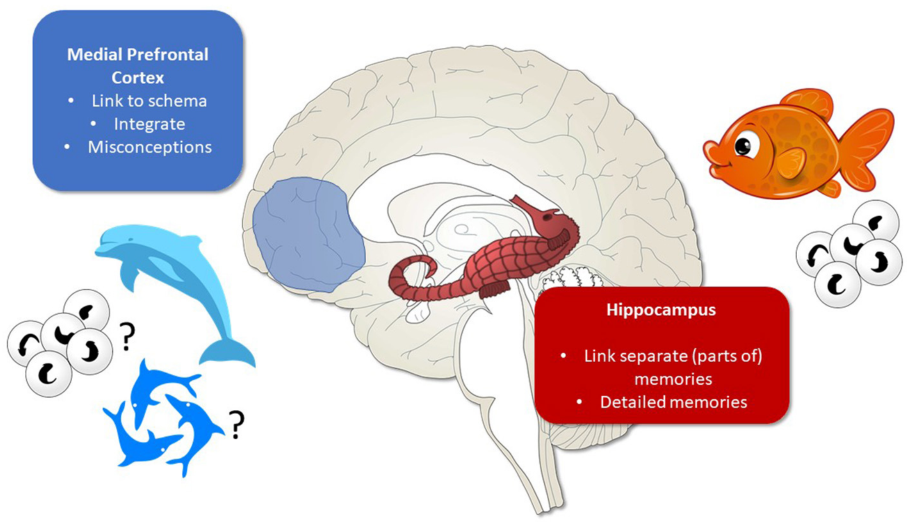

Figure 1

Figure 1

This is a picture of your brain cut through the middle. You can see both the hippocampus, in red, and the medial prefrontal cortex, in blue. The hippocampus links separate parts of a memory, making sure the memories stay detailed and vivid, such as when you remember that time when your goldfish laid eggs. The medial prefrontal cortex can also help you to remember information, but it is thought to do so by integrating new knowledge with existing schema knowledge, so the memories become less detailed and more generalized. This process can also lead to misconceptions, such as when you mistakenly think that a dolphin, because it resembles a fish, also lays eggs while in fact it gives birth to live baby dolphins. Adapted from: https://commons.wikimedia.org/wiki/File:Frog-spawn-Rana-temporaria-11d.svg and http://www.clker.com/clipart-brain-3.html.

MEDIAL PREFRONTAL CORTEX

A brain region that helps you to integrate new memories with your schema knowledge.

Another brain region, called the **medial prefrontal cortex**, can also help you remember information, but scientists think that this region learns differently than the hippocampus [3]. Based on your schema knowledge, the medial prefrontal cortex figures out where to best place new information and then connects it with your schema. This means that when you learn a new type of fish, like a goldfish, your medial prefrontal cortex will immediately connect that to "laying eggs," because that is what you have remembered before. This process is called integration, which means to combine into one. The integration process helps you to uncover connections between new and old knowledge For example, if you know that fish lay eggs and that a goldfish is a fish, you could uncover that goldfish lay eggs [4]. This is a new fact that your medial prefrontal cortex helped you discover. So, you can see that it can be helpful to use this integration process when learning new information.

SCHEMAS AT SCHOOL

Especially at school, it can be very helpful to actively use your schema knowledge when you learn new information [5]. You can do this in different ways. Before starting a lesson, you can revisit what you have learned before about a certain topic (for example, that fish lay eggs). Or, while studying, you can pause often and think about what you just learned and how the new knowledge links to what you already know. This will help you to use your medial prefrontal cortex to integrate new information and remember it better for tests. In addition, such integration helps you to build better schemas so you can remember new, related information even better in the future.

METHOD OF LOCI

A memory technique in which you link things that you want to remember to a well-known place.

Sometimes, we can use memory "tricks" to link new knowledge to our schema knowledge. For example, when learning a list of words, you can link these words to places in your room or another familiar environment. This is called the **method of loci** (loci means "places" in Latin [6]). It is used by many people to remember arbitrary information that is hard to connect to schema knowledge, like a long grocery list. While you look at the grocery list, you can imagine every item somewhere in your living room (for example, a box of ice cream on the couch), and when you are in the supermarket, you just have to think about your couch to remember what you wanted to buy. With a bit of training, this method will work for you too!

BE AWARE OF INCORRECT MEMORIES

Unfortunately, it is not all good news. Relying very strongly on schema knowledge can also lead to incorrect memories. For example, consider the "fish lay eggs" example we gave earlier. What happens when you then learn about dolphins? Because dolphins look like other fish, and you already know a lot about fish, you could think that they

MISCONCEPTION

A wrong memory.

lay eggs as well. However, this is not true. Dolphins are mammals, so dolphins give birth to live dolphin babies, just like humans. We call such false memories **misconceptions**. These misconceptions can arise when your schema knowledge about something (in this case how fish make babies) is very strong. The misconception will make it very hard to remember when you learn something that does not fit (that the dolphin does not lay eggs). In this case, your medial prefrontal cortex should not integrate the dolphin with your fish schema. Instead, your hippocampus should kick in to make a separate memory. How do you do this?

TIPS

Here are a few tips to help you use your schema knowledge when learning new things at school. These tips should also help you to avoid or get rid of misconceptions:

Reactivate: When you learn new information, reactivate related schema knowledge. Close your eyes and take a moment to remember what you have learned about this topic before and how it connects to the new information you want to learn.

Elaborate: Try to link new information to different kinds of schema knowledge. For example, when you must learn in biology that dolphins are mammals, you can now link it to your memories about schemas and the example of fish that you read here. The more links you make, the better you can integrate new information and remember it well. Making strong and detailed links can also avoid the formation of misconceptions.

Space, repeat, and alternate: You can best create and extend schemas by learning and repeating new information in small pieces over time: hours, days, even weeks. Alternating different topics, so you do not always study the same thing, can also benefit your memory.

Recall and ask questions: After you have learned something, put away your book or computer and try to remember what you have just learned, just by using your brain. Or, you can ask questions about what you learned. This will help you to integrate information and you can use the questions later to quiz yourself and your classmates. To avoid misconceptions, make sure you always check whether your memory was correct!

Teach others: A very good way to organize your schemas is to teach your classmates. Take turns: read something, link it to your schema knowledge, let it sink in, then try to explain it to someone else. Again, always check afterwards whether you have made mistakes and discuss things you do not really understand.

Sleep: Perhaps this is the odd one out because it does not happen at school, but sleep helps build strong schemas, and helps you forget less important information. Think about that when your parents tell you it is time for bed!

Track misconceptions: Always be aware when information contradicts your schema knowledge or when you notice that you have formed a misconception along the way. Try to make a new, very vivid memory. For the dolphin example, think about a funny dolphin with a very big belly who is jumping out of the water and squeaking loudly. Imagine how wet you will get and how you will pat its nose and feed it a fish. The more details and senses you use for this memory, the better!

ENJOY!

Try using these tips when you are learning new things at school or at home, and you will notice that you will remember a lot better. We hope this article will help you to enjoy learning!

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

DR. H. BAVINCK SCHOOL, AGES: 8–12

We are Spectrum classes 5–6 and 7–8 of the Bavinckschool in Haarlem, the Netherlands. This is a group of 40 kids (19 in group 5–6 and 21 in group 7–8) who are eager to learn a bit more than the regular school program. They had a lot of fun reviewing for FYM, and went through the articles with great focus and enthusiasm, and made a critical evaluation. They really enjoyed contributing to science and helping out!

ELIZA, AGE: 10

Hi! My name is Eliza. I love to read and bake muffins. I have two dogs, named Arnie and Benji. I also like to do math with my dad. My mom has a Ph.D. in neuroscience, which I think is really interesting.

MALLETS BAY SCHOOL, AGES: 9–10

These fourth graders love the outdoors of their beautiful state, where winters are long, summers are short, and the mud season is always around the corner. They also enjoy playing American football, hotwheels, fortnite, and hockey.

AUTHORS

MARLIEKE VAN KESTEREN

Marlieke van Kesteren is a post-doctoral researcher in Educational Neuroscience at VU University Amsterdam. She investigates how we can best use our prior knowledge to learn new information. To do this she puts students in an MRI

scanner while they are learning new things. She really likes to teach her findings to children in schools and is thrilled to be able to do this through Frontiers Young Minds. *marlieke.van.kesteren@vu.nl

MARTIJN MEETER
Martijn Meeter is a professor of education sciences, the science of how education works. His lab is at a university in Amsterdam, the Netherlands (www.vu.nl). He studies learning and education with many different techniques, and has built a lot of computer models of the brain: programs that simulate in a computer how our brain works. He is also the director of a teacher training program, a school that turns students into teachers for secondary education.

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NEUROSCIENCE
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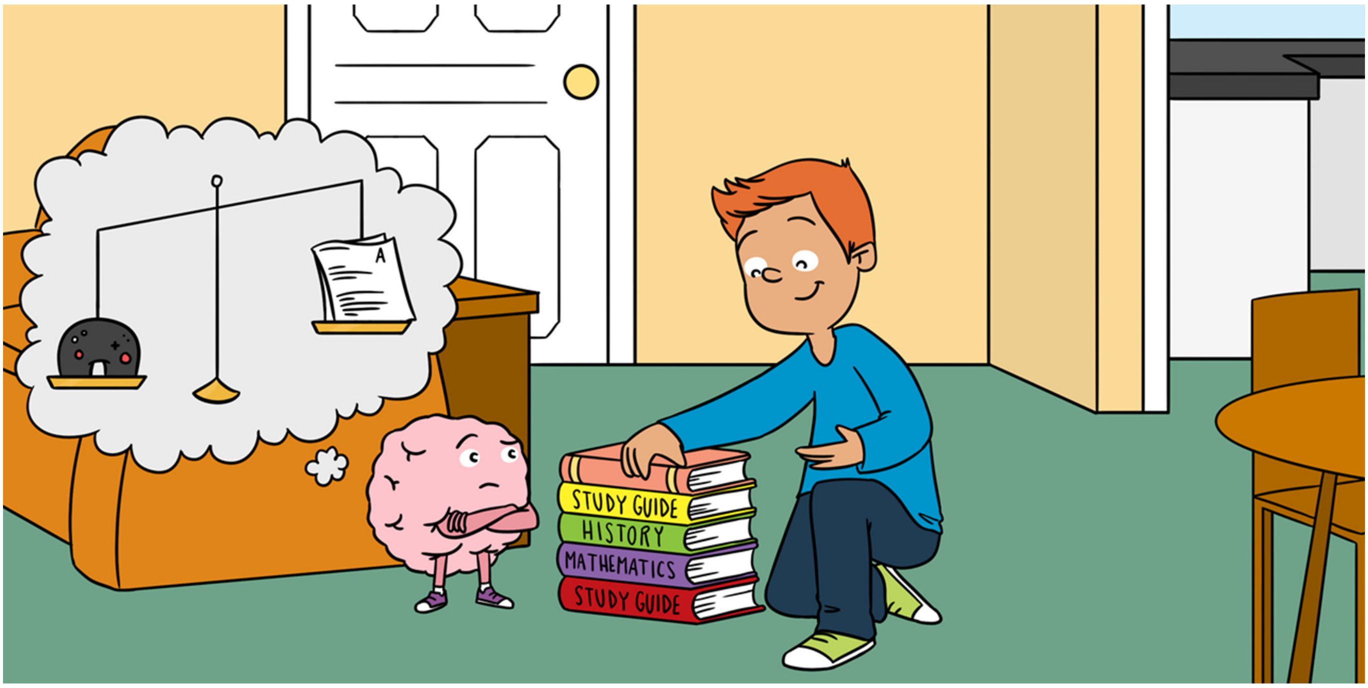

IS IT WORTH IT? HOW YOUR BRAIN DECIDES TO MAKE AN EFFORT

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YOUNG REVIEWERS:

SEAWELL ELEMENTARY

AGE: 10

Everything you do requires you to exert effort. For instance, basic things like walking or cycling require physical effort and have to do with using your body. Another type of effort is cognitive effort, which has to do with thinking and using your brain. For instance, think about trying to master a Rubik's cube. Would you want to put in your effort here? The pleasure of finding a solution might outweigh the effort of thinking hard. Or you may decide that finding a solution is not worth your effort. Why and when would you decide to think hard? In this article, we will explain how you decide to exert cognitive effort and what is happening in your brain while you make this decision.

INTRODUCTION

At school, your teachers may say that if you had put in a little more effort, you would have passed a test, or that, with a bit more effort, you would have gotten a higher grade. While you may feel that putting in more effort could lead to better outcomes, it is not always clear what that effort is, exactly.

Effortful actions can be seen as the opposite of automatic actions [1]. For example, you do not have to do anything special to make your brain see colors: it is an automatic process. In contrast, other actions involve non-automatic processes and take effort. Effortful actions are everywhere. Think about the effort it takes to walk or cycle to school. Such bodily actions require physical effort. On the other hand, actions that require **cognitive effort** have to do with your thinking. Cognitive effort is the thinking effort you put in to achieve a complicated task. For instance, you exert cognitive effort when studying for school, solving a complicated puzzle, or trying to solve a riddle.

COGNITIVE EFFORT

The thinking effort you put in to achieve a complicated task.

Many people report that effortful behaviors that are helpful in the long-run, such as studying for a test, feel unpleasant in the moment [2]. Why would exerting cognitive effort feel unpleasant? And maybe more interestingly, why does it sometimes feel like fun? In this article, we will explain why and when you may decide to put in cognitive effort, and what happens in your brain when you make this decision.

COSTS AND BENEFITS

Imagine that you have a test tomorrow that you need to study for. How much cognitive effort will you put in? Researchers have found that your behavior can be predicted by the calculation of the costs and benefits of studying [1]. What might these costs and benefits be?

To keep it simple, we can say that the benefit of studying is to obtain a good grade. Obtaining a good grade is better for your final report, and you may just like getting good grades. An important cost has to do with the level of cognitive effort you must exert—to obtain a good grade, you will sometimes have to think harder.

Researchers describe your decision to use cognitive effort as a function of the potential benefits and costs. You could think of this as a math equation: the sum of costs and benefits results in a certain value. The more you value something, the more likely you are to put cognitive effort into it.

In Figure 1, you can see that if you have to study very hard for a good grade, the value of getting that grade decreases. That means cognitive effort probably also decreases or discounts the value a good grade. This is what scientists call **effort discounting**.

EFFORT DISCOUNTING

The phenomenon that something loses its value if more effort is needed to obtain it.

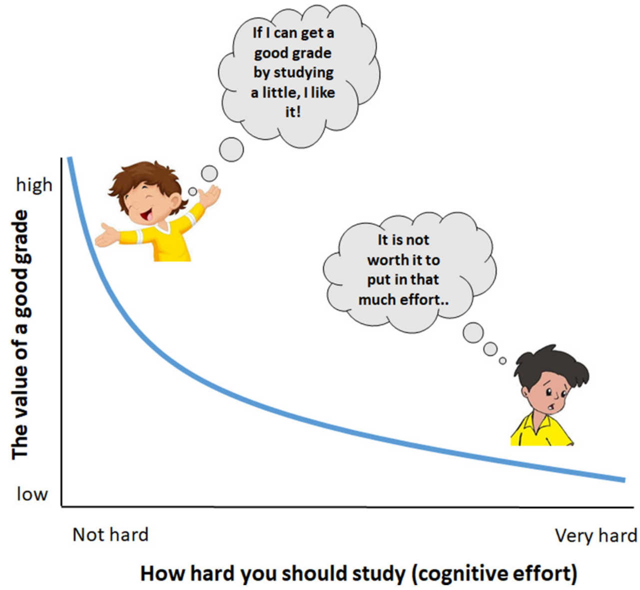

Figure 1

Figure 1

The blue line represents the value a good grade as a function of how hard you have to study for it. As you can see, the value of a good grade will decrease if you need to exert more cognitive effort (study harder). This is what scientists call effort discounting: you like something less because of the effort it requires. The blue line is therefore called an effort-discounting curve.

Box 1 | How do neuroscientists measure brain activity?

Functional magnetic resonance imaging (fMRI) is a brain imaging technique used by scientists to visualize what the brain is doing in different circumstances. The brain consists of around 100 billion cells, called neurons. These neurons communicate with each other through chemical and electric signals. If neurons send more signals to each other, they need more oxygen. This oxygen is delivered via the blood, and if the blood contains more oxygen, it is more magnetic. Thus, with fMRI techniques, we measure how much oxygen different brain regions use by measuring its magnetic signal. This tells us indirectly how active a certain brain region is. For more information about how MRI scanners work, see another Frontiers for Young Minds article [3].

BUT … WHAT HAPPENS IN THE BRAIN WHEN DECIDING TO EXERT COGNITIVE EFFORT?

To measure what happens in your brain when deciding to exert cognitive effort, researchers can use a technique called **functional magnetic resonance imaging** (fMRI) (for an explanation of fMRI, see Box 1). With fMRI, we can find out which brain areas are active, meaning which ones you are using at that very moment. From fMRI studies, we learned that your brain constantly computes the values of your future actions, by considering the costs and benefits of these actions. A specific brain region that is important for signaling potential benefits is called the **ventral striatum**. This region lies deep in the brain and is involved in signaling all kinds of benefits [4], for instance, money, yummy food, or getting a good grade. But what about costs? Scientists observed that the cost of cognitive effort is signaled mainly by a different brain region, which is called the **anterior cingulate cortex** [5].

FUNCTIONAL MAGNETIC RESONANCE IMAGING (FMRI)

A brain imaging technique used to visualize which brain areas are active at a given moment.

VENTRAL STRIATUM

A brain area involved in signaling benefits of expending cognitive effort.

ANTERIOR CINGULATE CORTEX

A brain area involved in signaling costs of expending cognitive effort.

Figure 2

The brain from the front (left) and from the side (right) of your head. On the left, you can see the ventral striatum ("benefit region"). On the right, you can see the anterior cingulate cortex ("cost region") and the ventral medial prefrontal cortex ("sum-of-costs-and-benefits region").

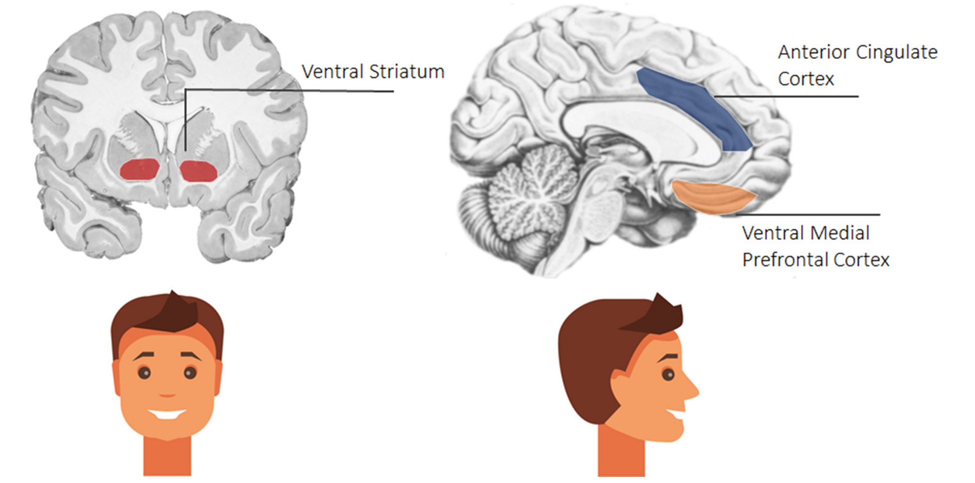

Figure 2

After your brain has considered the costs and benefits, the ventral striatum and the anterior cingulate cortex will work together to exchange information. Thus, in our example, your brain weighs in the costs (cognitive effort) and benefits (good grade) of studying, and then calculates how much you value obtaining a good grade and, as a consequence, whether it is worthwhile to study. Researchers think this exchange of information happens in a brain region toward the front of your brain, called the **ventral medial prefrontal cortex** (Figure 2).

VENTRAL MEDIAL PREFRONTAL CORTEX

A brain area where the costs and benefits are weighted.

WHEN DO YOU WANT TO EXERT COGNITIVE EFFORT?

Now that we know what cognitive effort is and what happens in the brain when deciding how much cognitive effort to put in, we can return to the question we started with: when do you want to invest cognitive effort?

By now, you may realize that the brain considers cognitive effort to be costly. Therefore, too much effort typically feels unpleasant. You may think that your brain makes you lazy, but that is not necessarily the case. Your brain is trying to balance whether it is worth putting in cognitive effort.

However, your willingness to exert cognitive effort is not always the same. You may recognize that sometimes you feel like putting in cognitive effort and sometimes you really dislike thinking hard. The willingness to exert cognitive effort is not always the same—it is changeable! How hard you feel like thinking can depend on the time of day (morning or evening), how you feel (tired or rested), and whether or not you enjoy the activity that needs your effort [6].

Figure 3

(A) A standard effort-discounting curve: the value of a good grade decreases with increasing cognitive effort. The red cross in both pictures indicates a point where the value of a good grade is average, and the gray dotted line shows the amount of studying needed to get to that average-value grade. **(B)** If you take away distractors, like your phone or the TV, adding more effort now decreases the value of a good grade less quickly. This will lead you to study more, because the cognitive effort feels less costly.

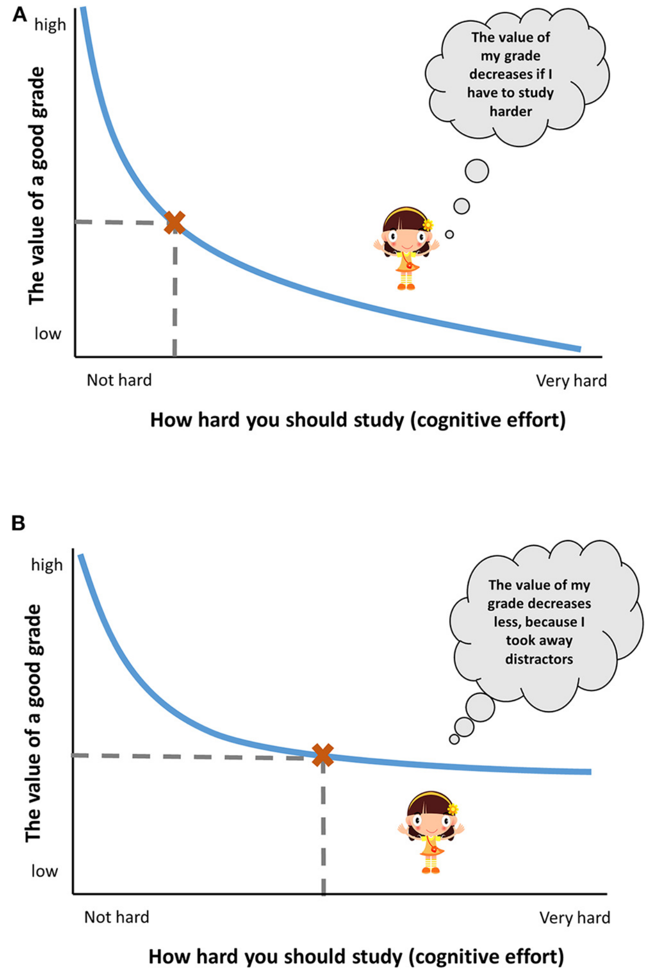

Figure 3

TIPS FOR EXERTING MORE EFFORT

If your willingness to exert cognitive effort is changeable, then a very important question is: can you increase your willingness to exert cognitive effort for your test tomorrow? Well, the answer is … yes! Based on the knowledge you now have, you can try three simple tips.

First, lower all other costs for your thinking brain [1]. So, take away distractors, such as your phone, to help you focus. To see what might happen, take a look at Figure 3. Removing distractors makes cognitive effort feel less costly.

Second, increase the benefits. For example, you could reward yourself with a treat after studying hard for 1 h. Or you could tell yourself that if you get a good grade, you will buy yourself something nice.

Third, try to increase your enjoyment of the effortful task itself. For example, if you do not like maths, use a math game to make it more fun. In this way, you might even come to enjoy the efforts you spend on learning maths.

With these tricks, you will surely get your homework done with more ease. Good luck!

AUTHOR CONTRIBUTIONS

A-WK and AD wrote the manuscript together. HH and LK provided the critical revisions.

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YOUNG REVIEWERS

SEAWELL ELEMENTARY, AGE: 10
Our amazing classroom in NC is full of sparking, learning minds. We love helping each other. We think, solve, and learn! We do projects that stretch our brain, and sometimes when we work together, our ideas can get messy but the results are always fun. One of the ways we love to be awesome? Embrace your inner editor! We love to read and peer edit, and were so excited to have the opportunity to work with Frontiers for Young Minds!

AUTHORS

ANNE-WIL KRAMER
I am a Ph.D. candidate at the University of Amsterdam. I fill my time with a variety of efforts. I like to expend physical effort by cycling through Amsterdam and swimming (not in the canals). I also enjoy expending cognitive effort, for example by playing games or thinking about how things work. Sometimes I look at my cat, wondering why he can be fine not expending any effort all day! But honestly, I also sometimes feel like that. Because of this, I wondered how this all works? To study effort, we conduct research in which we let people make decisions about how much effort they want to spend. *a.kramer@uva.nl

HILDE M. HUIZENGA
I am a professor in Developmental Psychology at the University of Amsterdam. I use a lot of math to study how children grow into adults and how adults grow into older people. Sometimes I think hard when I am standing at my desk, sometimes I also do so when I am running, or talking with our teenage daughters, or cycling through Amsterdam. While cycling, I came up with the figures in this paper. I hope you like them.

LYDIA KRABBENDAM

I am a professor in Developmental Neuropsychology at the Free University of Amsterdam. I know all about cognitive effort in education, as I have three school-going children myself! I further investigate social interactions in classrooms and how this relates to the interplay between social interactions and brain and cognitive development. I find this an interesting topic, because if you work or study together with people you like, this may also make effort feel much more fun.

ANNA C. K. VAN DUIJVENVOORDE

I am an associate professor in Developmental Psychology and brain development at Leiden University. I want to know everything about motivation, learning, and how the brain works. Is not it interesting that your motivation changes as you age? Does that relate to the development of your brain? I was not always motivated in school, but when I got to choose my own studies of neuropsychology, I found it fascinating. Working hard was not difficult anymore! With my work, I hope to be able to build motivational experiences and help children learn.

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NEUROSCIENCE
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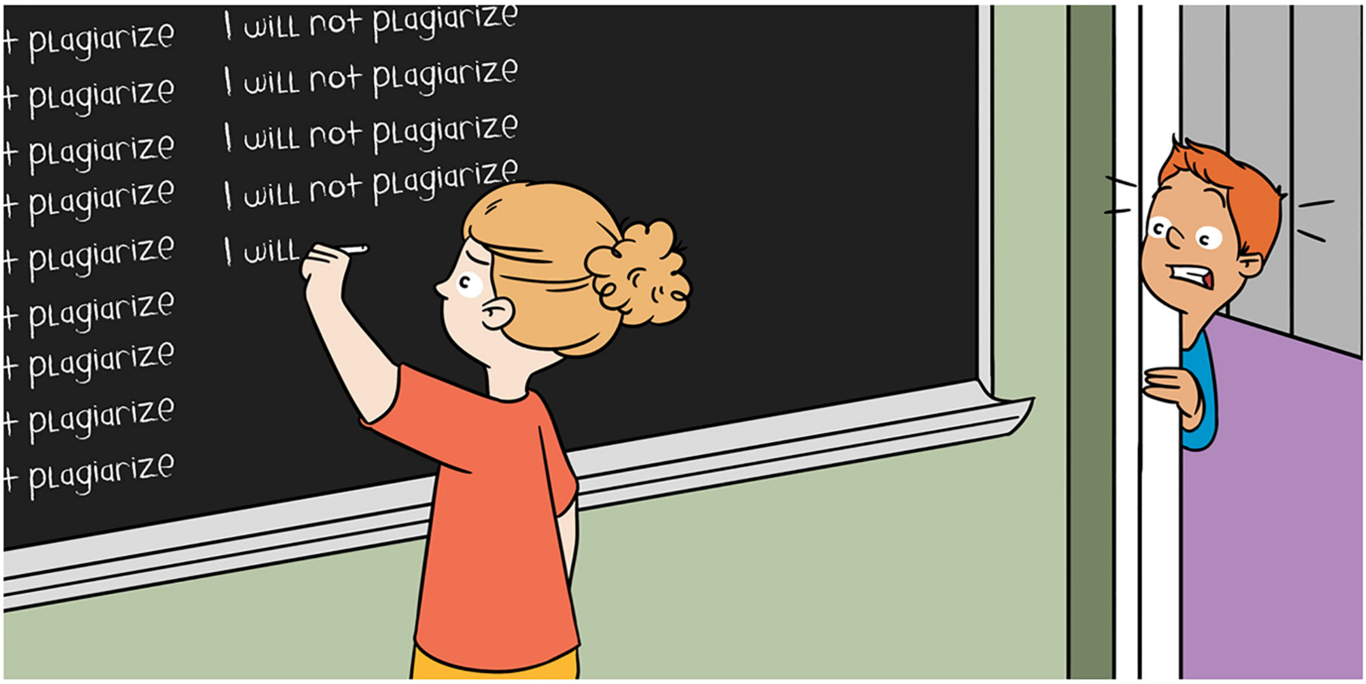

SOCIAL LEARNING AND THE BRAIN: HOW DO WE LEARN FROM AND ABOUT OTHER PEOPLE?

***Bianca Westhoff*[1,2*], *Iris J. Koele*[1,2] *and Ilse H. van de Groep*[2,3,4]**

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YOUNG REVIEWERS:


ANISHA
AGE: 13


ELI
AGE: 13


HENRI
AGE: 13


SARAH
AGE: 14


SPANDANA
AGE: 12

When you think about learning, you probably think about things you are taught at school. But have you ever realized you use a different type of learning as well, on a daily basis? This type of learning is called social learning, and it has to do with the people around you. That is, you learn from and about others by watching and interacting with them. For example, seeing someone else's mistakes may teach you to avoid falling into the same trap. Although social learning happens very often, you may not yet know much about it. However, social learning is very important because it helps us to learn more efficiently and to determine how best to behave around others. In this article, we introduce two different types of social learning, and explain how your brain plays an important role.

WHAT IS SOCIAL LEARNING AND WHY IS IT IMPORTANT?

When you think about the most recent thing you learned, the first thing that comes to mind is probably something you learned at school. For example, the French vocabulary you need to know for your upcoming test. Learning such things may be useful in the future: if you ever go to France on holidays, you will be able to ask for directions, for instance.

Clearly, learning knowledge (such as the French vocabulary) can be quite important. However, in addition to learning from books, you can also learn from and about the people around you. This is called **social learning** because, for this type of learning, people are the source. Most of the time, you are surrounded by other people, including your family, teachers, and school friends. Therefore, you probably learn from and about others every day, perhaps without even realizing it!

SOCIAL LEARNING

Learning new information in a social context, with other people being the source of this information. Examples are learning from or about other people.

Because humans are such social beings, social learning is an important skill. Social learning is a very efficient way to learn things. For example, you do not have to figure everything out on your own, because you learn from other people's mistakes and successes. Also, social learning can enable you to get to know others better, and therefore to better understand how to behave around them. Such social learning skills help you to have good relationships with others, which is good for your well-being.

In this article, we explain two types of social learning: learning from other people and learning about other people. To show that you already use these types of social learning frequently, we will provide examples that you may encounter in school. Finally, because your brain plays a critical role in learning, we will explain how social learning works in the brain.

HOW DO WE LEARN FROM OTHER PEOPLE?

One important type of social learning is learning from someone else, by watching what they do. The idea is that other people's mistakes and successes can teach you whether you should behave the same way, or differently [1].

For example, imagine you are taking a test in school, but you just do not know enough of the answers to get a good grade. Your friend is sitting next to you, and you see she has already written down her answers. You may be tempted to take a quick look … but then, suddenly, one of your classmates gets caught cheating and is punished. Now you will probably think more negatively about cheating, because you have seen that it may result in punishment! In other words, you have learned from someone else's mistake that it is better not to cheat during a test.

When you learn from watching other people, you are learning about the choices they make (such as cheating), and the results of those choices (such as punishment). If the results are positive, you are more likely to make the same choice. However, if the results are negative, you will probably make a different choice.

Scientists have discovered that people are good at learning about the best choices to make. However, we learn even better if we can also watch other people learning the same thing [1]. When we watch others' choices, whether the results are good or bad, we have extra information on what the best choice may be. We use that extra information to improve our own choices. So, we benefit from learning from others, as it helps us to make better choices ourselves. This makes learning from other people's mistakes and successes more efficient than figuring things out on our own.

HOW DO WE LEARN ABOUT OTHER PEOPLE?

We have just explained that people learn efficiently from other people, by watching them. Another common type of social learning is learning about other people, by interacting with them. When you learn about other people, you learn what they are like and how they behave. For this type of learning, you need to pay attention to other people's behavior so you can use this information in future decisions.

For example, imagine you tell one of your classmates that you like the boy sitting two tables away. However, it turns out your classmate is actually untrustworthy: your secret ends up being passed on to the entire class and you are very upset! In this case, you may have learned that it is better not to tell her your secrets again.

Although there are a lot of things you can learn about other people, many scientists study how we learn about other people's trustworthiness. Learning who you can trust is very important, because it helps you to decide whether you can believe the things a person says.

Scientists have discovered that, during the teenage years, we become better and faster at learning who we can trust and who does not deserve our trust [2]. So, during development, we become better at learning about others. This type of social learning therefore helps us to decide how to behave around others, which is necessary to build good relationships.

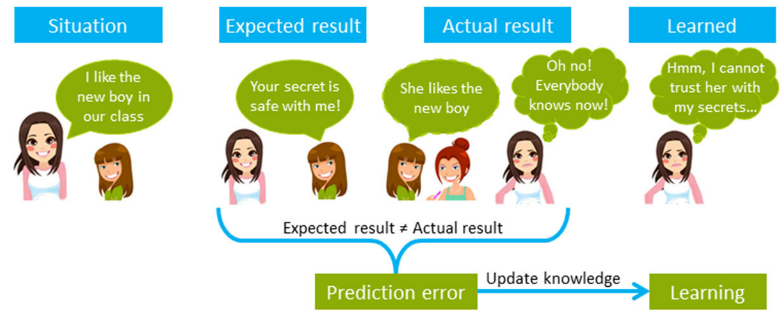

Figure 1

Figure 1

Prediction errors result in learning. If there is a difference between what you expect to happen (expected result), and what actually happens (actual result), there is a prediction error. This prediction error is then used to update your knowledge: you have learned something new.

HOW DOES SOCIAL LEARNING WORK?

Now that we have introduced these two types of social learning, we will explain how social learning works. When you learn something, you are updating the things you know with the new information. Your brain is involved in this updating: it works like a calculator. That is, your brain is constantly calculating the difference between what you expect to happen, and what actually happens. If something unexpected happens, this may surprise you. The surprise is called a **prediction error**—you made a mistake (error) in what you predicted would happen. Your brain notes this prediction error and makes sure you learn from it, updating what you already know with the new information.

PREDICTION ERROR

The "surprise" when there is a difference between what you expect to happen, and what actually happens.

In the case of social learning, consider the example we discussed earlier, when you told your classmate about your secret crush (Figure 1). You expected her to keep quiet, but she did not. So, what happened was quite surprising because it was different from your expectation. Your brain notes the prediction error and uses this new information to update what you know about your classmate. That is, you have learned about your classmate, and you will not easily trust her with your secrets again[1] .

[1] Want to know more about the calculations your brain does when you are learning something? Why not read [3]?

WHICH PARTS OF THE BRAIN ARE INVOLVED?

To make all the calculations necessary for social learning, several areas of your brain are used [4]. Scientists have discovered at least two brain areas that are important for social learning, called the **ventral striatum** and the **medial prefrontal cortex (mPFC)** (Figure 2). They made these discoveries by using an MRI scanner to scan people's brains. In Box 1, you can read more about how an MRI scanner works.

VENTRAL STRIATUM

Brain area that is, among others, involved in (social) learning because it calculates prediction errors.

MEDIAL PREFRONTAL CORTEX (MPFC)

Brain area involved in, among others, social learning because when there is a prediction error, the mPFC updates your incorrect expectations in the brain with the new information you learned.

The ventral striatum is an area in the middle of the brain that you use when you make decisions, when you enjoy something, and when something is rewarding. Also, the ventral striatum is important for calculating prediction errors [4]. It is therefore an important brain area for regular learning and social learning.

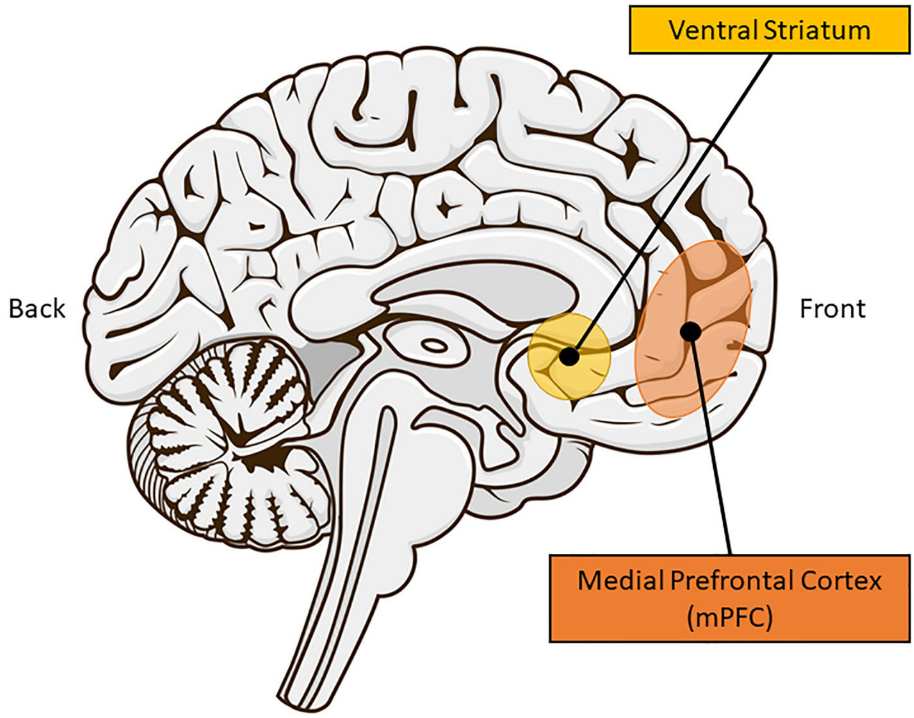

Figure 2

Figure 2

Brain areas involved in social learning. The ventral striatum (in the middle of the brain) calculates prediction errors, and these newly learned expectations are updated in the medial prefrontal cortex (mPFC, in the front of the brain). These two brain areas are therefore important in social learning.

The mPFC is an area in the front of the brain (behind your forehead), that seems particularly important for thinking about what others are thinking, and for making decisions that involve other people. Also, the mPFC is involved in learning: After prediction errors are calculated by the ventral striatum, your MPFC updates the expectations you had with the new information [4]. The mPFC is, therefore, another important brain area for social learning.

So, the ventral striatum and the mPFC both play roles in social learning. However, it is important to realize that these brain areas are involved in other behaviors, in addition to social learning. Also, the ventral striatum and the mPFC are not the only parts of the brain used during social learning—many brain areas are involved. All these brain areas work together and communicate with each other while you are learning in complex social situations.

RECAP: WHAT YOU HAVE LEARNED ABOUT SOCIAL LEARNING

In this article, we have explained the two types of social learning and why social learning is an important skill. First, learning from other people's behavior and their resulting mistakes and successes is more efficient than figuring things out on your own. Second, learning about other people by interacting with them can help you to learn who you can trust and help you to build good relationships. When what

Box 1 | Studying the brain: how do we know what is going on there?

To understand how social learning works, many scientists study the brain using a magnetic resonance imaging (MRI) scanner (Figure 3). This scanner is a huge magnet that can take pictures of the brain through the skull. Scientists may use MRI to take pictures of someone's brain while that person is playing a computer game involving learning from or about others. In this way, scientists can find out which parts of the brain are involved during social learning. To find out more about how MRI scanners work and how they are used to study the brain, see [5].

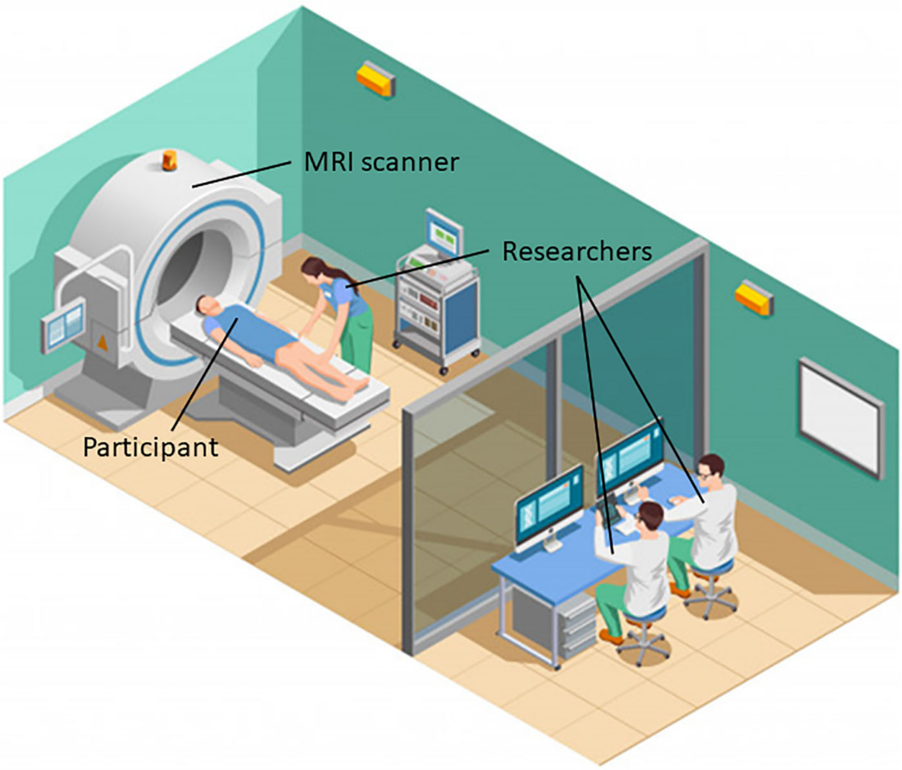

Figure 3

Figure 3

Researchers use MRI scanners to study people's brains. A research setting in which one researcher positions a participant on a bed that will slide into the MRI scanner. Two other researchers are behind a computer screen, where they will see images of the participant's brain after they start the MRI scanner.

actually happens does not match what you predicted would happen, prediction errors are calculated in the brain, and these prediction errors result in learning. Prediction errors are calculated in the ventral striatum, which the mPFC uses to update the information already stored in the brain.

Now that you know more about social learning, perhaps you can think of your own examples of when you learned from or about others. Maybe you can think of ways social learning helped you to learn more efficiently, or to decide the best way to behave around others. The next time you watch or meet other people, think about the amazing calculations that are going on in your brain!

ACKNOWLEDGMENTS

We would like to thank those who assisted in the translation of the articles in this Collection to make them more accessible to kids outside English-speaking countries, and for the Jacobs Foundation for providing the funds necessary to translate the articles. For this article, the authors themselves translated it into Dutch as well. We would also like to thank Anna van Duijvenvoorde and Marieke Bos for comments on an earlier version of this article. BW was supported by an Open Research Area (ORA) grant (464-15-176) financed by the Netherlands Organization for Scientific Research (NWO), awarded to Dr. Anna C. K. van Duijvenvoorde. IK was supported by the NWO Westerdijk Grant (014.041.030), awarded to Prof. Berna Güroğlu. IG was supported by the Ammodo Science Award 2017 for Social Sciences, awarded to Prof. Eveline Crone.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

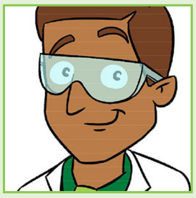
YOUNG REVIEWERS

ANISHA, AGE: 13

I am a seventh grader at Synapse School. I am passionate about neuroscience, quantum physics, mathematics, and singing!

ELI, AGE: 13

I am a seventh grader at Synapse School. I enjoy cooking, baking, and reading.



HENRI, AGE: 13

I am an eighth grader at Synapse school. I enjoy reading Frontiers articles.

SARAH, AGE: 14

I am an eighth grader at Synapse School who loves anything related to math, science, or the outdoors, from testing chemical reactions in the kitchen to finding the distance I covered and my average speed while skiing down a mountain. Though I love running around and exploring new things, I also enjoy simpler parts of my day where I can sit with my cat and read. Balancing these activities keeps me engaged with life but also calm.

SPANDANA, AGE: 12

My name is Spandana. My favorite subject in school is science. My best friend is imagination and I love to write stories. Some of my hobbies are talking, watching TV, playing volleyball, and drawing. I love animals and dogs are my favorite. I like to ask questions. My favorite colors are teal and purple.

AUTHORS

BIANCA WESTHOFF

I am a researcher at Leiden University in the Netherlands. I am interested in how we learn about the people around us. Also, I study the brain and how it develops during the teenage years. I am especially interested in how this brain development affects the ways we behave and learn about others. *b.westhoff@fsw.leidenuniv.nl

IRIS J. KOELE

I am a researcher at Leiden University in the Netherlands. I am particularly fascinated by the way teenagers learn from their friends and other classmates, how these social relationships change over time, and what happens in the brain during this sort of learning. Furthermore, I am interested in what happens in the brain when young people with an attention deficit and hyperactivity disorder win rewards for themselves and for their friends.

ILSE H. VAN DE GROEP

I am a researcher at Erasmus University Rotterdam, and the Amsterdam UMC in Amsterdam, in the Netherlands. I am interested in understanding why some people show persistent antisocial behavior (such as aggression) throughout their lives, whereas others do not. To be able to understand these differences, I look at the brain and behavior of young adults who were arrested for a crime when they were children. Amongst other things, I am curious to find out whether social learning and decision-making works differently in these individuals.

frontiers FOR YOUNG MINDS

NEUROSCIENCE
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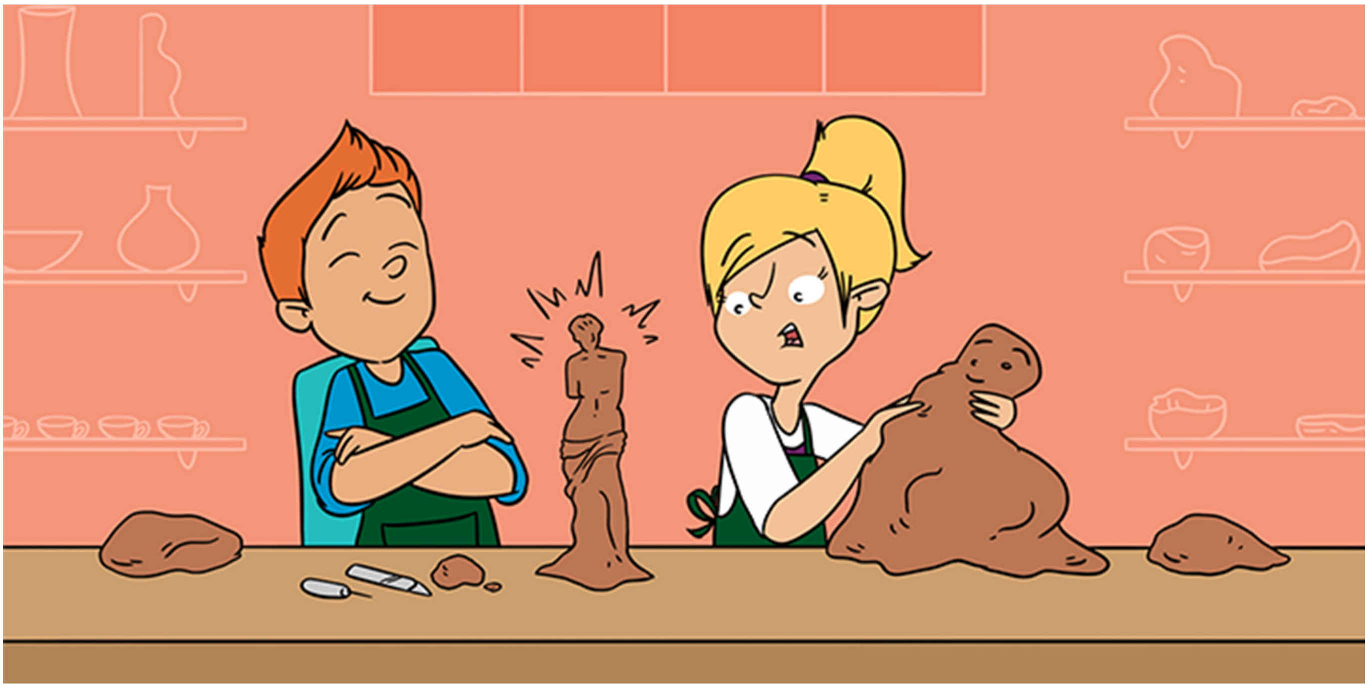

NEURO-MYTHS IN THE CLASSROOM

Victoria C. P. Knowland [1,2*] ***and Michael S. C. Thomas*** [2,3]

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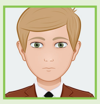
YOUNG REVIEWERS:


ANYA
AGE: 7

DR. H. BAVINCK SCHOOL
AGES: 8–12


LIAM
AGE: 8


MONICA
AGE: 6


OLIVER
AGE: 10


PALOMA
AGE: 8

Have you ever heard that we only use 10% of our brains? It is a nice thought that we could tap into hidden brain power—but could most of our brains really be doing nothing all day? No! Every bit of your brain is busy 24 hours a day. There are lots of these so-called neuro-myths floating around: ideas about the brain that sound true, but are not. There is usually a good reason why a neuro-myth got started: maybe there is an element of truth to it, or maybe people would just like it to be true. In this article we explore three widely believed neuro-myths about the growing brain, and explain why it is important for you to know what is true and what is not. We will explore whether you can change how clever you are, whether girls and boys think differently from each other, and whether some children are "left brained" and some are "right brained."

WHAT IS A NEURO-MYTH?

A myth is something that a lot of people think is true, but actually is not (for example, that King Arthur was a real king in England) and "neuro" tells us that we are talking about the brain. So, a neuro-myth is a statement about the brain that is often thought to be true, but is not. There are lots of neuro-myths, like that we only use 10% of our brains, or that our brains are not active while we sleep. You may well have come across these ideas yourself, and whether you realize it or not, they could be making a difference to the way you think about your own brain and the way you learn in school. Importantly, neuro-myths are also things that parents and teachers might believe and that can affect how they think about the growing mind. Neuro-myths can influence how teachers teach and how parents, you know, parent. In this article, we will spend a little time exploring three neuro-myths, then think about why it matters that you know how to spot a myth when you hear one.

MYTH #1: INTELLIGENCE IS FIXED

The idea here is that how well you can do on things like school exams or tests of **intelligence** depends on your **genetics**. Genetics means something that runs in families—things like eye color and height usually depend strongly on genetics. If your intelligence were fixed by genetics, then how well you do on school exams would depend on how well your parents do on tests of intelligence, or how well they did on school exams. It is clear where this idea came from, because children can indeed be very similar to their parents. Actually, we can measure how similar children and their grown-ups are. If you take a group of twins, some identical and some non-identical, and choose a behavior—say, juggling—you can work out how much differences in that behavior are influenced by genetics and how much the differences are due to the environment in which the children were raised. This is because identical twins share 100% of their genetic make-up, while non-identical twins only share 50%, yet both sorts of twins share very similar environments (they live in the same house, they have the same number of juggling classes, etc.). If juggling ability is more similar between identical twins than non-identical twins, this tells you that the identical twins' greater genetic similarity is producing more juggling similarity—so this behavior must be influenced by genetics. We call this genetic influence "heritability". Zero heritability means differences are totally due to the environment, while 100% heritability means all the differences in behavior come from differences in genes.

INTELLIGENCE

Intelligence is a word often used to mean how clever someone is. For example, how well people do on tests to measure things like problem solving. But ask a group of scientists what intelligence is and they'll probably all have a different answer!

GENETICS

Something that is passed on from parents to their children in DNA, so the color of your hair is determined by genetics, but the length of your hair is not.

Using the twin technique, we can see how much genetics has to do with one person doing better than another on a school test. It turns out that a little over half (60–65%) of the difference between children in how they perform at school is due to genetics (Oliver et al. [1] show this for science and maths). Of course, genetics is not the whole story, far from it. After all, no one would know much about anything if they were not taught it!

There are plenty of things that can influence how well you do in the classroom that have nothing to do with your parents: things like believing that your performance can change with learning, or having a great teacher. Every teacher knows that they can make a real, positive difference for a child. One study showed this elegantly: they found that reading ability was more influenced by genetics in classes with better teachers [2]. Here is why this is elegant: if you have a rubbish teacher, this holds everyone back, no matter how good their reading genes are. If you have a perfect teacher, the differences in reading ability are more down to each person's different genetic potential. Let us think of children as plants. Plants should end up being all different heights, like their different parent plants. However, if the little plants do not get enough water, then it does not matter how tall their parent plants are, they would not grow to their full potential. Only when it has enough water (a great teacher) can a plant be as tall as its genetics allow (do as well as it can in school). Work like the study on reading shows us that, while there is truth to the idea that intelligence is passed on from your parents, it is not true that it is fixed. The way your intelligence is revealed depends on you and the world around you.

MYTH #2: GIRLS AND BOYS THINK DIFFERENTLY

The idea here is that girls are born to be better at some classroom activities and boys are born to be better at others. Generally, girls are thought to excel at more creative things, like English, while boys are thought to be better at technical things, like maths. Many scientific studies have been published that show group differences between males and females; for example, males are better at turning images of objects around in their minds. Not everyone believes that males and females are so different though. One scientist **analyzed data** from a bunch of studies including around seven million people in total, looking at gender differences across a range of activities, from talking to throwing [3]. She found that over three quarters of the studies showed gender[1] differences to be small or almost absent. This was true even in areas where people thought there were big differences, like maths ability.

ANALYZE

To decide what a set of information can tell you.

DATA

A set of information.

[1] We use "gender" to mean biological differences between males and females, rather than how people see themselves.

The other important thing is that studies of group differences look at just that: groups. If you take a group of boys, some of them will be great at maths, most will be ok at maths, and some will be bad at maths. The same is true of girls. Even if, as a group, the boys do slightly better on a particular test, that tells you nothing at all about any specific individual (as you can see in Figure 1). The two groups will overlap considerably. Any individual boy will probably do better than lots of girls, and any individual girl will probably do better than lots of boys.

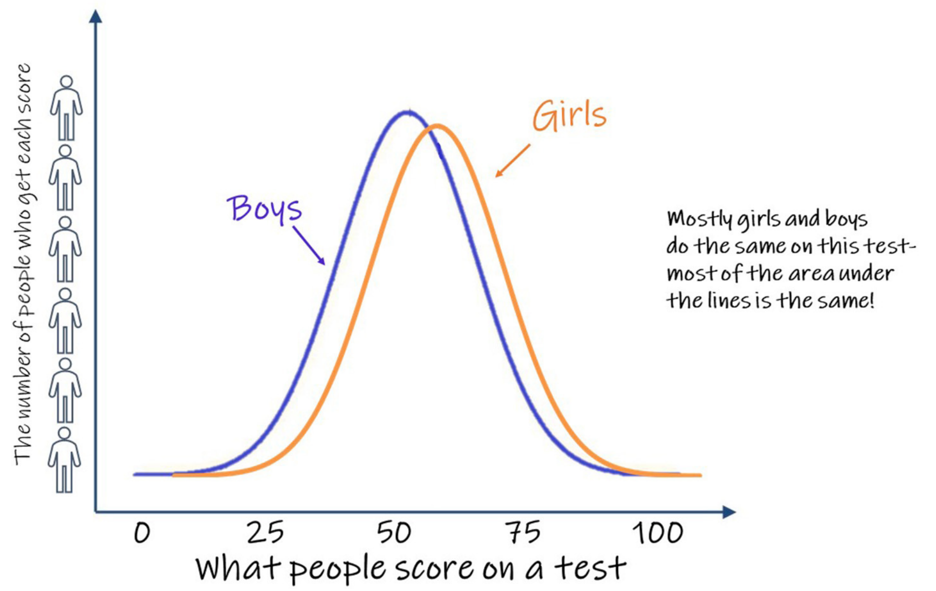


Figure 1

Figure 1

This is an example graph showing how a group of girls and a group of boys did on a pretend test. See how even though the girls do slightly better as a group (the "girls" curve is slightly to the right of the "boys", showing they got slightly higher scores), mostly the two groups overlap.

So, while there may be some differences between the way girls and boys think, those differences are small, and group differences really do not tell you anything about any individual, anyway.

MYTH #3: SOME CHILDREN ARE "LEFT-BRAINED" AND SOME ARE "RIGHT-BRAINED"

There are really two ideas here: (1) the brain is divided into a logical, wordy left half and a creative, emotional right half; and (2) people have one side that is more active than the other, so they are better at either left-brained or right-brained activities.

As we have seen with the other neuro-myths, there is some truth lurking around here. Looking at the brain, one of the most striking things is that there are two very distinct halves (called **hemispheres**) that, to a large extent, are mirror images of each other (as illustrated in Figure 2). It is also true that different areas of the brain specialize in different jobs, like moving your hands or making you scared of spiders. Sometimes that **specialization** can be seen completely (or mostly) on one side of the brain: this is called "lateralization". The classic example is that language (talking and listening to others talk), relies on the left half of the brain in most people. However, even language is not exclusively left-brained: the right brain is important for many aspects of language. For example, the right hemisphere is crucial for understanding why jokes are funny once the left hemisphere has understood the sentence [4]. The two halves of the brain almost always work together like this.

HEMISPHERE

One half of something round—the brain has two hemispheres (left and right), so does the earth (north and south).

SPECIALIZATION

If you specialize in something you do that one thing really well, so someone might specialize in playing the cello. In the article we talk about areas of the brain specializing in doing one thing, like reading words or moving your hand.

Figure 2

This is a drawing of the two halves of the brain.

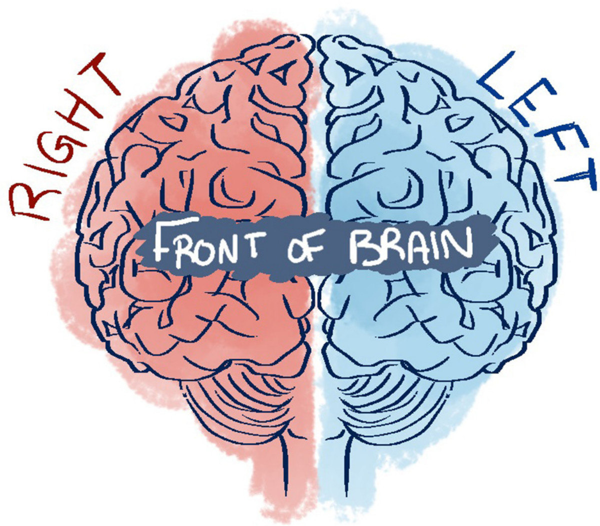


Figure 2

Although we do often use different sides of the brain for different things, this does not mean that people are right-brained or left-brained, as such. A huge study of over 1,000 individuals showed that, overall, people do not have one half of the brain that is more active than the other half [5]. Rather, where activity happens in the brain depends on what you are doing. It also depends on how good you are at doing it. For example, musicians have more brain matter in some parts of the left brain compared with non-musicians [6]; but these differences are seen in specific, small areas of the brain, not generally in one hemisphere or the other. So, although tasks might be more right-brained or left-brained, people are not.

WHY DO NEURO-MYTHS MATTER?

Neuro-myths matter because they affect people's thoughts and behavior: they can change how we see ourselves and how we see each other. Let us take the example of gender again. At age 8 to 9, there is no difference in how well girls and boys do at maths, yet girls (and their parents) rate their maths ability to be lower than boys [7]. This suggests that what people believe (in this case, that girls are not as strong at maths) may have a real impact on how children see themselves, which may in turn affect their actual performance. In one study, when a group of college students was given a maths test, men did better than women when they were told that the test usually shows gender differences, but when they were told it was a gender-fair test, women did just as well as men [8]. This is important because, by the end of education, differences that were once small become massive: 94% of maths professors in the UK are men [9]. This is a good example of why we should be careful about neuro-myths—what you believe about your brain and the brains of those around you may just come true. So, start believing you can do maths!

AUTHOR CONTRIBUTIONS

Written by VK and edited by MT.

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YOUNG REVIEWERS

ANYA, AGE: 7

I like to be active and do many sports with a lot of enthusiasm and as well as I can. My favorites are swimming and gymnastics. I also like to hear new stories through books, storytelling, and movies, and I like to create my own when I play. But I also like mathematics which is my favorite subject at school. I like singing and everything musical, and I make my own muffins for breakfast whenever I can.

DR. H. BAVINCKSCHOOL, AGES: 8–12

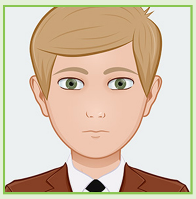
We are Spectrum classes 5–6 and 7–8 of the Bavinckschool in Haarlem, the Netherlands. This is a group of 40 kids (19 in group 5–6 and 21 in group 7–8) who are eager to learn a bit more than the regular school program. They had a lot of fun reviewing for FYM, and went through the articles with great focus and enthusiasm, and made a critical evaluation. They really enjoyed contributing to science and helping out!

LIAM, AGE: 8

I am in third grade and love stuffies and my mom. I am an artist and I love to ski. When I grow up, I want to travel all over the world and in space.

MONICA, AGE: 6

I like to draw pictures... because I want to express what is on my mind. I enjoy going to new cities and countries. I am extremely creative, and I love cooking. I also like to read books and learn things by children all over the world. I like sports like swimming and skating.



OLIVER, AGE: 10

I am in fifth grade and love robotics, math, and science. I just started to learn to play the trumpet. I cannot wait for ski season to start. When I grow up, I want to be an astronaut and travel to Mars!

PALOMA, AGE: 8

Hi my name is Paloma, my favorite things are school and traveling because I like learning new things. Science is my favorite subject because it is really interesting and I have a great teacher. I also really enjoy reading graphic novels because they are fun! I am also really worried about pollution and water conservation and I hope to 1 day find solutions to these problems.

AUTHORS

VICTORIA C. P. KNOWLAND

Vic is a researcher at the University of York. Her job is to try and understand how sleep in childhood might be important for learning language. She is interested in how and why children's language skills are different to each other, for example why some children might know more words than others. She is also interested in how to support children who find communication a challenge. Together with Michael, Vic has written a series of short articles about neuromyths that are relevant to learning in the classroom. *victoria.knowland@york.ac.uk

MICHAEL S. C. THOMAS

Michael is a professor of cognitive neuroscience at Birkbeck, University of London. He is the Director of the University of London Centre for Educational Neuroscience (`http://www.educationalneuroscience.org.uk/`). He uses different methods to understand how the brain works and how people differ in their thinking, including those with developmental difficulties like autism. Within educational neuroscience, his work includes understanding how children learn science and maths and investigating how using mobile phones might change teenagers' brains.

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NEUROSCIENCE
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IT IS COMPLICATED: LEARNING AND TEACHING IS NOT ABOUT "LEARNING STYLES"

Breanna C. Lawrence [1*], ***Burcu Yaman Ntelioglou*** [2] ***and Todd Milford*** [3]

[1] *Department of Educational Psychology and Student Services, Faculty of Education, Brandon University, Brandon, MB, Canada*
[2] *Department of Curriculum and Pedagogy, Faculty of Education, Brandon University, Brandon, MB, Canada*
[3] *Department of Curriculum and Instruction, Faculty of Education, University of Victoria, Victoria, BC, Canada*

YOUNG REVIEWERS:


EMILY
AGE: 11


MIHAJLO
AGE: 16

Learning styles is perhaps one of the most widespread and believed myths in education. The idea is based on the claim that all students can be classified according to their particular learning style, and that they learn best when teachers match instruction to the preferred style of the student. This popular theory has been proven false by many learning scientists. Learning styles theory reduces sophisticated and complex processes like teaching and learning into overly simple categories and labels students in ways that can limit their potential. Studies performed by scientists who study the brain and education have found that learning and teaching are much more complicated than simply matching teaching to a student's learning style.

WHAT DOES THE IDEA OF LEARNING STYLES CLAIM?

You might have heard some teachers say that students have different **learning styles**. For example, maybe they said some people are "visual learners" who prefer to learn by seeing, or that other students are "auditory learners" who learn best by listening, or "kinesthetic learners" who learn best by doing. Maybe you have even taken a survey or test to find out your own learning style. Many people believe that all students can be classified according to their preferred learning styles and that students learn best when teachers match the way they teach to the preferred learning style of the student. Although the theory of learning styles is very popular, it has been proven false by many **neuroscientists**. Despite evidence to suggest that learning styles are not true, many educators still believe it [1]. The idea of learning styles is an example of a **neuromyth**, which is a commonly held false belief about how the brain functions. In this article, we will describe why the learning styles claim is a neuromyth and discuss why it could be harmful to believe this myth. We will also explain how **neuroscience**, which is the study of how the brain works, helps us to understand the complexities of teaching and learning.

LEARNING STYLES

A theory about how people can be classified according to a preferred way of learning, such as visually, auditory, or kinesthetically and instruction works best when it is matched to their preferred way of learning.

NEUROSCIENTISTS

Scientists that study the brain and how it impacts thinking and behaviors.

NEUROMYTH

A commonly held false belief about how the brain functions.

NEUROSCIENCE

The scientific study of the structure and function of the brain and nervous system.

WHY IS THE LEARNING STYLES CLAIM A NEUROMYTH?

The idea of learning styles lacks scientific evidence to support it. However, many teachers, and much of the general population, believe that learning styles exist. Learning styles is perhaps one of the most widely believed neuromyths [2]. One research group [3] found that over 90% of teachers believe in learning styles and another [4] showed that over 60% of teachers think that teaching to students' learning styles helps the students to learn.

Apparently, many people are easily convinced to believe in unproven claims if those claims seem to include neuroscience details. Learning styles is an example of an educational tool that seems so right because there are parts of the claim that are true[1]. For example, people do have preferences for how they learn, or ways they like to learn the best. Presenting information in several different ways is an important educational practice that teachers learn about in teacher's college. However, this does not that mean matching teaching to a student's preferred way of learning actually improves their understanding, because the brain does not work that way.

[1] See danielwillingham.com

WHY IS THE LEARNING STYLES NEUROMYTH HARMFUL?

The belief in learning styles can be harmful because the theory of learning styles reduces complicated processes like teaching and learning into overly simple categories and labels students in ways that

Figure 1

How you learn info graphic. The info graphic illustrates how you learn is not easily reduced or categorized. Created by Brendon Ehinger (http://ehinger.ca/).

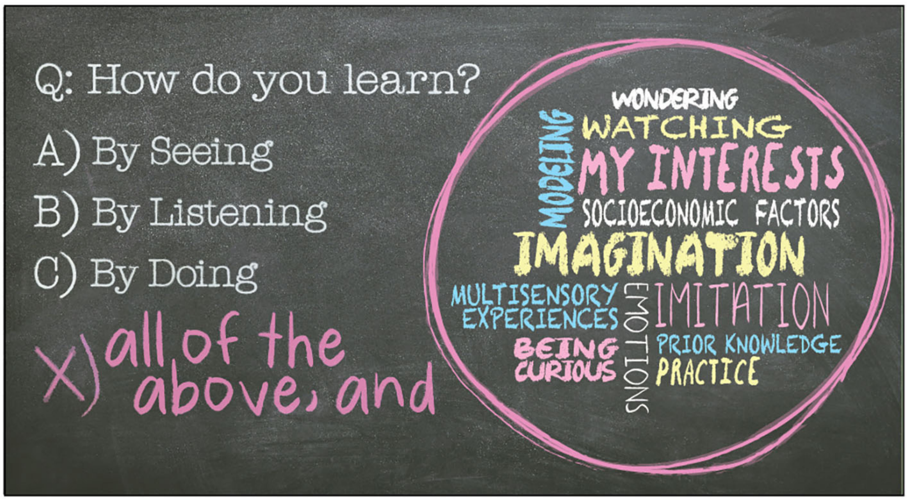

Figure 1

can limit their potentials (see Figure 1). It is appealing to assume that students could learn more easily if instruction was simply changed to match their individual learning styles, but the way the brain processes information is much more complicated than that.

Imagine this: you determine you are a visual learner, meaning you prefer instructions that are presented visually. In French class, you are working on developing your conversational skills and accent. You read and see many written examples of conversations and there are even phonetic spellings presented (the words are written out the way they sound), but your preference for visual information is really not helping you speak better French. You struggle to pronounce many words and to understand what a French speaker is saying. Your learning style, "visual learner," does not seem to help you learn better in this situation! Learning a language and the practice of that language require the coordinated use of seeing, hearing, and doing. In addition to these three skills, memory, emotion, motivation, thinking, and imagination are also important parts of the learning process [5]. It is often not possible for teachers to try to limit their teaching to specific learning styles, and it could potentially be harmful to learning if they try to do so—it could create a lot of frustration! We ask that teachers be extremely cautious of the neuromyth of learning styles, because there is no scientific evidence that teaching to specific learning styles actually produces better learning.

Instead, learning happens in an interconnected way. When you remember any piece of information, you process that information using multiple senses, combining what you heard, said, remembered, saw, felt, smelled, etc. Therefore, if teachers believe in the learning styles claim and attempt to limit students to a particular learning style, this could significantly reduce which senses and processes are used for learning, which could impair the ability of some students to learn new information.

NEUROSCIENCE HELPS US TO UNDERSTAND THE COMPLEXITY OF TEACHING AND LEARNING

PLASTICITY

The brains ability to form new connections, be flexible, and ability to be modified by experience.

NEURAL NETWORK

Consist of many interconnected neurons.

NEURON

A cell in the nervous systems that sends information to other cells (other nerve cells, muscles, or gland cells). Nerve cells are considered the basic units of the brain.

[2] See https://husman-memory.net/brain- neurons-synapses/

Neuroscience helps us understand the complexity of how the brain grows and changes when learning happens. Teachers should know that neuroscience research indicates that learning is based on experience, not learning styles. Therefore, learning about neuroscience helps teachers provide better instruction in the classroom. In teacher's college, we learn about how our brains have **plasticity**, which means our brains adapt to our experiences. So, teachers should expose students to a lot of experiences, in many different ways, and also take into consideration students' prior knowledge, abilities, and interests. Daily events in our lives and the lessons we learn in the classrooms create **neural networks** that help us use and remember what we have learned. A neural network consists of many interconnected brain cells, called **neurons**. At birth, a human has only a small percentage of the neural network and the vast majority of the network is created through life experience[2] Meaningful explorations and practice strengthen neural networks and also help students feel more confident, capable, and connected to what they are learning. In response to experiences, neurons form and eventually whole networks of connections can become specialized for functions like speaking an additional language. So, as we learn new things, our brains adapt by creating new connections between neurons, changing the neural network. Learning takes time and practice, just like learning to speak a new language the more you practice and the more you are exposed to the language, the more efficient you will be at processing and performing skills like speaking and comprehending.

LEARNING IS COMPLEX

MULTIFACETED

Includes many parts.

The neuromyth of learning styles can be very problematic, as it reduces learning and teaching process into overly simple processes that do not actually help students learn more efficiently. Even though this theory has been proven false, many people still believe it! Learning styles is one of the most popular neuromyths among teachers. What is important to remember is that learning actually involves underlying thinking processes and relies on our experiences. We know that students' background knowledge, abilities, and interests are central to their learning, not learning styles. The process of learning and the ways that our bodies and brains are interconnected is **multifaceted**, and scientists who study learning are still discovering and understanding how these processes work. Learners need to be exposed to a variety of tasks and have information presented in multiple ways. The ways information is presented must be meaningful not only to what is being learned (like a new language), but also to the learner. We hope you can see that teaching is much more complicated than simply matching a learner to a learning style!

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YOUNG REVIEWERS

EMILY, AGE: 11

My name is Emily and I am an 11-years-old aspiring lawyer and astronaut. I live in London, England and will move to secondary school this year. My favorite subject is English literature. In my free time I enjoy swimming, Irish dancing, and reading Harry Potter.

MIHAJLO, AGE: 16

Hi. I am Mihajlo and I am currently a sophomore at Third Belgrade Lyceum. My favorite thing about science is that you never know what is going to happen in the end. What drives me to neuroscience is the fact that we know so little about the brain and the nervous system and that there are many things waiting to be discovered by us, passionate scientists. I like learning new things and it is the reason why I do a lot of scientific research with my science mentor.

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Breanna is a professor of educational psychology (the study of teaching and learning) and a counselor educator. She teaches students who would like to become teachers about child and adolescent development and learning theories and also teachers about becoming school counselors. Breanna researches issues related to child and youth resilience, which has been informed by her professional background working in educational and clinical mental health settings with families over the past decade. She loves prairie sunsets and outdoor adventures with her husband and two kids. *lawrenceb@brandonu.ca

BURCU YAMAN NTELIOGLOU

Burcu is an education professor at Brandon University in Canada. She teaches students who would like to become teachers, and teaches graduate courses to teachers and principals who would like to improve their teaching. Advocating for diversity and equity in education, Burcu is interested in how students develop their languages and literacies in an increasingly global world. Burcu gets to watch a lot of ice hockey games in her free time since she is the proud parent of two boys Deniz (16) and Derin (10) who are both hockey players.

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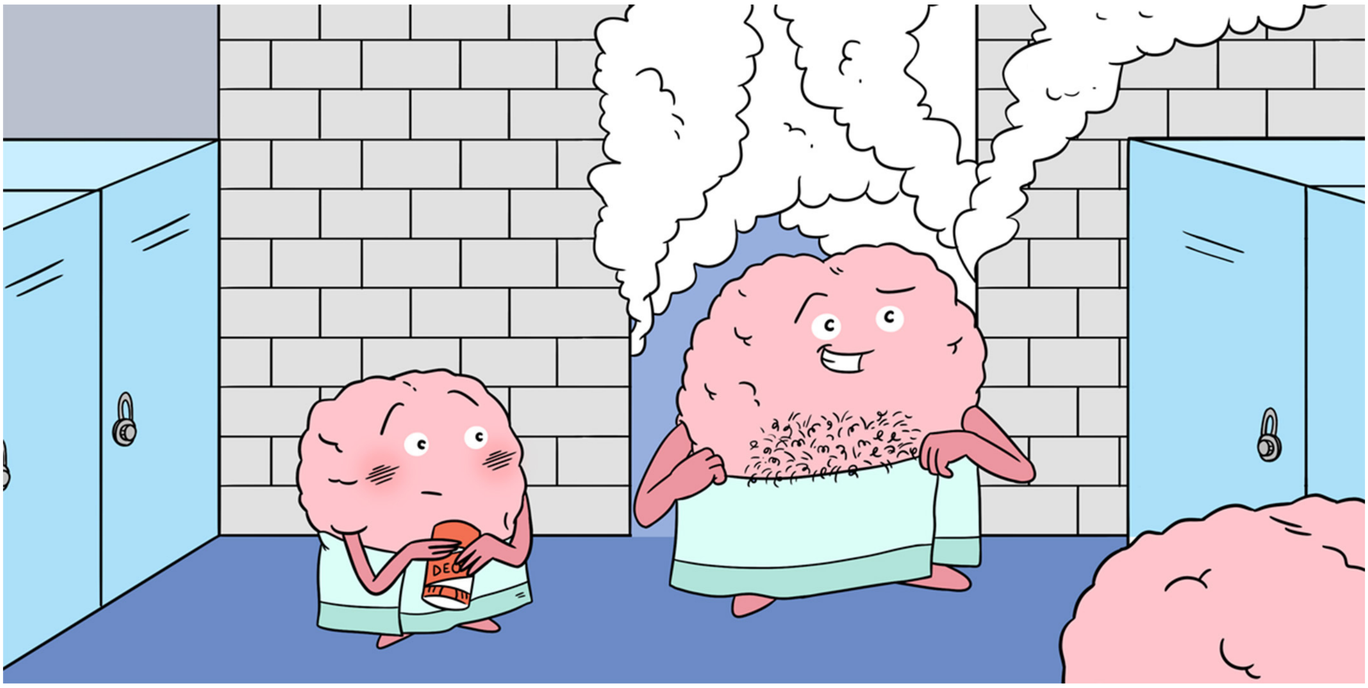

YOUR BRAIN ON PUBERTY

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YOUNG REVIEWER:

BENJAMIN
AGE: 11

Puberty is a normal part of development, but it is also different for everyone. For some teenagers, puberty comes earlier than for others, and for some it goes faster than for others. Because of this, kids of the same age can look very different from each other—their bodies are growing at different rates. However, researchers have discovered that puberty not only changes your body, but also your brain. This is because puberty involves changes in hormones that also attach to your brain cells and change how the brain learns and grows. These changes are useful because they help shape the brain for new forms of learning. They might also lead to some "bumps in the road"—for example, you might take some risks that do not quite work out. In this article we explain what puberty does to the brain, and why these brain changes are important to prepare you for adulthood.

WHAT IS PUBERTY AND WHAT ARE HORMONES?

Puberty is a normal part of development that happens in the early teenage years. When you think of puberty, you might think of zits, body odor, and hair growth—among many other, sometimes awkward body

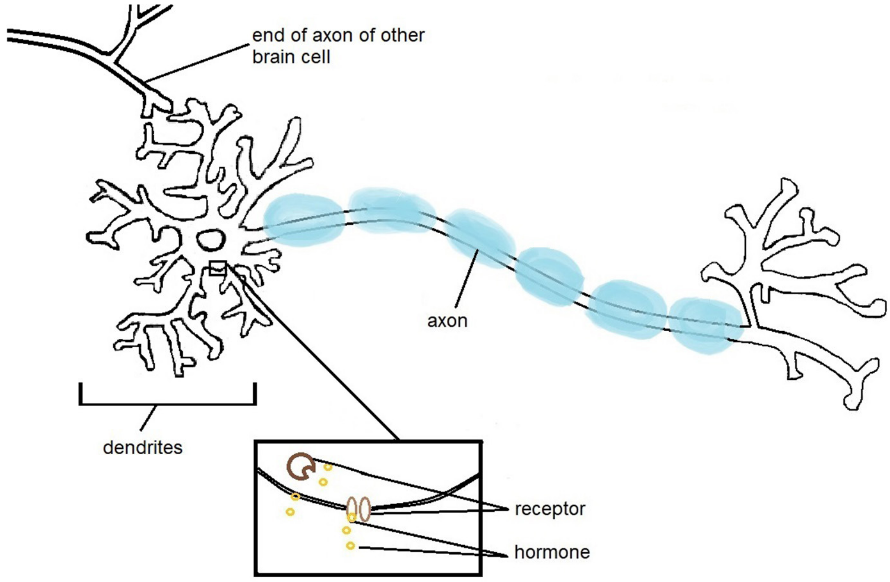

Figure 1

Figure 1

A brain cell and all its parts. The box is a zoomed in view of how hormones can attach to receptors in or on the cell. In blue is myelin, a protective sheet that wraps around the axon and allows the signals to travel faster.

changes—but do you know what happens in your body to cause these changes? The brain signals the body to start puberty by passing along messages in the form of **hormones**. Hormones are small molecules made by your body that travel in your bloodstream to various parts of the body, including the brain. Hormones are important for passing messages over long distances in your body, so that different organs can communicate with each other. When a hormone reaches its destination, it attaches to what is called its **receptor** on or in a cell (see Figure 1). This triggers a response in the cell that can influence the cell's behavior and even its survival. How the cell responds depends on the type of cell and type of hormone.

HORMONES

Small messengers that travel in the bloodstream to various parts of the body. Testosterone and estradiol are two hormones that are important for puberty.

RECEPTOR

A structure in or on a cell that a hormone or other messenger can attach to.

Hormones are really important for kicking off the process of puberty. This is because puberty starts when the brain signals the body to make more of certain hormones. Figure 2 explains how this works.

Testosterone and estradiol are two important hormones that cause a lot of the body changes that people associate with puberty. Levels of testosterone increase much more in boys, while estradiol increases more in girls. Testosterone can, for example, travel to the hair cells, leading to darker and thicker hair, and hair growth on the underarms or face. Estradiol is important for breast development in girls. Both testosterone and estradiol are also important for fertility, making it possible for people to have children.

The age at which this whole process happens varies a lot from person to person. On average, girls tend to start puberty around age 10, while boys start a year later. Part of the individual differences are based on genes, but they are also partly related to experiences earlier in childhood. For example, children who have been through

Figure 2

This figure shows how a signal from the brain leads to increases in puberty hormones. It starts in a brain region called the hypothalamus. That makes a hormone called GnRH, which travels to the pituitary gland, a small organ at the bottom of the brain. In the pituitary gland, other hormones are made (LH and FSH). They then travel to your sex organs (these are testes in male bodies and ovaries in female bodies), which make testosterone and estradiol.

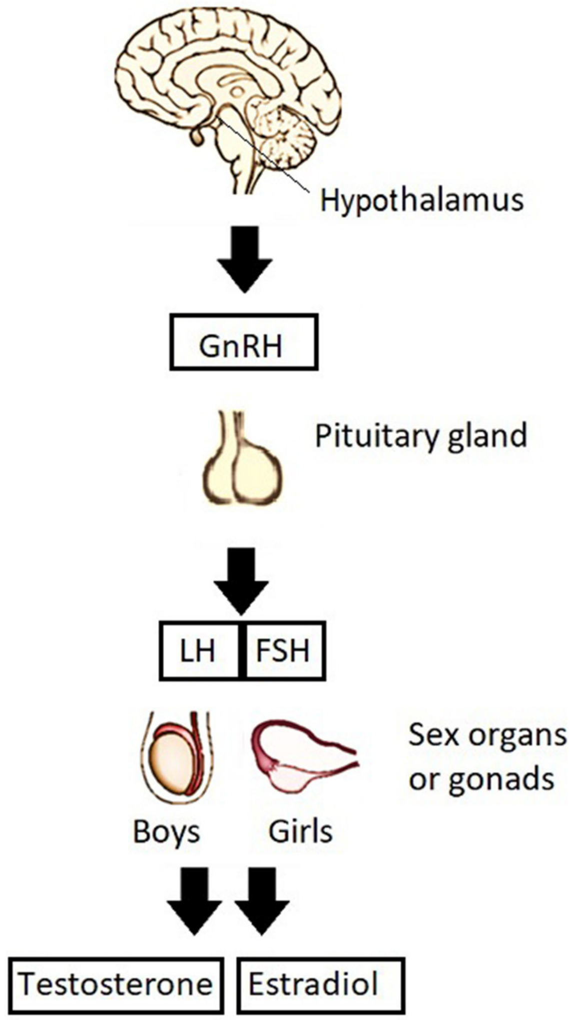

Figure 2

a lot of stressful times early in life tend to go through puberty at an earlier age.

HORMONES CAN CHANGE HOW THE BRAIN IS ORGANIZED AND HOW BRAIN CELLS BEHAVE

Hormones like testosterone and estradiol can attach to your brain cells. A brain cell looks different from cells in other parts of the body: it has a cell body, but also has parts that look like wires sticking out (see Figure 1). A brain cell often has many shorter "wires," called **dendrites**, for receiving signals from other cells. These cells also have one longer "wire" called an **axon**, which sends signals to other cells.

There are two main ways that hormones can influence your brain cells [1].

DENDRITE

The part of the brain cell that receives signals from other cells.

AXON

The part of the brain cell that sends signals to other cells.

AMYGDALA

A small region near the bottom of the brain that is important for processing emotions like fear.

First, hormones can influence how the brain is organized, and these are changes that take some time to occur. Changes in brain organization can include changes in the number of cells, or changes in the size and shape of dendrites or axons. Testosterone, for example, influences the development of new cells in a brain region called the medial **amygdala**. Because boys make more testosterone during puberty, this region becomes bigger in boys than girls [2]. This was found in animal research, but studies on humans that looked at hormone levels and the size of the amygdala suggest it works the same in humans.

Second, a hormone can influence the way that brain cells become activated in response to a situation or environment. Hormones might help or prevent a cell from exchanging signals with other cells. This can also lead to long-term changes in brain cells. For example, the levels of testosterone in mice (and humans) increase during a competition or fight. One study showed that mice who win a fight develop more receptors for testosterone in brain regions that are important for reward and social behavior [3]. These new receptors might also change the behavior of the mouse in the next fight. This shows a process where experiences, like winning a fight, and hormones work together to shape brain development. This process is especially important during puberty, when the hormone levels are higher than during childhood and the brain is still developing.

There is still a lot we do not know about how hormones influence the organization and actions of brain cells in humans. We do know that these effects are different in some ways between boys and girls, and between regions of the brain. Researchers are just starting to figure out how the hormone-related changes in the brain are important for behavior and learning, so there are a lot of unanswered questions.

PUBERTY MAY MAKE IT HARDER TO LEARN SOME THINGS, BUT EASIER TO LEARN OTHERS

Children can learn certain things better than teenagers or adults can. For example, young children are particularly good at learning new languages. It becomes much harder to learn a second language after a person is 9–11 years old. This is probably because of changes in the way the brain processes speech and other language information. One study looked at the role of puberty in these changes. The researchers let children listen to speech from a fake "alien" language and studied how the brain tried to make sense of this [4]. The activity in several brain regions important for language changed as children got older. Activity in some of these language-related brain regions was also lower for children who were further along in puberty. This suggests that puberty might play a role in the brain's changing responses to language.

However, puberty might open a window for other types of learning. It might bring opportunities for learning about yourself and learning social and emotional skills that prepare teenagers for adulthood. The brain might change during the teenage years in ways that support such learning. For example, one important part of learning new skills is responding to feedback—that is, how your brain uses information telling you whether or not you have gotten the right answer. One study of over 200 children, teenagers, and adults looked at how the brain responds when learning from feedback. How well people learned from feedback was related to activation in different parts of the **striatum**, a key brain region for learning. Some parts of the striatum were more active in teenagers than in children or adults, suggesting that people might learn from feedback differently during their teenage years [5].

STRIATUM

An area in the middle of the brain that processes rewards and feedback. It is called the striatum because the alternating types of tissue there make it look striped.

Another important part of learning new skills requires exploration and risks, like sharing information about yourself, trying out a new hobby that you might not be good at, or trying to talk to someone you have a crush on. Deciding to take a risk might be more likely when you think you have something to gain—like a reward. Scientists have seen that part of the striatum also activates when a person receives rewards, including food and money. One study of people ages 8–27 focused on this brain region. The researchers found that people who were further along in puberty and people who had more testosterone in their bodies showed more activation in this part of the striatum when winning a reward. This suggests that hormones may be important for making your brain more sensitive to reward during puberty [6].

These studies show that the way the brain responds to feedback and rewards changes around puberty. This may encourage teenagers to learn more about themselves and others, supporting self-discovery and personal growth. However, these brain changes might also be related to the reality that certain mental health problems and drug addictions tend to develop during the teenage years. For example, if teenagers are more sensitive to rewards, they might also be more sensitive to the rewarding feeling from taking alcohol or a drug. Also, kids who go through puberty earlier or faster than their peers can have more mental health struggles, which researchers think could be partly due to hormones having a different impact on their brains—but more research is needed to see if that is true. Most kids go through puberty without any mental health problems, and researchers are studying ways to encourage positive outcomes for even more kids.

CONCLUSION

Puberty is a time of great change, including changes that might be at times awkward, confusing, or overwhelming. Some of these changes come from the actions of hormones on cells throughout your body, including your brain. Hormones can influence your brain in the long term by directly changing how it is organized, or by changing how it responds to certain situations. These changes might be important for opening up new opportunities for learning that prepare teenagers for adulthood, although the same brain changes might also close windows for other types of learning that happen earlier in childhood. Schools might be able to take advantage of these brain changes in their students, for example by creating opportunities for positive forms of exploration and risk taking. Learning is more than maths and reading—making decisions that help us to better understand ourselves and others is another important kind of learning that the brain might be especially sensitive to during puberty.

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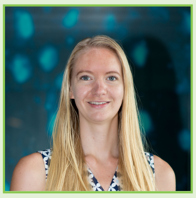
YOUNG REVIEWER

BENJAMIN, AGE: 11

My favorite subject in school is maths and english because I like to learn new information and love to be challenged. The extracurricular activities that I enjoy the most is water-polo because I love working in a team and have made many new friends. Since I saw a living brain cell firing in Oxford I have been working toward the goal of becoming a doctor. I have done this by reading many articles and listening to lectures, and I love dogs.

AUTHORS



MARJOLEIN E. A. BARENDSE

I am a post-doctoral researcher in Developmental Social Neuroscience at the University of Oregon. Before I started working in Oregon, I studied in the Netherlands and Australia. I am fascinated with how the brain works and how puberty works, and all the things that influence brain development in children and teenagers. In my free time I like to go rock climbing and travel to places I have never been before. *barendse@uoregon.edu

THERESA W. CHENG

I study psychology and neuroscience in the beautiful state of Oregon. In my work, I figure out how puberty, stress, and social experiences change the teenage brain. I used to be a middle and high school science teacher, and one of the best parts of my job is talking to people about science. When I am not researching, I like to cook, dance, and hike. For my eighth grade science project, I tried to show that our school cafeteria food was illegal—in other words, not nutritious enough for federal rules!

JENNIFER H. PFEIFER

I study how the major changes adolescents experience in their brains, bodies, and social worlds relate to their well-being. I focus on times when many changes happen all at once—like when you start puberty and go to middle school, or when you finish high school and start college or work. These key transitions can be hard, but are great opportunities to set young people on positive tracks. I like playing the piano and hunting for gems at the coast.

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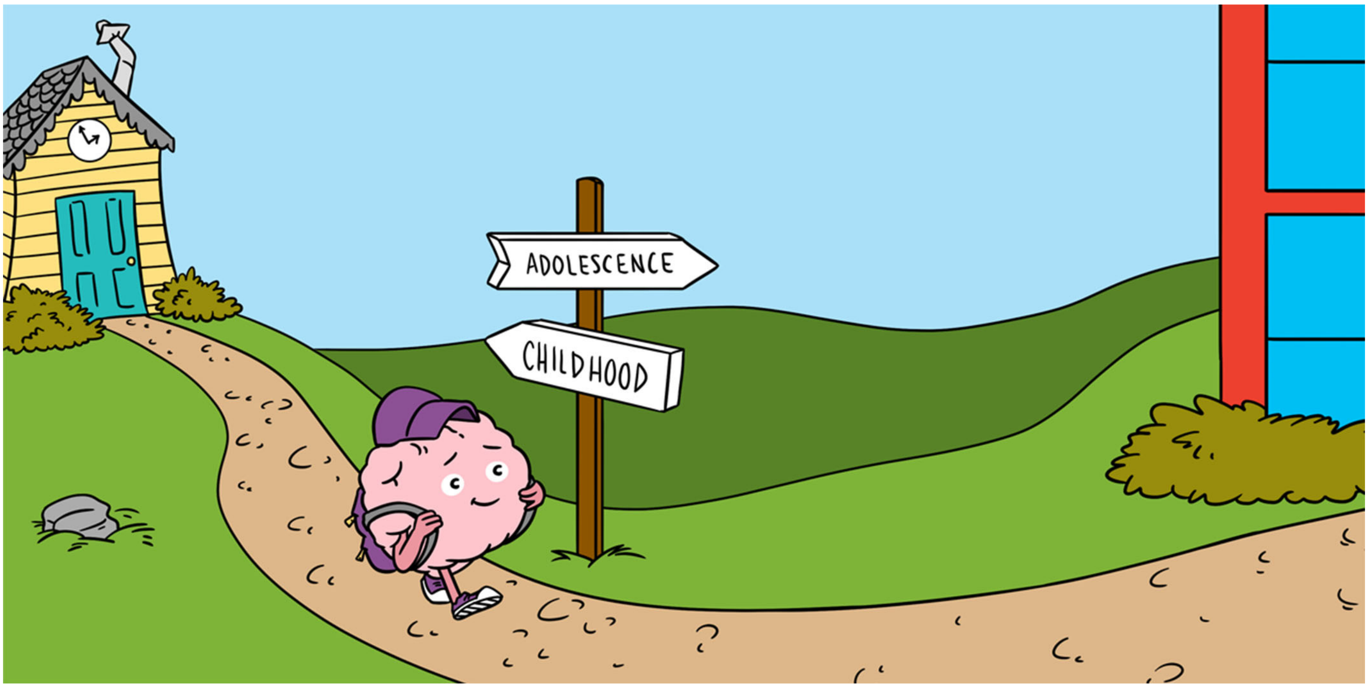

THE ADOLESCENT BRAIN IS LITERALLY AWESOME

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YOUNG REVIEWERS:

ISABELLA

AGE: 13

ALINE

AGE: 13

MARILIA

AGE: 13

The human brain undergoes a long period of development. While the brain is changing dramatically in childhood, there are also changes during the second decade of life that make this period, known as adolescence, awesome. Adolescents have brains more capable of change than adults and, unlike children, adolescents have a greater ability to actually shape the brain's development. Heightened information processing abilities and social sensitivity during adolescence also make this a time of increased ability to navigate our complex social world. This article discusses how current research on brain development can be used to empower adolescents as capable learners of the world around them. We make recommendations on how educational settings can nurture brain development and optimize the learning environment during adolescence.

INTRODUCTION

AWESOME

Inspiring great admiration, apprehension, or fear.

The adolescent brain is **awesome**, and here we explain why. Adolescence is the period of life that often begins with changes in the body related to puberty. But the brain is also changing during this time, and continues to change even after we finish puberty—well into our twenties [1]! The changes in the brain are reflected in the changes in behavior that we can often see during adolescence, such as the desire to explore, form new relationships, and navigate our changing social world.

BRAIN STRUCTURE CHANGES DURING ADOLESCENCE

MAGNETIC RESONANCE IMAGING

A way to scans the body to take pictures of its inside, like the brain.

Researchers use a technique called **magnetic resonance imaging (MRI),** which uses magnets and radio waves, to take photos of the brain while a person is lying inside what looks like a giant donut (Figure 1). MRI studies can show us how the human brain changes in its structure (anatomy) and organization (how it is linked up) across adolescence.

CEREBRUM

The front part of the brain, which is involved with thought, decision, emotion, and character.

NEURON

A nerve cell.

CORTEX

The outer layer of the cerebrum, composed of folded gray matter.

The brain is composed of many parts, but here we focus on the tissues of the **cerebrum**, which is the largest part of the brain (Figure 2A). The cerebrum is made of two kinds of tissue, called gray matter and white matter. The gray matter, which is made of brain cells called **neurons** and their connections, can be found on the outside of the cerebrum (called the **cortex**), as well as deep inside the cerebrum. Gray matter contains most of the neuronal cell bodies and makes up regions of the brain that are essential for muscle control, sensory perception, decision making, and self-control. Gray matter decreases during adolescence, by about 1.5% a year ([1]; Figure 2B). However, this decrease is not a bad thing! The decrease in gray matter is thought to be related to the fine-tuning of connections between brain cells, and also related to the increase in the other tissue in the cerebrum: the white matter.

AXON

A long thin part of a neuron that sends the signal from one end of the neuron to the other end.

The white matter of the cerebrum is found under the cortex, and is made of long fibers of neurons, called **axons**, that send the signals that connect together different parts of the brain. White matter increases in early adolescence but seems to be stable by the mid-teens (Figure 2C). The increase in white matter is thought to be related an increase in the speed of signals sent between brain cells. Anatomical illustrations of gray and white matter are shown in Figure 3.

HOW DOES BRAIN ORGANIZATION CHANGE DURING ADOLESCENCE?

Researchers can also use MRI to see how the brain is organized, in terms of how different parts of the brain are connected. Because the

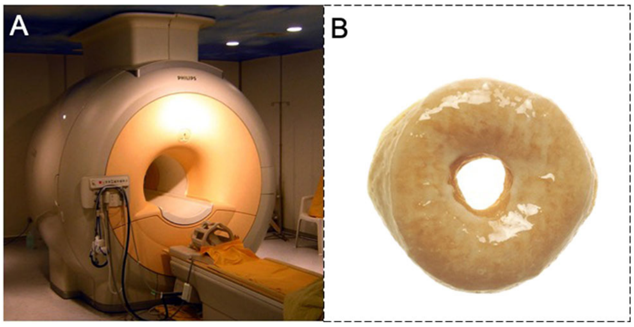

Figure 1

Figure 1

(A) A magnetic resonance imaging (MRI) machine looks like **(B)** a donut.

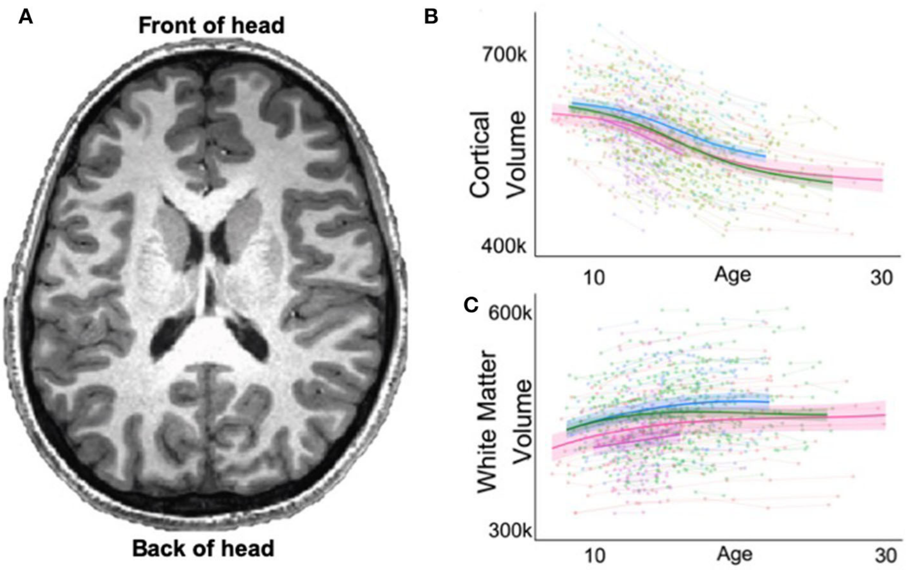

Figure 2

Figure 2

(A) An image of a section of a human's cerebrum, obtained using MRI. The view is as if you were looking from the top of the head down into the brain. The gray squiggles that curve around the white areas are gray matter of the cortex, and the white areas are the white matter. **(B)** The amount of gray matter in the cortex decreases during adolescence. **(C)** The amount of white matter in the cerebrum increases during adolescence. In both B and C, each dot on the graph represents the brain measure of one individual at one time, as acquired with MRI. Dots are connected to show the measurements gathered from one individual. Data was collected in four different research labs, and the average of the data at each site is shown with the four bold lines (figure adapted from Tamnes et al. [2] and Mills et al. [1]).

brain is changing so much in adolescence, its organization can be influenced by what we do, our experiences, and the environments we live in. The brain is a large network—different regions of the brain communicate with each other as a person performs different functions or behaviors, such as thinking about other people or moving around in the world. These brain communication patterns can be studied using a slightly different technique, called functional MRI (fMRI). This technique examines the amount of oxygen in the blood flowing throughout the brain as a measure of brain activity. When different regions of the brain show similar patterns of brain activity, they are said to be functionally connected.

Typical behaviors that we see during adolescence, such as thinking about other people and making decisions, have been seen to relate to certain patterns of brain activity between functionally connected regions in the brain. Not every adolescent has the same brain organization, and not every adolescent engages in typical adolescent behaviors. The way individuals differ in their patterns of brain activity can relate to differences in behavior.

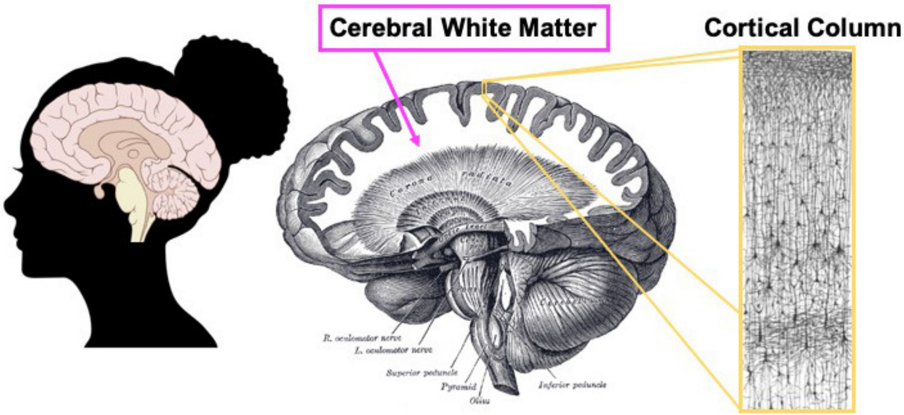

Figure 3

Figure 3

A silhouette of a girl with an image of the human brain overlaid to illustrate another view of the human brain. In the middle is a drawing of a cross-section of the human brain, showing the white matter underneath the cortex. The white matter tracts make up the white matter, with one set of white matter tracts (called the corona radiata) illustrated. A drawing of the cortical column of a developing human is illustrated in the yellow box. This drawing shows how neurons are arranged in the cortex, but cortical gray matter volume also includes many cellular components not seen here, including glial cells and blood vessels. These drawings were obtained from two repositories of free-use images: WikiMedia Commons and Pixabay.

One example of a behavior that changes during adolescence is called **temporal discounting preference**. This behavior has to do with how long we are willing to wait for rewards, particularly whether an individual will choose a smaller reward that is available immediately, or a larger reward that he or she must wait for. We studied how this preference changes in the transition into adolescence. We found that patterns of brain activity that link together regions of the brain involved in controlling our behavior to regions of the brain involved in valuing things in the world related to an individual's temporal discounting preference [3]. While there might be the stereotype that adolescents, in general, do not have the patience to wait for a larger reward when a smaller reward is immediately available, our study found that individuals differ in their behavior, and this difference is related to an individual's brain organization.

TEMPORAL DISCOUNTING PREFERENCE

An individual's preference for whether they would choose a smaller sooner reward or be willing to wait for a larger later reward.

Brain imaging studies have shown that the brain reorganizes in adolescence. Because our brains are changing so much, our experiences in adolescence can help shape the brain's organization. By engaging in certain patterns of behavior, we are making certain patterns of brain activity stronger. This makes leaps in intellectual and emotional development possible during adolescence.

WHY THE CHANGING ADOLESCENT BRAIN REPRESENTS A UNIQUE OPPORTUNITY

Changes in the brain's structure and organization during adolescence are greater than what we see in adulthood, but less than what we see during infancy and childhood. But, unlike childhood, adolescence is a time when we have a greater ability to actually shape how our own brains are developing. This is because we can understand more about ourselves and the world, we are more motivated and engaged, and we have an increased ability to make choices that can impact the changing brain. This is what makes the adolescent brain awesome.

Some of the brain's abilities that increase during adolescence include abstract thinking, considering many points of view, and being able to think about the process of thinking. Some research suggests that adolescents even have a greater capability than adults and children to solve problems in new and creative ways due to their ability to think about different concepts at the same time [4]. The brain's abilities that are already present during adolescence can be used to encourage further healthy brain growth, but this requires giving adolescents the freedom to make their own choices. For example, encouraging adolescents to set their own goals will encourage the brain activity involved in forming self-identity and considering long-term consequences. Adolescents are often quite concerned about how they are perceived by their peers. While this aspect of social sensitivity is often talked about as a negative aspect of adolescent behavior, it can actually be a positive when the social environment is healthy [5]. Another example of social sensitivity that increases during adolescence is concern with larger social structures and world events [6]. Adults, who often have a greater ability to change the social environment than adolescents, should work toward giving adolescents more opportunities for positive brain growth.

WHAT CAN YOUR TEACHERS DO TO OPTIMIZE THE LEARNING ENVIRONMENT OF ADOLESCENT STUDENTS?

Because the brain can be so easily shaped during adolescence, it is important for teachers and parents to nurture the developing brain. Optimizing the school learning environment is one of the most effective ways to support adolescents. What we know about the developing brain is that, compared with younger children, adolescents have a greater ability to understand more complex topics. Understanding what is happening in their own brains can help adolescents impact their own development. One way this can be done is through integrating developmental topics, such as decision-making, drug addiction, conflict resolution, and educational planning in the school curriculum. Here are some other ways to optimize the school learning environment. Consider sharing them with your teachers!

MAKE LEARNING COLLABORATIVE AND DIVERSE

Rather than ignore the motivation to socialize during adolescence, teachers can utilize this social motivation by encouraging group discussions and engagement among students. Asking for student advice and feedback on classroom activities can help students feel interested and more involved in the learning environment. Including students from different grades could help students learn new skills and see the project from different perspectives as students from different age groups can contribute different skills to a discussion or project.

CHANGE CLASSROOM ENVIRONMENT

Think about your classroom. How are the tables and chair arranged? Are they in straight long rows or are they in small circles? It might feel socially isolating to sit in long rows and only be able to see classmates from the back or side. This type of arrangement of the desks and/or the chairs can be changed to welcome collaboration and learning. Consider asking your teacher if they are open to experimenting with trying new arrangements like small circles. In addition to respecting the inherent social motivation of adolescence, rearrangement of classroom furniture can help with social anxiety, because it might be easier to reach out and talk to other students in the group.

FOSTER INDEPENDENCE

Teachers can foster independence in the classroom by allowing students to lead the way. This could include allowing students to come up with a part of the syllabus or the guidelines for a project. Allowing students to explore what they are interested in will drive learning. When students are able to create their own guidelines and overcome difficulties through hard work and collaboration, they will be more prepared to take on new challenges and thrive in difficult situations.

INTERACT WITH THE COMMUNITY

The typical classroom environment might be too artificial and structured. Students should be encouraged to collaborate with the world outside of the classroom. Community-based field trips might help students to apply things they have learned in class to the real world. This complements the increased sensitivity to one's own social world that happens during adolescence.

WHAT DOES THIS MEAN FOR YOU?

Adolescence is a period of rapid growth, development, and learning. This presents a unique opportunity for adolescents to have a greater ability to actually shape the brain's development. We can make certain patterns of our brain activity stronger by engaging in certain types of behaviors. One of the ways you can engage in your own development is by learning and understanding what is happening in your own brain. Awesome, right?

AUTHOR CONTRIBUTIONS

KM outlined the paper. KM and JA wrote the paper.

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YOUNG REVIEWERS

ISABELLA, AGE: 13

My name is Isabella and I am 13 years old. I was born in New York and I live in Switzerland. I love art, reading books, singing, dancing, and playing the piano. My favorite sport is swimming. I also have great interest in math, nature, and science, especially everything about space, time, and matter. In the future, I would like to be an aeronautic engineer or an architect. I am always very curious to learn more about the world around us.

ALINE, AGE: 13

My name is Aline, I am 13 years old. My favorite hobbies include theater, playing the clarinet, drawing, and reading. I am fascinated with Greek mythology; my favorite books include the Harry Potter and the Percy Jackson series. At school, I really enjoy Maths and Science.

MARILIA, AGE: 13

Hallo! My name is Marilia. I am 13 years old and I like ice skating, rythmic gymnastics, and playing football. I have a small dog which I love! One day I would like to travel to Australia and see the coalas. I enjoy to be with my friends and go swimming or watch a film with them.

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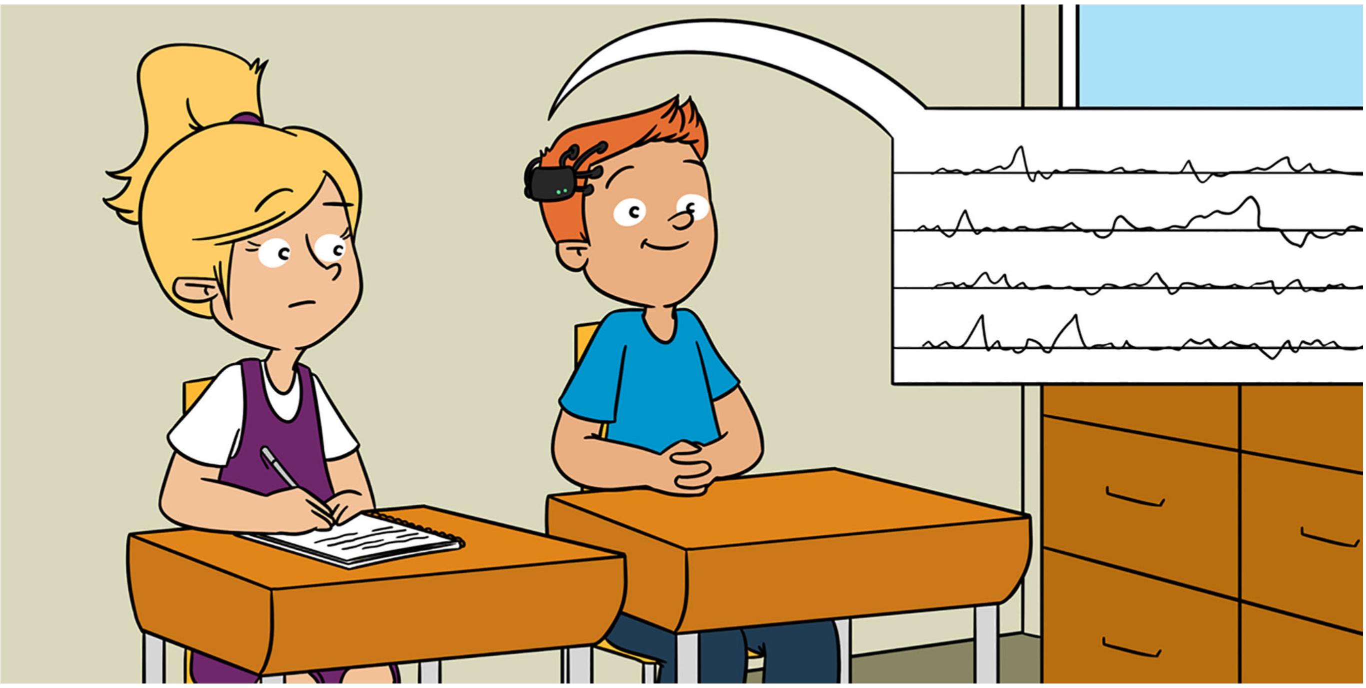

MEASURING BRAIN WAVES IN THE CLASSROOM

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YOUNG REVIEWERS:

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT

AGES: 14–15

Brain researchers used to study the workings of the brain only in special laboratories at universities or hospitals. Recently, researchers started using portable devices that people can wear on their heads outside of the laboratory. For example, these devices allow researchers to measure the brain activity of students in classrooms, as they go through the school day. This sounds futuristic, and maybe also a bit alarming. In this article, we will explain what such devices do and do not measure—for example, they cannot read your mind! We will also explain how this kind of research can be useful to you and your classmates.

Have you ever heard about **brain waves** and maybe wondered what they are? In this article, we will explain what brain waves are, how they can be measured in the lab and in the classroom, and why it is interesting to measure them.

BRAIN WAVES

Cycles of electrical currents generated by groups of neurons that are active at the same time.

EEG: MEASURING ELECTRICAL ACTIVITY IN THE BRAIN

The cells in your brain are called **neurons**, and your brain has roughly 86 billion of them. These neurons are very chatty, just like students in a classroom. Instead of using words, neurons communicate via tiny electrical signals that they generate. These signals go up and down in intensity, resembling waves: these are your brain waves. We can measure brain waves using a technique known as electroencephalography (**EEG**), in which small detectors, called **electrodes**, are placed on a person's head [1]. Usually, all these electrodes (up to 256!) are held in place by a cap, although portable devices have recently been developed that use fewer electrodes, in fancier-looking headsets. EEG cannot measure the electrical activity of individual brain cells, because the electrical currents that any one neuron generates are too small. These currents can only be measured when many neurons transmit similar electrical signals at the same time. Imagine a music festival with thousands of people. When only one person claps, the band on the stage will not hear it, but when the whole audience claps at the same time, they surely will.

NEURONS

The cells in your brain that communicate with each other by transmitting electrical signals.

EEG

Electroencephalography, a technique in which small detectors, called electrodes, are placed on a person's scalp using a cap or a headset. EEG measures the electrical activity of groups of neurons that transmit similar electrical signals at the same time.

ELECTRODE

A detector placed at the scalp, used in EEG to record the electrical currents generated by neurons in the brain.

BRAIN WAVES: SLOW AND FAST

Brain waves vary in speed. You can think about slow brain waves as large waves in the ocean, moving a ship up and down, and fast brain waves as small ripples on the water's surface. When we use EEG, we get a mixture of fast and slow brain waves happening at the same time.

So why is this interesting? Imagine yourself early in the morning, not quite awake and still dreamy. If we measured your brain waves with EEG at that very moment, we would see relatively slow brain waves. Now imagine you are at school taking an exam, focusing intensely. In this situation, we might detect faster brain waves. These examples show that the speed of the brain waves is related to the state you are in. The speed of brain waves is called the **frequency**. We can identify different frequency ranges using EEG. For example, the Delta range corresponds to relatively slow brain waves that go up and down 1–4 times in a second, or 1–4 Hertz (Hz), which is the unit of frequency. Figure 1 shows an overview of frequency ranges (also called **frequency bands**) and how they relate to your mental state.

FREQUENCY

Speed of a brain wave; number of times a brain wave goes up and down in 1 s. The unit of frequency in Hertz (Hz); 1 Hz means one cycle per second.

FREQUENCY BAND

A range of brain wave frequencies that is associated with a certain mental state. For example, frequencies in the range of 1–4 Hz are called the delta-band, which is associated with deep sleep.

BEYOND SLOW AND FAST: EVENT-RELATED POTENTIALS

Although EEG frequency bands are very interesting, not all questions can be answered by examining them. For example, what if you want to know how the brain understands the words you hear or how it controls impulses, like not hitting your younger sister if she drives you

Frequency band	Speed (Hz)	Mental state	Electroencephalography (EEG) recording
Delta	1-4	Deep sleep	
Theta	4-8	Drowsy	
Alpha	8-12	Relaxed	
Beta	12-30	Focused	

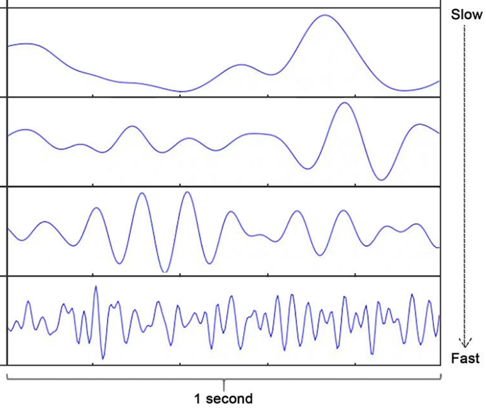

Figure 1

Figure 1

EEG frequency bands from slow to fast and how they relate to mental state. Brain wave frequency is measured in Hertz (Hz), which is the number of waves per second.

mad? For such questions, researchers analyze brain waves in another way: by calculating the event-related potential, or **ERP**. ERPs are the electrical brain responses to specific events, such as reading a word or controlling an impulse. In the ERP method, the parts of the EEG signal caused by these specific events are examined. To use this method, the EEG is recorded while the participant performs a computerized task that is specifically designed to study a certain function of the brain, for example impulse control.

ERP

Event-related potential, measured using EEG. ERPs are the electrical brain responses to specific events, such as hearing a sound or reading a word. In the ERP method, the participants perform a computerized task in which the specific event of interest is often repeated. The parts of the EEG signal caused by these events are averaged together. This averaging causes random brain activity to be averaged out and the relevant part of the EEG to remain; this is the ERP.

Here is a description of such a task, called a "Go/No-Go" task (Figure 2). Different letters appear on the screen, one by one. An "X" means "press the button" (Go!), and an "O" means "do NOT press the button" (No Go!). The "X" in this task is presented much more frequently than the "O," so participants automatically prepare to respond whenever a letter appears on the screen—even an "O." Participants need to control their impulse to press the button in the case of an "O." When the task is over, the researchers examine the EEG recorded during the presentations of the X's and O's on the screen. Can you guess which letter they are most interested in?

Researchers are most interested in the EEG response to the "O"s, because this is when the participant needs to control the impulse to press the button. To examine the brain response to the "O"s, the researcher isolates the EEG response to each presentation of an "O" and averages all these responses together. The averaged EEG response to this specific event is the ERP, and it reflects the brain's attempt to control an impulse. You can think about the process of calculating the ERP as a sieve, filtering out pieces of the EEG signal that are of no interest, leaving only the signals that researchers are the most interested in.

Figure 2

The Go/No-Go task. The letters X and O appear on the screen one at a time. The participants are asked to press the button ASAP when they see an X, and to NOT press the button when they see an O. The X appears very often and the O only occasionally. This makes it hard to inhibit the impulse to press the button when an O appears on the screen.

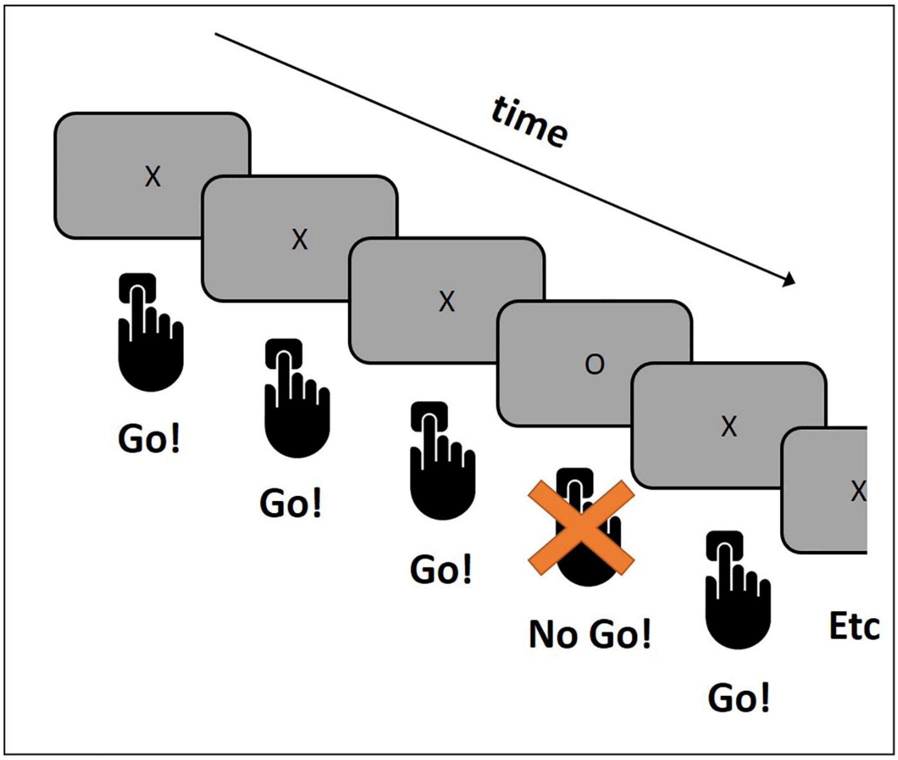

Figure 2

THE LIMITATIONS OF LAB EXPERIMENTS

Scientists have learned a great deal about how the brain works from doing EEG and ERP experiments in laboratories. When we do such experiments, we usually measure brain activity when people perform computerized tasks. Such tasks are designed to measure a certain brain function, for example reading words, doing arithmetic, or controlling impulses. Usually, such laboratory tasks are quite different from things that we do in our day-to-day lives.

For example, think about the task with the frequent "X"s and rare "O"s used to study impulse control. Is this the same as controlling your impulses to move around or to chat with another student while your teacher is giving instructions? In the EEG lab, you would be sitting alone, in a quiet room, doing a task like pressing buttons and occasionally trying not to press a button. This lab experiment can tell us some things about how the brain controls impulses, but what does it say about how children deal with their impulses at school? This is a limitation of lab experiments: they measure brain activity in rather unnatural situations [2].

USING PORTABLE EEG IN THE CLASSROOM

Another aspect of human behavior that is difficult to study in a laboratory is how people interact with one another, for example,

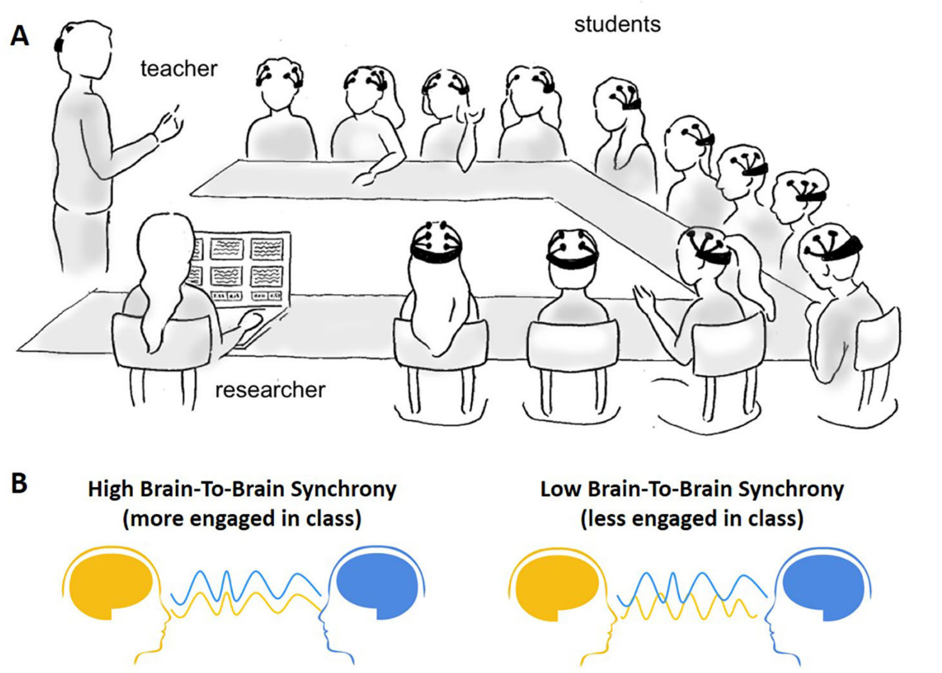

Figure 3

(A) EEG can be used to measure the brain waves of students in a high school classroom (from: Dikker et al. [3]). **(B)** Students' brain waves can show high synchrony with other students, which was found for students that were more engaged in class (left). Low synchrony with other students (right) was found for students who were less engaged.

the way students interact with each other in school. Laboratory experiments are extremely limited in answering this question, but recent developments in portable EEG now allow scientists to conduct brain research outside of the laboratory.

This is exactly what a team of researchers at New York University did recently [3]. They partnered with a local high school and measured the brain activity of a teacher and a group of students during 11 biology lessons (Figure 3A). In each lesson, the students participated in different learning activities, such as lectures, instructional videos, and group discussions. The researchers found that, during these classroom activities, students' brain waves were in **synchrony**. In other words, their brain waves went up and down together, in sync. Even more interestingly, students who reported being more engaged in class were even more in sync with the other students (Figure 3B).

SYNCHRONY

When brain waves go up and down together. This can either be within one brain (e.g., brain waves from different parts of the brain) or between brains. This latter example is called brain-to-brain synchrony.

Portable EEG devices are exciting because they can be used not just for research, but also for teaching purposes. In "BrainWaves," a neuroscience high school program that was developed at New York University, students use EEG to learn about their own brains, and about how neuroscience works. Students work with a scientist to develop their own research projects. For example, they can use EEG to explore how the brain responds to images of famous and non-famous faces, or how listening to music affects our ability to concentrate.

Portable EEG was not invented to replace laboratory EEG research. Rather, it complements lab research by providing insights on brain processes in day-to-day situations. But the advantage of studying the brain in a more natural setting comes with some trade-offs. The quality of the data collected by portable EEG is not as high as the data collected in the lab, because portable devices have far fewer electrodes and participants move around more. Also, the environment outside the lab is not under the researcher's control, so the experimental results might be more difficult to interpret.

DOES THIS SOUND LIKE SCIENCE FICTION?

So, after reading all of this, what do you think? Would you be interested in wearing an EEG device in your classroom, or do you find this thought a bit scary? Well, to reassure you, so far portable EEG only provides a general measure of brain activity. EEG certainly cannot read your mind. So, you do not need to worry that researchers or your teacher could read your thoughts if you ever put on one of these EEG devices at your school. We want to reassure you that mind reading is still science fiction!

Some commercial companies that make and sell EEG devices do claim that EEG can be used to monitor students, by reading the strength of different brain waves and decoding this into "concentrated" or "distracted." We do not think this is a very good idea, for various reasons. First, we need to do much more research before we understand enough about what the EEG signals mean in terms of brain functions. Second, students do not necessarily need to be concentrating all the time. We know that the brain also needs some time to rest, and mind wandering can actually be useful for learning [4].

CONCLUSION

Portable EEG devices offer some great opportunities, such as the ability to study how the brain works in natural environments, like classrooms. Study of the brain in natural situations can especially benefit our understanding of social interactions, as portable EEG can be used to measure the brain activity of several people at once, while they are interacting with each other. Moreover, portable EEG can also help students to better understand how the brain works. However, science advances in small steps, so let us leave mind reading for science fiction films, and in the meantime discuss whether we will ever want that to be a reality [5].

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The illustration in Figure 2 has been reprinted from Dikker et al. [3], Copyright (2017), with permission from Elsevier.

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YOUNG REVIEWERS

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT, AGES: 14–15

We are a class of students from all over Nashville, who come together once per week at Vanderbilt to learn more about science, technology, engineering and mathematics. We conduct experiments in our classroom and in labs on campus!

AUTHORS

NIENKE VAN ATTEVELDT

Nienke is a neuroscientist and combines different methods to study individual differences in learning and motivation. She is passionate about finding ways in which neuroscience research about learning and development can be made relevant for learners and teachers. Her ultimate aim as a researcher is to contribute knowledge and tools to be used in education to make more children enjoy learning. Nienke leads the Lab of Learning at the Vrije Universiteit in Amsterdam, see `www.laboflearning.com` *n.m.van.atteveldt@vu.nl.

TIEME W. P. JANSSEN

Tieme is a neuroscientist and often works with electroencephalography (EEG). He is passionate about understanding how brains work, and how brains work differently, for example in children with ADHD. One of his research lines involves the application of neuroscience to societal needs. For example, he uses EEG neurofeedback to train attention in ADHD, or to show children they have control over their own brains. Tieme takes neuroscience research out of the lab and into working classrooms and other real-life settings, using portable EEG technology.

IDO DAVIDESCO

Ido is a neuroscientist who is interested in making connections between brain science and education. He conducts research in classrooms using portable devices that allow measuring students' and teachers' brain activity. He is also interested in developing ways for students to interact with scientists and engage in real-world research related to brain and behavior.

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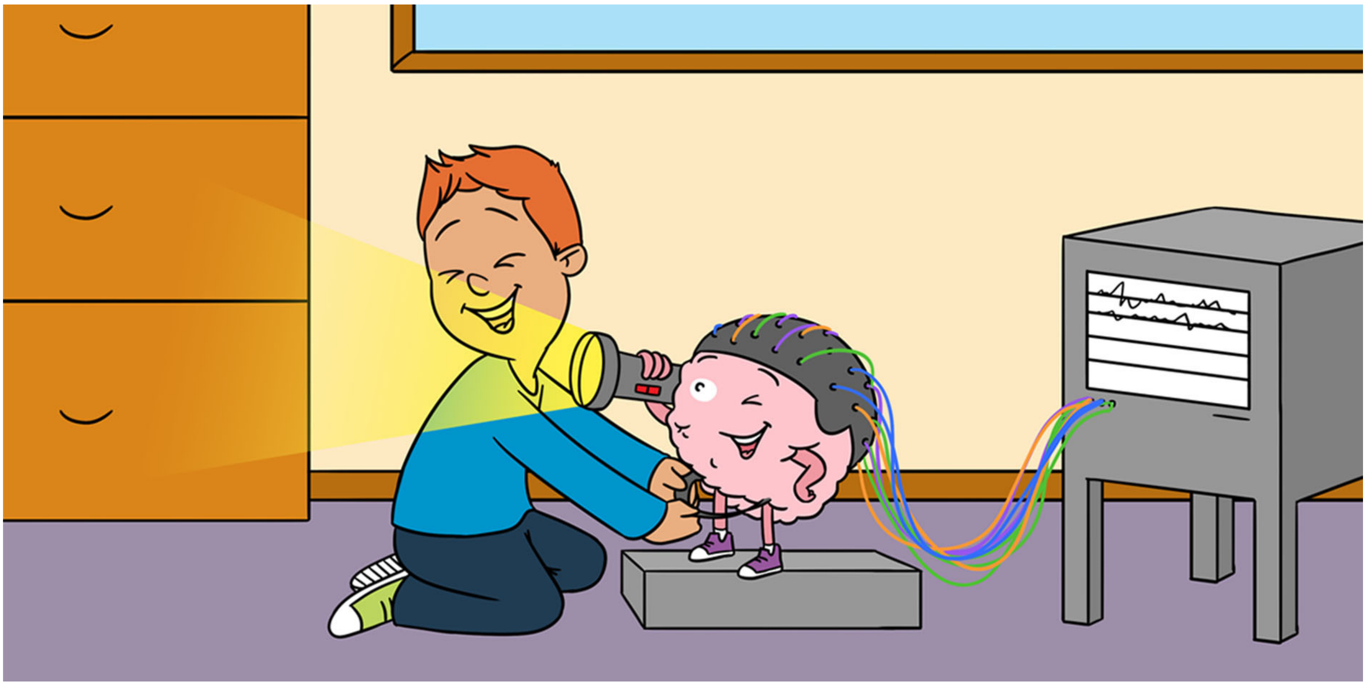

USING LIGHT TO UNDERSTAND HOW THE BRAIN WORKS IN THE CLASSROOM

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YOUNG REVIEWERS:

ISTITUTO EUROPEO LEOPARDI

AGES: 11–12

Did you know that we can study the brain in the classroom? Many people think that studying the brain is only possible in complex laboratories with huge, complicated devices. Functional near-infrared spectroscopy (fNIRS) is a new technique that uses light to monitor how active the brain is. fNIRS has several advantages that make it particularly good for observing the brains of babies and children. Also, it is one of the best techniques to study brain function in daily life and real situations, such as in the classroom or during a conversation. However, like all other brain measurement techniques, it cannot be used for everything, meaning that it has limitations. In this article, we discuss how fNIRS works and how it can be used, its advantages, and its limitations. We conclude that, when used in the field of Educational Neuroscience, fNIRS can help scientists to understand how children learn.

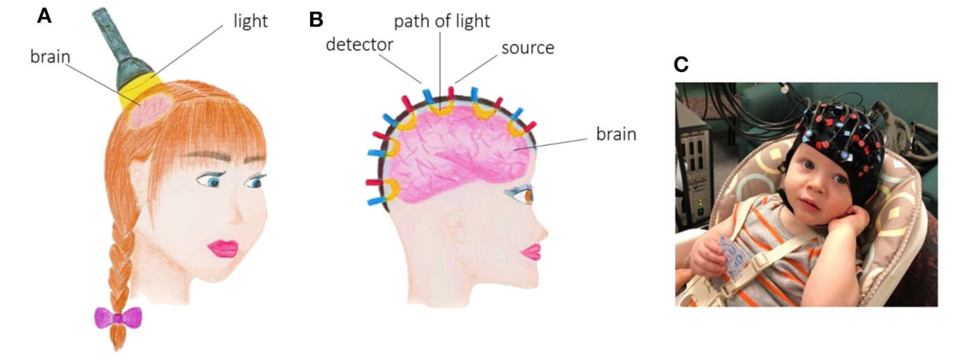

Figure 1

Figure 1

(A) fNIRS uses light to look at brain function. **(B)** Sources (red) and detectors (blue) of the light in fNIRS. The light passing through the brain is shown as yellow banana shapes. **(C)** An fNIRS cap on the head of a baby.

FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS)

A new technique that can help scientists easily monitor how the brain works by using a special type of light called near-infrared light.

NEAR-INFRARED LIGHT

A special type of light that can go through skin, bone, and brain and be used to measure what is going on in the brain.

WHAT IS FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS)?

Functional near-infrared spectroscopy (fNIRS) is a new technique that helps researchers easily monitor how the brain works. fNIRS uses a special type of light called **near-infrared light** (Figure 1A). Near-infrared light is special because it can go through skin, bone, and brain. The light is sent into the brain from a light source (red in Figure 1B) and then received by a detector when it comes back out (blue in Figure 1B). The difference in the amount of light sent into the brain and the amount of light received shows how active the brain is. But why there is a difference between the sent and received light? Is a part of the light lost on its way through the brain?

To answer these questions, we need to understand how the brain works. The brain works by using oxygen. Oxygen is brought to the brain by the blood. When the brain is active, there is more blood flow and that means there is more oxygen in the brain. Blood absorbs near-infrared light, so when we send this light into the active brain, less light comes back, because some was absorbed by the blood. So: the more light absorbed, the less light we get back out, and the more active the brain is.

WHAT ARE THE ADVANTAGES, USES, AND LIMITATIONS OF FNIRS?

fNIRS has several advantages including:

- it allows testing while participants are sitting or standing
- it is easy to carry around and can be used almost anywhere
- it is easy and only takes minutes to set up
- it is cheap to use
- it measures brain function several times per second
- it neither hurts nor makes noise
- it can be used together with other brain measurement techniques
- it tolerates body movements, like talking, writing, or walking.

Figure 2

Figure 2

fNIRS can be used in many different situations in daily life, such as during eating, conversation, dancing, and playing music. It can be used to see what happens in the brains of a mother and her baby when they communicate with each other.

These advantages make fNIRS good for several uses (Figure 2). For one, we can study the brain in a natural environment and daily-life situations rather than only in laboratories. This is possible because some fNIRS devices are small enough that they can be carried to wherever the study will be performed. Furthermore, during measurements, the participants do not have to be lying down. They can sit behind a desk and do some homework or work on the computer. fNIRS can be used to study more complicated mental tasks than some other brain measurement techniques can and not just multiple choice tasks. Also, fNIRS is pretty comfortable for the participant. This means that we can study the brain even in babies and children (Figure 1C). It is usually difficult to study the brain in these young populations because they move a lot, making other brain measurement techniques impossible to use. Additionally, it is possible to measure brain function for a long time (up to 1 h), and in many participants at the same time. Most of these advantages make fNIRS a unique technique for studying the brain in situations and people that are usually difficult or sometimes impossible to access with other techniques.

These advantages and uses, however, come with a price. We need to be aware of the limitations of fNIRS. First, fNIRS measures around 3 cm of the brain at one time. When we are talking about the brain this is a big area, because different parts within the brain are so small. So, an fNIRS measurement might include parts of the brain with different functions and therefore will not be as precise as measurements done with some other techniques [1]. Additionally, fNIRS can only measure the activation of areas around 1.5–2 cm deep into the brain. Therefore,

Figure 3

While a child solves a mathematics problem, her brain function is recorded by fNIRS.

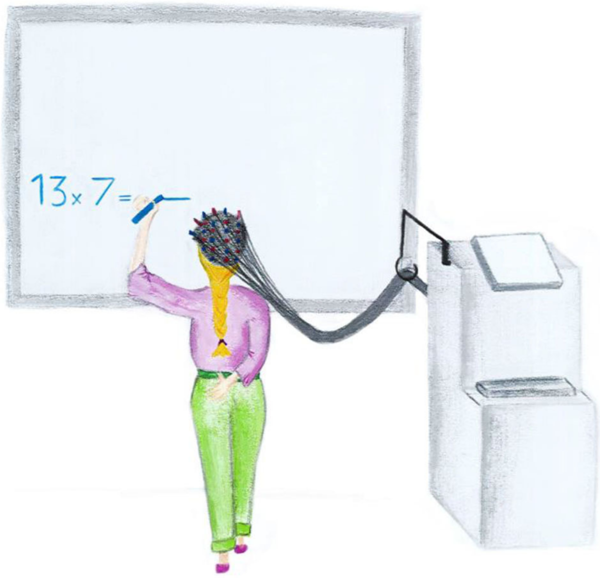

Figure 3

it is not good for measuring functions that are located deep inside the brain. Next, fNIRS provides information only about functions and not structures [1]. That means we can understand how the brain works, but not what the brain looks like. Furthermore, because it measures the amount of blood, fNIRS is sensitive to the heartbeat, blood pressure, and veins in the skin. So, some non-brain changes might be mixed up with brain function measurements. Finally, because fNIRS is a new technique, not everyone uses the same method of data analysis. Data analysis is a procedure to combine and transform the collected brain data of different people to show it in a way that everybody understands. In summary, when scientists want to measure brain function with fNIRS, they need to be aware of both its advantages and its limitations.

HOW IS FNIRS PERFORMED AND HOW IS ITS DATA USED?

Depending on the study and research question, participants can be measured individually or in groups. To perform fNIRS, we need to follow a few steps. First, we measure the head of the participant to find some important points, like the center of the head. By using these points, we can estimate which part of the brain is measured by each sensor. Second, we attach the light sources and detectors on the head, using an elastic cap. Third, we ask our participant to perform a task while his/her brain function is measured by fNIRS (Figure 3). The task can be anything, for example, mathematical problems. Fourth, after the participant has finished the task, we turn off the fNIRS machine and take the cap off the participant's head, and the experiment is finished.

We usually repeat the same experiment with many participants (about 40 children). Then we can analyze the data of all participants. But what does that mean? Let us imagine that our research question is "Which parts of the brain are active during calculation?" To answer this question, we measure brain function in two situations: when participants are solving mathematical problems and when they are just resting. Using computer software, we can read and combine the data of all participants. We then calculate the brain function levels during calculation and rest for all participants. Then we compare these brain function levels. We observe a huge difference between brain function levels during calculation and rest in some parts of the brain, but not in others. Therefore, we can conclude that only those parts of the brain that showed a huge difference between calculation and rest are important for calculation.

CONCLUSION

fNIRS is a technique that allows the measurement of brain function, even in special groups, such as babies and children [2], and in real-life situations, such as the classroom [3]. These capabilities make fNIRS very good for **Educational Neuroscience** research [4]. Educational Neuroscience uses techniques, such as fNIRS to study the brain and uses the results of brain studies to make education better in schools. While most of the commonly used brain techniques are great for studies in adults, they have several limitations when used in children, which is why we still do not know much about how the brain changes as we grow from babies to adults. Fortunately, fNIRS allows us to monitor brain changes and learning in children [5, 6]. We believe that using fNIRS in Educational Neuroscience will eventually help us to understand how children learn to read, write and calculate.

EDUCATIONAL NEUROSCIENCE

A field of brain study that aims to make education better in schools.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ISTITUTO EUROPEO LEOPARDI, AGES: 11-12
We are a group of students from the Istituto Europeo Leopardi and we are in 1st year of middle school. Our names are Lucrezia, Sofia, Benedetta, Eleonora, Francesco, Matteo, Marco, Emma, Greta e Lidia. We live in Milan (Italy) and we are 11–12 years old. We are a funny, nice, creative class, and we like Science and Sport. Good Bye from the 1st A!

AUTHORS

MOJTABA SOLTANLOU

I am a researcher at the University of Western Ontario in Canada. Before going into research, I used to work as a therapist, helping children who had various disorders. In my research, I would like to understand what happens in the brain when a child learns something like mathematics, and why some children have difficulties in learning. In my free time, I like doing sport, playing the Tar, and reading about history.

*mojtaba.soltanlou@gmail.com

CHRISTINA ARTEMENKO

I am a researcher at the University of Tuebingen in Germany. My research is about math and calculation. I want to know what is going on in the brain when someone is calculating, and I use fNIRS to study the brain. I want to understand what makes calculation difficult and why some people have problems with math. Besides research, I also enjoy playing the flute, ballet, and volleyball.

NEUROSCIENCE
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THE MAGICAL ART OF MAGNETIC RESONANCE IMAGING TO STUDY THE READING BRAIN

Nora Maria Raschle[1*], *Réka Borbás*[1], *Carolyn King*[2] *and Nadine Gaab*[2,3]

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YOUNG REVIEWERS:

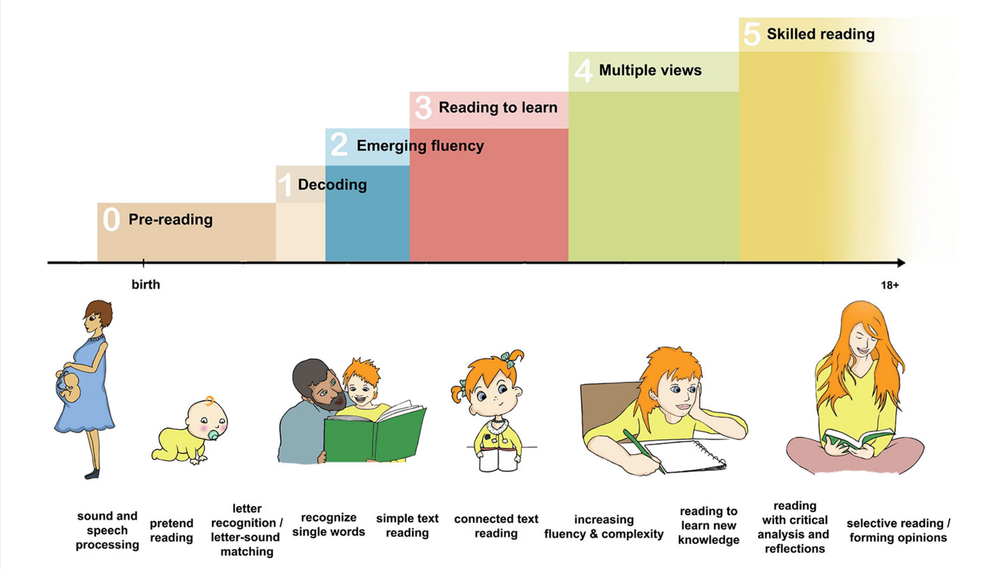
CASCADIA ELEMENTARY
AGES: 8–9

In the Harry Potter book series, the legilimency spell was used to access and read another person's mind. However, magic always come with a great responsibility and should only be used with caution. Similarly, magnetic resonance imaging (or MRI) is a powerful tool that lets us take detailed images of different parts of the body, including the brain. But MRI should also only be used and interpreted with caution. MRI gives us an opportunity to look at different parts of the body from the outside. Some muggles (non-wizards) use MRI to study the secrets of the human brain. While it cannot be used to read someone's mind, it can tell us how a brain looks, works, grows, and learns. For example, MRI can help us understand how the brain learns to read and what may be different in children who struggle with learning to read.

Do you like to read? Have you read the Harry Potter books? Reading is an ability that is learned through instruction (e.g., a teacher or parent

Figure 1

Step-by-step, we learn to read. There are several stages that we may take to become fluent readers. Learning to read starts from the time a baby starts growing and continues throughout schooling and until young adulthood (Illustrations: N. M. Raschle; the top part of this graphic is adapted from Chall [1]).



teaching you) and needs much practice at home or in school. Many different things help us become great readers. As we grow up, we have many experiences, and our bodies, our thinking, our feelings, and the environment around us are always changing. Early in life, we learn the easier skills, like understanding the meaning of certain sounds, recognizing faces, or walking. In fact, learning starts even before we are born! As we grow, we learn more complex skills, like speaking words and sentences, reading, and how to interact with others. Learning new skills goes hand-in-hand with the development of the brain. But many different things can affect how we develop, including changes in our environments, our learning experiences, or even our DNA, which is the biological information that our parents pass on to us.

This is also true for reading. Reading is an ability that we practice for a long time before we become good at it. But this practice starts long before we pick up our first book or go to school. Before we are even born, we start listening to sounds and hearing basic parts of language. These experiences shape areas of the brain that later help us to develop reading skills. In 1983, a professor named Jeanne Chall [1] said that learning to read happens in several stages (Figure 1). Today we know that many different factors can affect these reading stages and that learning to read can differ among individual children and across the globe. Such differences exist because many things can affect reading development, like where we grow up, which language we speak, the vocabulary of our language, our ability to play games with speech sounds (e.g., say "banana" without saying the sound /b/), and how good we are at understanding stories [2].

HOW THE BRAIN LEARNS TO READ

Brain imaging techniques, such as magnetic resonance imaging (**MRI**) make it possible to study how the brain learns. MRI is like a big camera that can take images of different parts of the body—for instance, the brain. MRI works by measuring signals coming from water molecules in the body. Every single part of the body is a little bit different, and because of that, the MRI signal coming from each part differs a bit, too. Using computers scientists can create detailed images from these signals (if you are interested in reading more about the physics of MRI, you can read "The physics of MRI and how we use it to reveal the mysteries of the mind" written for children by Kathryn Broadhouse [3]). MRI allows us to study both how the brain works while we are doing or feeling something (the brain's function), as well as how the brain is built (its structure).

MRI

Stands for magnetic resonance imaging. MRI allows scientists to take images of all parts of the human body. It works with strong magnets and radio waves.

When the brain grows and learns, connections between different parts of the brain are created. Over time, these connections build networks. Networks are different parts of the brain that work together. Like a well-trained musical group, brain networks help us learn skills like reading. While we learn, the cells of the brain (called **neurons**) connect to each other by reaching out their tiny arms (called **axons**) or even by growing new arms. Over time, many axons connect to each other and build long highways, called **white matter tracts**. These highways allow information to travel from one part of the brain to another. Using MRI, scientists have learned that we can read because different parts of the brain become more active and communicate with each other as we learn. These brain areas have funny-sounding names: occipitotemporal area, or the "letter box" of the brain (where we process letters and words); temporoparietal area (helps us to play with the sounds of our language, such as figuring out that "banana" without the sound /b/ is "anana"); and inferior frontal region (the "captain" that directs us). When brain areas talk with each other often, the highways can become stronger.

NEURON

Nerve cells within the brain or spinal cord.

AXON

A part of the nerve cell that can connect with other cells and in this way transport information from one cell to another cell.

WHITE MATTER TRACT

A collection of many axons connecting different brain areas with each other.

An important highway for reading is a collection of axons that we call the arcuate fasciculus, because it is shaped like an arc. Within the network of brain areas that help us to read, paths like the arcuate fasciculus allow the transportation of information from one area to another. In children who struggle with reading, the brain's reading network is sometimes built a bit differently or the information takes other routes. In some brains, the highways transporting the information between the reading areas may be narrow, like having just one lane of traffic instead of two. Or, the highways may be less smooth, like a road with a bumpy surface or many traffic lights. These differences make communication between the brain regions challenging and, in some children, reading becomes a difficult task (Figure 2).

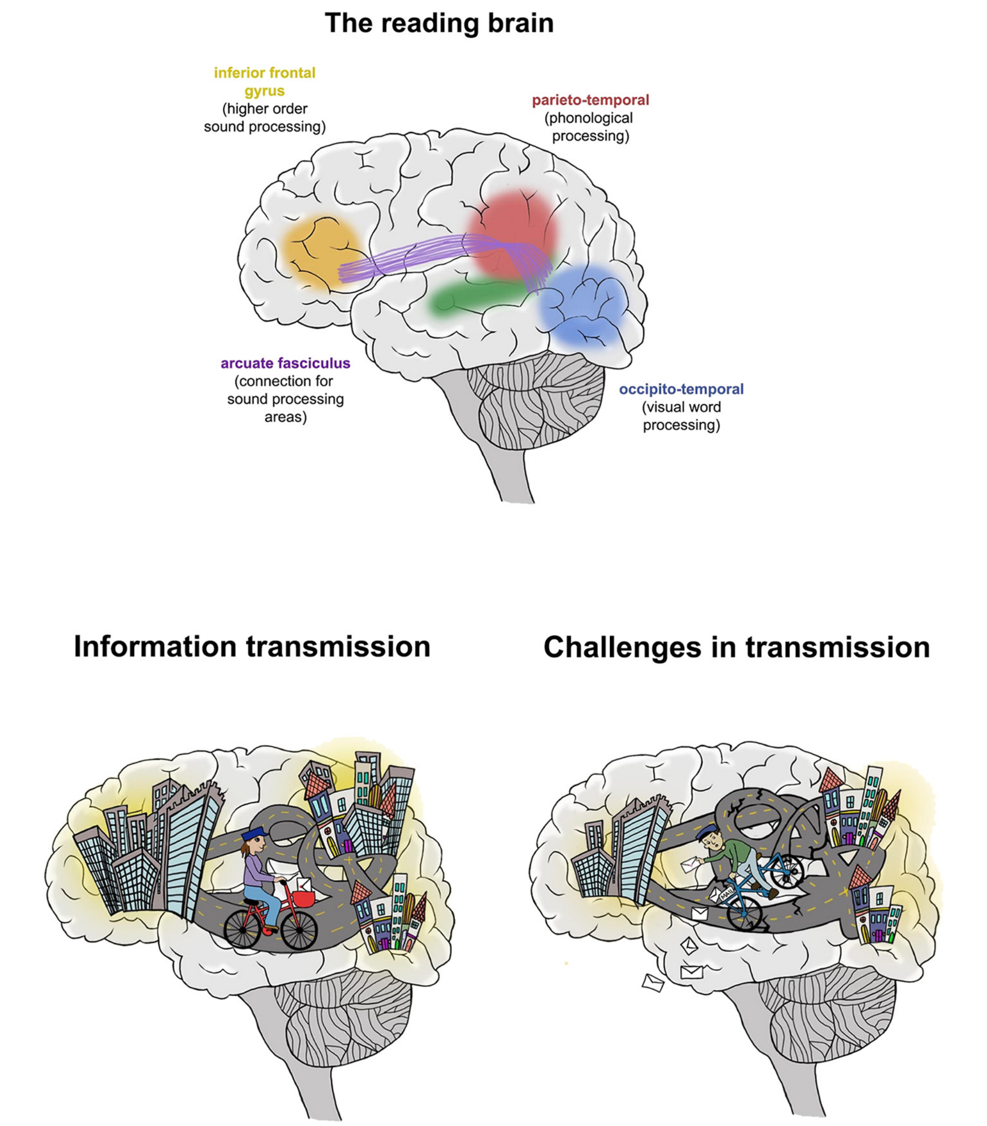


Figure 2

Figure 2

The reading brain. At the top, you can see the names and functions of brain regions that are used for reading. Together, these brain regions form the brain's reading network. During reading, these areas become more active and talk with each other. Sometimes information transmission in this network goes smoothly (bottom left), but sometimes it can be more challenging (bottom right) (Illustrations: N. M. Raschle).

DEVELOPMENTAL DYSLEXIA AND THE DYSLEXIA PARADOX

The development of the human brain is complex, and it is not surprising that some brains develop differently than others. Sometimes these differences can have consequences that are discovered only much later in life. In a regular school class, about one or two in a class of 20 children find learning to read extremely challenging. Many researchers would like to be able to predict, as early as possible, which children may struggle with reading. It is much easier to help a child when the problems start than to wait and try to help them years later. When we are young, our brains are much more flexible for things like language, and this makes it easier to learn new things and address problems. Also, if help comes very late, some struggling children may become sad, frustrated, or experience bullying and may even stop wanting to learn. Some parents may become impatient and think their

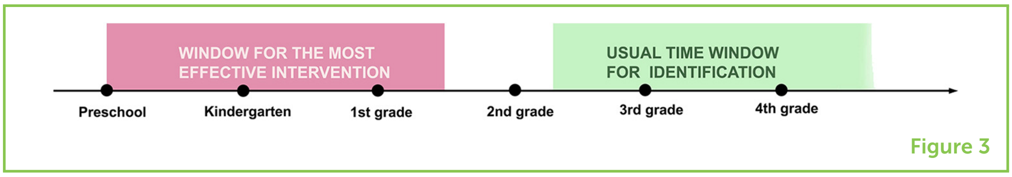


Figure 3

The dyslexia paradox. In most children, reading problems are not discovered until the second or third grade (green area). However, the best and most effective window for helping them is much earlier (pink area).

child is not trying hard enough. These are important reasons why scientists want to help identify these children as early as possible.

Some children who have reading difficulties may be diagnosed with developmental **dyslexia**, which is a type of reading disability. Usually, this diagnosis is made after the children have been trying to learn to read for quite some time (like in second or third grade). The struggle to read has nothing to do with missed practice, laziness, or lack of trying. However, by this time, children need to catch up quite a bit to do well in school, which is a big challenge. As mentioned before, research has shown that the best time to help children with reading is in kindergarten or first grade, when the brain is a lot more moldable. The difference between when we identify children who struggle with reading and when they could best be helped is called the dyslexia paradox, because it is something that contradicts itself (Figure 3).

DYSLEXIA

A learning disorder that involves difficulty reading due to problems identifying speech sounds and learning how they relate to letters and words.

Scientists have shown that we can detect early signs of reading difficulties through spoken, written, or computer tests. We were curious to know whether MRI could also be used to detect early differences in the brains of children who would ultimately have difficulty reading. We found that young children who later struggle with learning to read seem to have a different reading network [4–6]. But, with support and the right teaching, this can be changed.

THE MAGIC OF HELPING OTHERS

Unlike the wizards in Harry Potter, scientists cannot read people's minds or use any other forms of magic. But we have come up with various methods and technologies to study the learning brain, one of which is MRI. MRI has allowed scientists to study the parts of the brain that enable us to read and has shown us what might be happening in the brains of children who struggle with reading. With each study, scientists learn more about how we learn and why it is harder for some people to learn than it is for others. Eventually, this information may help us to support each child to reach his or her goals. And being able to do so is true magic.

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We would like to thank those who assisted in the translation of the articles in this Collection to make them more accessible to kids outside English-speaking countries, and for the Jacobs Foundation for providing the funds necessary to translate the articles. For this article, we would especially like to thank Nienke van Atteveldt and Sabine Peters for the Dutch translation. We would like to say thank you and dedicate this article to all children who are or were struggling with learning to read as well as the educators, parents and professionals who help them.

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YOUNG REVIEWERS

CASCADIA ELEMENTARY, AGES: 8–9

Our class is the Harbor Seals! We are a group of third grade kids who love reading and math. We have 9 girls and 14 boys in our class. We are an energetic bunch who love discussing our ideas together and learning about new things. We have been focusing a lot on collaboration, speaking, and listening to each other this year and we are so excited to be a part of the Frontiers community!

AUTHORS

NORA MARIA RASCHLE

Nora is an Assistant Professor of Psychology at the Jacobs Center for Productive Youth Development at the University of Zurich in Switzerland. Her team at the NMR Kids Lab is interested in knowing more about how the human brain grows, changes, and learns. Nora also loves to draw science cartoons and believes that knowledge can be taught in a way that is fun and understandable for all. She likes to try out new things with her three kids, like baking a giant cake, singing karaoke songs even though she is a horrible singer, building stuff (like robots), or visiting exciting places. *nora.raschle@jacobscenter.uzh.ch

RÉKA BORBÁS

Réka is a doctoral student in Neuropsychology at the Jacobs Center for Productive Youth Development at the University of Zurich in Switzerland. She is working with families and is super interested in how kids and their parents' brains work. For this, she is preparing families to go inside an MRI scanner to take a peek at their brains. Within the NMR Kids Lab, she tries to make research fun for everyone and is developing exciting games to play in the scanner. In her free time, she enjoys playing board games, snuggling with her furry cat, and baking for her friends and family.

CAROLYN KING

Carolyn is a Research Assistant at the Laboratories of Cognitive Neuroscience at Boston Children's Hospital and Harvard Medical School. She works with kids every day to understand how some kids learn to read and do math differently than others. She spends a lot of her time playing thinking games with preschoolers and kindergarteners, and she also gets to travel across the United States to test out new games. Carolyn loves to hike the tallest mountains she can find and play with alpacas, bunnies, and cats at her grandmother's alpaca farm. One of the alpacas has even hiked a mountain, and Carolyn hopes to day hike with him!

NADINE GAAB

Nadine is a professor at Boston Children's Hospital and the Harvard Medical School. Her usual work week includes looking at children's brains, chatting with her students, teaching a class, sitting in boring meetings, or playing with kids who come to the lab. She also travels to (mostly cool) places and tells people about dyslexia, reading development, and the brain. In her free time, she likes to play board games with her three children and enjoys watching her daughter play soccer and her son play baseball. She loves seafood and chocolate ice cream. When she grows up, she would like to become a chef.

NEUROSCIENCE
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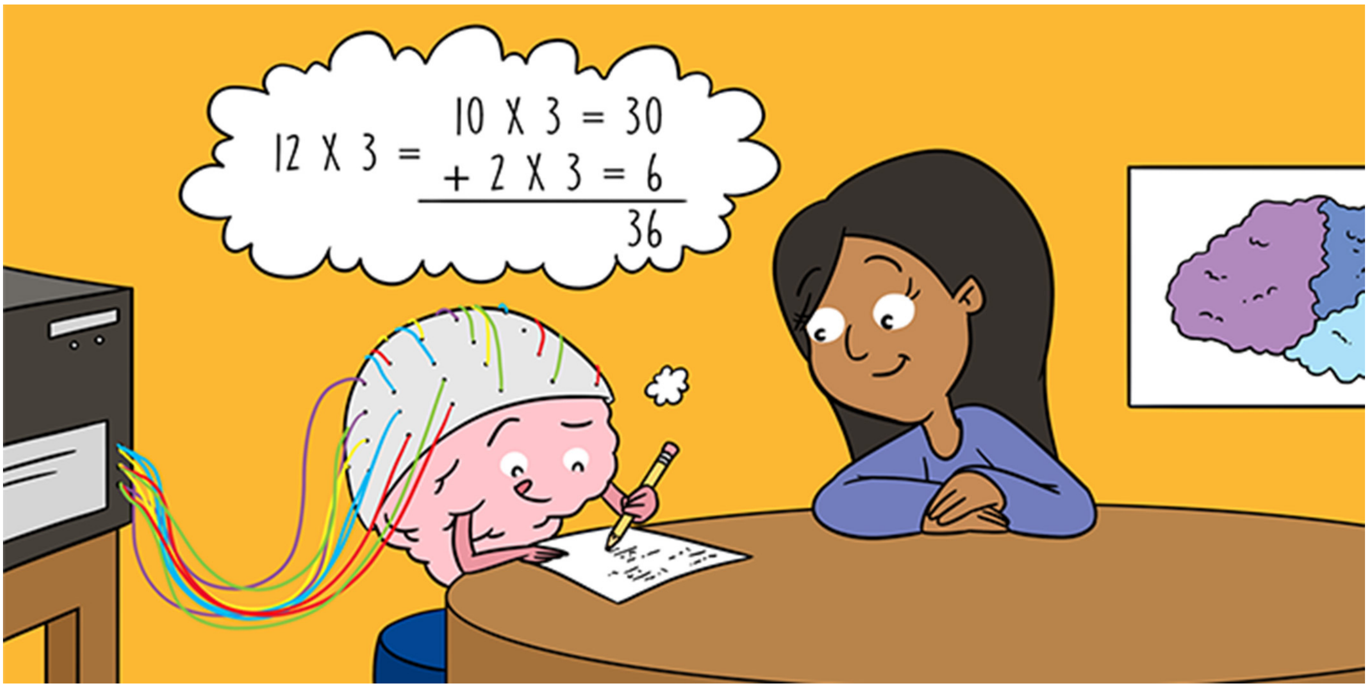

HOW MUCH IS 2 × 4? UNDERSTANDING HOW THE BRAIN SOLVES ARITHMETIC PROBLEMS

Nikolaus Koren[†], *Judith Scheucher*[†] *and Stephan E. Vogel*[*]

Section of Educational Neuroscience, Institute of Psychology, University of Graz, Graz, Austria

YOUNG REVIEWERS:

DR. H. BAVINCK SCHOOL

AGES: 8-12

LIJIA

AGE: 12

How much is 2 × 4? Sounds like an easy question, but have you ever thought about how you solve that problem? In this article you will learn about two different strategies that we use to solve arithmetic problems. You will also get to know the different brain areas—like the intraparietal sulcus—that work together when you use these different strategies. Which strategy and which brain regions you use changes over time as you get more familiar with arithmetic. This transition is especially visible in the way brain areas work and communicate with one another—some areas become more active, while others become less active. After reading this article, you will know more about the techniques we use to solve arithmetic problems and the brain areas needed to find the answers for your next math homework assignment.

INTRODUCTION

Because math is one of the most important skills to master, understanding how arithmetic problems are solved can have a very

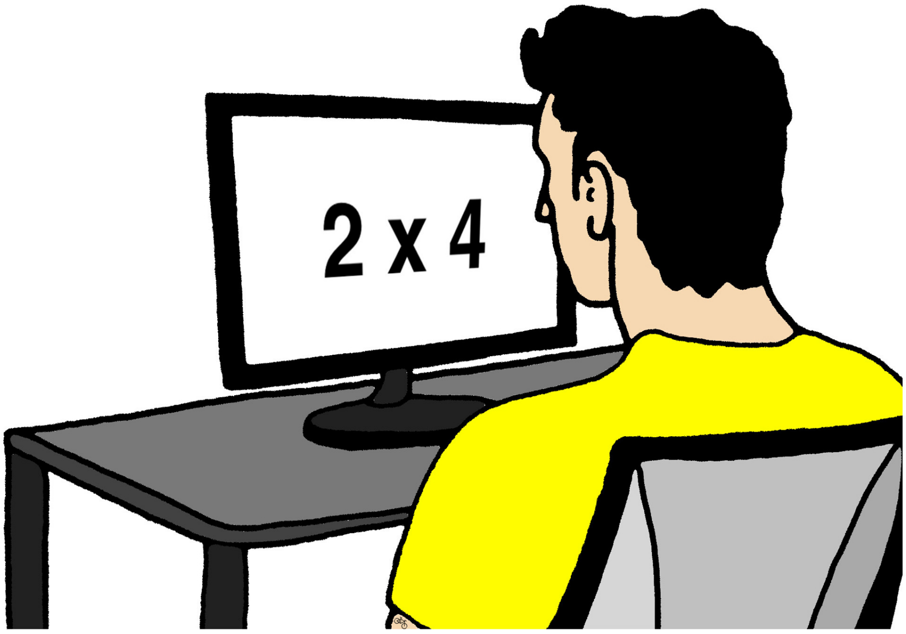

Figure 1

Figure 1

Example setup for a study investigating arithmetic problem solving. Participants are presented with an arithmetic problem on a computer screen. Once the answer is given, a new problem appears. For each problem, researchers record the time it took to solve the problem (speed) and if the answer was correct (accuracy).

big impact. Not only do you need math every day at school, but also as a grown-up. If you want to become a programmer, an engineer, or a scientist, you will deal with numbers on a daily basis. Because math is important in almost every job, people who are not good at math sometimes have a hard time finding a job. Some of them might even suffer from something called **developmental dyscalculia**. Therefore, understanding what happens in the brain when you calculate can be very helpful for kids who struggle with math. Understanding the reason for these difficulties enables teachers to structure their lessons in a way that allows children to learn more easily. And of course, just being curious about how things work is always reason enough to conduct an experiment!

DEVELOPMENTAL DYSCALCULIA

Is a difficulty in learning or understanding arithmetic. For a good overview look at the Young Minds article; When your brain cannot do 2 + 2: a case of developmental dyscalculia [1].

ARE THERE DIFFERENT WAYS TO SOLVE AN ARITHMETIC PROBLEM?

To study arithmetic, children and adults are usually asked to solve arithmetic problems as fast and accurately as they can. The problems are usually presented on a computer screen, one after the other (see Figure 1). Once the participant provides an answer, the next problem appears. To study the different strategies that we use during arithmetic, scientists usually use a mix of different arithmetic operations of varying difficulty.

Using these methods, scientists found that arithmetic problems can be divided into two categories: small and large problems. Small problems are solved very quickly, and participants make fewer errors when solving these problems. A good example would be "2 × 4." Large

Figure 2

Figure 2

Children taking part in one of our functional Magnetic Resonance Imaging (fMRI, left) and Electroencephalography (EEG, right) studies. These two tools let scientists study the brain while it is working.

problems are usually a bit harder to solve. Participants take longer to solve these problems and also make more errors. A good example would be "12 × 3." Scientists sometimes disagree on where to draw the line between small and large problems. How hard it is to solve a problem depends on your age and ability. However, speed and error differences between small and large problems suggest that we use two main strategies to solve them [2].

The first strategy, calculating the answer, is often used with large problems. It is called procedural strategy, because coming up with the answer involves multiple steps—or multiple procedures. For example, to solve "12 × 3" you might split the problem into two easier ones like "10 × 3 = 30" and "2 × 3 = 6." Afterwards, you can add up the results to get the answer "36." But adding extra steps has its downsides. It takes more time and each step also increases the chance of making errors. You do not, however, use the same strategy to solve the same problem forever. After solving it multiple times, the correct answer will 1 day just pop into your head. This shows that the way you solve this problem has changed.

Now you are using the second strategy: knowing the answer by heart—often called fact retrieval. By practicing the same problem multiple times, you stored its answer in your long-term memory. The switch from using procedural strategies to using fact retrieval is an important step during the development of arithmetic abilities [3]. Instead of calculating the answer, you are now able to remember it. Additionally, by becoming better at solving easier problems, you are also becoming better at solving more difficult problems. To better understand these changes, we need to look inside our brain while it solves arithmetic problems. To do so, scientists use different tools, such as **electroencephalography** (EEG) and **functional magnetic resonance imaging** (fMRI, see Figure 2).

ELECTROENCEPHALOGRAPHY (EEG)

A neuroscientific tool to measure the electrical signals a brain produces. This method can tell us with high accuracy at what time point brain areas are performing a specific task.

FUNCTIONAL MAGNETIC RESONANCE IMAGING (fMRI)

A tool to measure oxygen differences in the brain. Because active areas need more oxygen during a task, we can tell with high accuracy which parts are doing the job.

Figure 3

In this figure you can see a number of brain areas and one connection that are important for arithmetic. Two of them are in the frontal cortex (red) and two are in the parietal cortex (yellow). How they work together when you calculate depends on your age and your ability. Another important brain area, the hippocampus, is in the very center of your brain and therefore hidden from view.

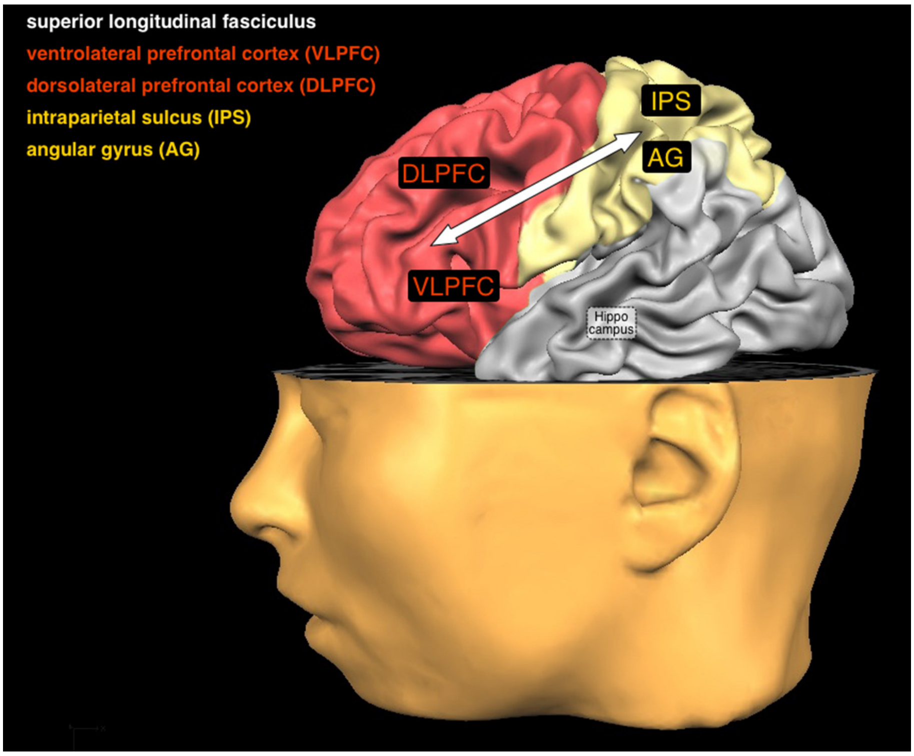

Figure 3

WHICH BRAIN AREAS ARE INVOLVED IN SOLVING ARITHMETIC PROBLEMS?

BRAIN AREAS

The brain can be divided into four major parts: the frontal cortex, the parietal cortex, the temporal cortex, and the occipital cortex. Each cortex contains brain areas with unique functions.

Trying to understand how the brain works can sometimes feel like solving a complicated puzzle. Similar to the way a puzzle is made up of different pieces, your brain is made up of different **brain areas** (see Figure 3). Understanding each brain area's function will give you a clearer picture of how it fits into the puzzle.

The first piece of the puzzle is the intraparietal sulcus. It is located in the parietal cortex and is responsible for understanding the meaning of numbers [4]. The first step when solving an arithmetic problem is to understand a number's magnitude. For example, you have to know that "4 dogs" are more than "2 dogs." You also need to understand the order of numbers (i.e., "1" comes before "2," that "2" comes before "3," and so on). While calculating, you use your understanding of magnitude and order to find the correct solution.

The next pieces of the puzzle involve three brain areas in the frontal cortex. The ventrolateral prefrontal cortex works with regions in the parietal cortex to blend out distractions, such as daydreaming about your next bike ride with your friends. The dorsolateral prefrontal cortex is needed to manipulate numbers, like splitting up a large problem into easier steps. The inferior frontal gyrus has been found to play an important role in ignoring similar but incorrect answers [5].

The last pieces in our puzzle are the hippocampus and the angular gyrus. The hippocampus is located deep inside your brain. It plays an important role in storing arithmetic facts [6]. The hippocampus is the "save" button of your brain. When it comes to math, it works with the frontal cortex to help you store the answers of arithmetic problems as arithmetic facts in your long-term memory. The angular gyrus is then involved in finding these facts when you solve arithmetic problems.

HOW DOES SOLVING ARITHMETIC PROBLEMS CHANGE AS YOU GET OLDER?

Have you and your friends ever worked on a challenging puzzle together? If so, you probably worked together to solve it. Your brain works in a similar way. Different brain regions work together when solving a problem. The last piece in our puzzle is understanding how these brain areas work together when you calculate. As you now know, the way you solve arithmetic problems changes as you get older. Instead of mostly using procedural strategies to solve arithmetic problems, you start using fact retrieval more often. But this is not the only thing that changes. Scientists found that during this process the way the different brain areas work together changes as well. For example, while you are young, the frontal cortex has a very important role. It manages your **working memory** and attention, because the way you solve arithmetic problems involves multiple steps (procedural strategies). As you get older and start to use fact retrieval, the role of your frontal cortex changes. When you look at the frontal cortex using fMRI or EEG, you can see that it becomes less active as you get older. It is still involved in the process of finding the right answer, but it does not have to work as hard as before. Maybe you have experienced something similar when cooperating with your friends. At first, one of you might have had to keep an eye on everyone's progress and give instructions what to do next (similar to the frontal cortex). After you have successfully solved a few puzzles together, you will be able to work together without needing someone to always check on the progress. The role of the hippocampus changes too. During fact retrieval it is more active in young children than in adults [7]. This is because when you are young, the hippocampus is still working hard to save the answers to arithmetic problems to your long-term memory. As you get older your hippocampus has to work less and less, because you come across fewer new answers that have to be saved.

WORKING MEMORY

A crucial function of your brain. Similar to the working memory of a computer, it stores information in your mind in order to work with it when you need it.

All of the brain areas work together by communicating with one another. This communication happens over a wide network of pathways (called white matter) that connect all brain areas. These networks are similar to the way in which roads connect different cities. One of these roads in the brain is called the superior longitudinal fasciculus. This road connects the prefrontal cortex with the parietal cortex (where the IPS is located) [8]. Because different brain regions are involved in the process of solving arithmetic problems at certain points in your life, the connections between these regions change as well. Scientists are still trying to fully understand how and why these connections change as you get older. That means, even though we already know a lot about how you solve arithmetic problems, we still need to do more research to complete the puzzle of the calculating brain.

SUMMARY

Even if it sounds like a simple process at first, solving an arithmetic problem actually involves many steps. Not only that, but as you get older you use different strategies to solve them. Almost every part involved in your brain changes. At first, many brain areas work together to solve an arithmetic problem. Some parts keep you focused on the task, others keep track and memorize the results of your calculations. The hippocampus saves the correct result in your long-term memory. As you get older, you only need a few specialized brain areas to solve the same problem. Your brain now works very efficiently. Next time you do your math homework, take a minute to think of all the different brain areas that are involved!

ACKNOWLEDGMENTS

We would like to wholeheartedly thank those who assisted in the translation of the articles in this Collection to make them more accessible to kids outside English-speaking countries, and for the Jacobs Foundation for providing the funds necessary to translate the articles. For this article, we would especially like to thank Nienke van Atteveldt and Sabine Peters for the Dutch translation.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

DR. H. BAVINCKSCHOOL, AGES: 8-12

We are Spectrum classes 5–6 and 7–8 of the Bavinckschool in Haarlem, the Netherlands. This is a group of 40 kids (19 in group 5–6 and 21 in group 7–8) who are eager to learn a bit more than the regular school program. They had a lot of fun reviewing for FYM, and went through the articles with great focus and enthusiasm, and made a critical evaluation. They really enjoyed contributing to science and helping out!

LIJIA, AGE: 12

LiJia is an avid reader since she was little, she would read most of the books independently she could find in the library or home including thick novels. She is curious about life and how human beings function. She is currently attending Year 8 classes in an international school in Southeast Asia.

AUTHORS

NIKOLAUS KOREN

I am a graduate student at the University of Graz, Austria, where I am currently finishing my master's degree in Psychology with a focus on Cognitive Neuroscience. My master's thesis focuses on electrophysiological correlates of arithmetic problem solving in children. I believe it is important to communicate scientific findings outside of one's own narrow field of research. If I am not in the lab, I am probably exploring the outdoors with friends either on foot, or on my bike.

JUDITH SCHEUCHER

I am a graduate student at the University of Graz, Austria where I am studying Psychology with a specialization in Cognitive Neurosciences. For my master's thesis, I am using electroencephalography (EEG) to investigate arithmetic problem solving in children. In the future, I aim to pursue a Ph.D. in the field of Neuroscience and keep on working in this fascinating field. My spare time is mostly spent playing in a concert band, learning to play new musical instruments and reading tons of Nordic crime novels.

STEPHAN E. VOGEL

I am an Assistant Professor at the Institute of Psychology, University of Graz. My research focuses on the development of the human brain. Specifically, I am very interested to better understand how the networks of the brain and its functions change as we get older. To study these processes, I use different neuroscientific tools such electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). I also work and interact with teachers, to help them better understand how the child's brain learns. During my free time, I like to mountaineer and ski in the beautiful mountains of Austria. *stephan.vogel@uni-graz.at

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NEUROSCIENCE
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MAKE SPACE: THE IMPORTANCE OF SPATIAL THINKING FOR LEARNING MATHEMATICS

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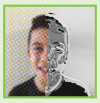
School of Psychology, University of Surrey, Guildford, United Kingdom

YOUNG REVIEWER:



GONI

AGE: 11

Spatial thinking allows you to understand the location and dimension of objects, and how different objects are related. It also allows you to visualize and manipulate objects and shapes in your head. Not only is spatial thinking very important for everyday tasks, new research shows that it is essential for mathematics learning. Children and teenagers who are good at spatial tasks are also good at mathematics questions. We also know that some of the same parts of the brain that are used for spatial thinking are also activated when we do mathematics. The good news is that many studies have shown that you can improve your spatial thinking through "training." This means that practicing spatial games and doing spatial activities can improve your spatial performance. In this article we discuss ways by which you can improve your spatial thinking and we look at evidence that suggests that spatial training may also improve mathematics.

INTRODUCTION

How do you know how to organize objects, such as packing a suitcase or fitting your books into your schoolbag? How do you know to put

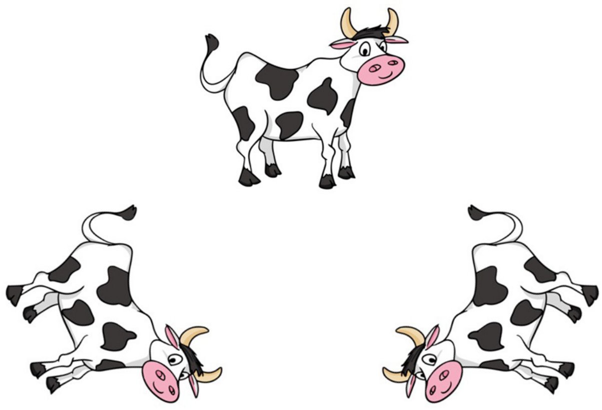


Figure 1

Figure 1

Sample mental rotation task.

your shoes on the right feet and how to button your shirt correctly? How do you find your way around a shopping center, and how do you know what to do if you get off the bus at the wrong stop? These tasks all rely on spatial abilities. People depend on their **spatial thinking** abilities hundreds of times every day without noticing. Even beyond everyday activities, most people, including teachers, do not realize that spatial thinking can influence how well you do in school, especially in **mathematics** classes. So, what is spatial thinking, and is it possible to become an expert spatial thinker?

SPATIAL THINKING

How the brain processes the position and shape of different objects.

MATHEMATICS

A subject relating to number and quantities.

SPATIAL THINKING: HOW DO WE MEASURE IT?

We use spatial thinking to understand the location (position) and dimensions (such as length and size) of objects, and how different objects are related to each other. It is important to understand that spatial thinking is not just one skill, but a set of different skills. Some of the most important spatial skills, and the tests scientists use to measure them, are described below.

Mental Rotation

Mental rotation allows us to turn (manipulate) images in our heads. You can try an example if you close your eyes and imagine an object like a car. Now, can you imagine what the car would look like if it was turned upside down? To do this you have to use mental rotation. In Figure 1, you can see a mental rotation test. Can you choose which picture on the bottom is the same as the picture on the top? To figure this out, you must turn the cows in your head. Then you can tell that the cow on the left is the same as the cow above it. No matter how much you turn the cow on the right, it will always be facing the wrong direction. Completing this test requires mental rotation. It is not only possible to turn objects in your head, you can also imagine what an object would look like if it was broken in half, folded, or bent.

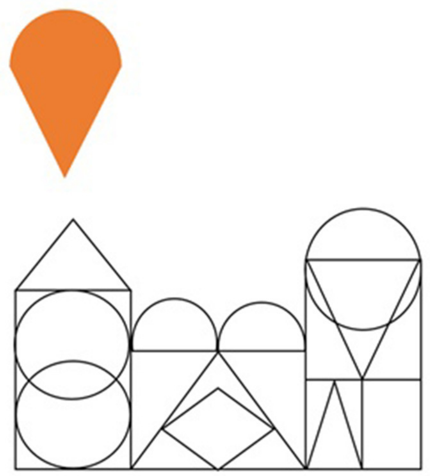


Figure 2

Sample disembedding task.

Disembedding

Disembedding skills are the spatial skills needed to separate one object or picture from a more complicated background. This allows us to understand how complicated structures are made up from separate parts. A very simple example of this is shown in Figure 2. Can you find the orange shape in the more complicated image?

Spatial Scaling

Spatial scaling is the ability to transform information between representations of different sizes. For example, spatial scaling is needed to be able to understand that the picture of a park you see on the map on your phone represents the same park that you are standing in. Another example is when we assemble furniture like a wardrobe using paper instructions with small diagrams. To build the wardrobe you must be able understand that the small picture of a wardrobe door in the diagram represents the life-size door that you have unpacked and need to assemble. In each picture in Figure 3, there is a ball positioned between two trees. Which picture on the bottom is the same as the one on the top? You will notice that the two pictures on the bottom are not the same size as the one on the top. This means that you must use spatial scaling when comparing them (correct answer is left).

Navigation

Navigation skills are vital for moving around our environments and getting us to the places we need to go. To navigate properly you must be able to understand the relationships between buildings, to use landmarks, to imagine what streets or buildings will look like from different perspectives, to learn routes, and to establish an understanding of the layout of your environment.

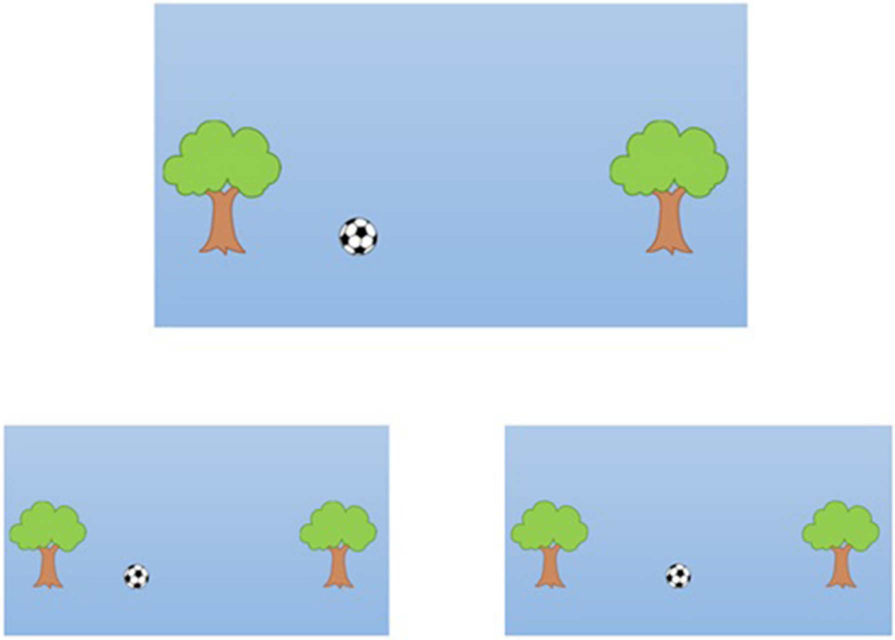


Figure 3

Figure 3

Sample spatial scaling task.

SPATIAL THINKING IS IMPORTANT IN SCHOOL AND WORK

Beyond its obvious importance in everyday life, it turns out that spatial thinking is also important for how well you do in school, particularly for mathematics lessons. People who are good at spatial thinking tasks also get high scores in mathematics tests. The link between good spatial thinking and good mathematics performance exists in people of different ages. For example, research has shown that infants who are better at constructing building blocks do better in counting and number tests [1]. For children in primary school, many researchers have shown that different types of spatial thinking are important for different mathematics tasks [2]. Children who are good at spatial scaling are also good at positioning numbers on a number line, and children who are good at mental rotation are better at doing calculation tasks with missing numbers like $3 + \square = 5$. For adults, having good spatial skills is very important for certain jobs. For example, engineers need spatial skills to visualize the structure of a bridge or building, geologists need spatial skills so that they can navigate landscapes, doctors need spatial skills to make sure that they give injections in the right position and to read x-rays properly, and biologists need spatial skills to understand how food moves through the different parts of our digestive system. Research shows that people who have good spatial skills when they are teenagers are more likely to have jobs in Science, Technology, Engineering, and Mathematics when they are adults.

WHAT IF I AM NOT GOOD AT SPATIAL TASKS?

The good news is that if you are someone who is not particularly good at spatial activities, you do not have to worry. Spatial thinking is one cognitive skill that seems to respond particularly well to being trained. Many research studies have attempted to improve spatial ability through different types of **cognitive training**. Although the word training is often associated with physical exercise, when cognitive (brain) scientists use the word training, they usually mean practice. This means that "Spatial Training" usually involves practicing paper and pencil spatial tasks, completing spatial games on a computer, or doing spatial activities like building structures with blocks. Many studies have shown that if you practice, your spatial thinking can be improved [3].

COGNITIVE TRAINING

Practicing or rehearsing specific thinking skills with the intention of improving them.

The even better news comes from new research that shows that if you improve your spatial thinking, you also improve in mathematics tests. When training in one skill leads to improvements in another, it is called transfer. Studies on other types of thinking show that it is very difficult to get brain training to transfer to untrained skills. You can read about other types of brain training and whether they work here [7]. Therefore, spatial training is quite unusual and important as there is evidence that training spatial thinking does transfer to other skills, for example mathematics.

Recent research that I completed showed that children obtained higher scores on a mathematics test after they watched a short video on spatial thinking [4]. Other researchers have also shown that using tangrams, which are a type of jigsaw puzzle, and other spatial games can improve mathematics skills [5]. Unfortunately, spatial thinking is not usually taught in schools. However, there are many ways that you can easily introduce it into your life at home and in school. This includes using more diagrams and graphs to help you when you are learning new topics in school, using more spatial language, including words like above, over, around, through, parallel, symmetrical, and gestures when you are explaining difficult ideas to your friends or younger siblings, practicing constructing things with blocks, Lego or puzzles, putting together furniture or even wrapping presents. It is also possible that some computer games like Minecraft (where players must use 3-D blocks to build structures like houses and cities) or games that require players to navigate mazes or unfamiliar spaces, might also improve spatial thinking.

WHY IS SPATIAL THINKING IMPORTANT FOR MATHEMATICS?

As researchers, one question that we are still trying to answer is why spatial and mathematics skills are linked. In other words, why are people who are good at spatial thinking also good at mathematics?

One possibility is that the same parts of the brain that we use for spatial tasks are also used for mathematics. One way to see what parts of the brain are activated (turned on) when we do specific types of activities is through functional Magnetic Resonance Imaging (fMRI). This technique uses a scanner that shows what parts of the brain are active at different times. For example, it can be used to tell what part of the brain becomes active when we do a mathematics activity. Research shows that some spatial and mathematics skills both rely on a similar part of the brain, the parietal lobe [6]. This means that training programs that encourage us to use spatial thinking might strengthen the connections between neurons (brain cells) in this part of the brain. This would be helpful for both spatial thinking and mathematics.

CONCLUSION

The next time you are trying to squeeze as many clothes as you can into your suitcase, or you are carefully following the map on your phone, remember how valuable your spatial abilities are. Perhaps even more than literacy and numeracy skills, spatial thinking abilities have a huge impact on how we get around and function in our day to day lives. Additionally, as outlined in this article, taking more opportunities to practice our spatial thinking might also improve our mathematics skills. Let us make space to develop our spatial thinking!

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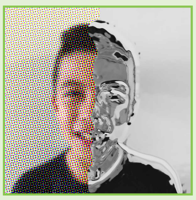
YOUNG REVIEWER



GONI, AGE: 11
I like reading, video games, and playing sports. I play soccer, basketball, fencing, and like running in cross country. My favorite food is pho or sushi. I like history, geography, and the study of animals. I play piano and know Hebrew, English, and I am learning Chinese. I just came back to the US from 1 year in Israel.

AUTHOR

KATIE A. GILLIGAN

My research explores how children learn mathematics and in particular how spatial thinking plays a role in mathematics achievement. I am interested in developing different types of training to improve children's mathematics skills in the classroom, e.g., playing computer-games that use shapes and spatial thinking, watching videos that teach spatial strategies, playing with manipulatives like building blocks and lego.* k.gilligan@surrey.ac.uk

frontiers FOR YOUNG MINDS

NEUROSCIENCE
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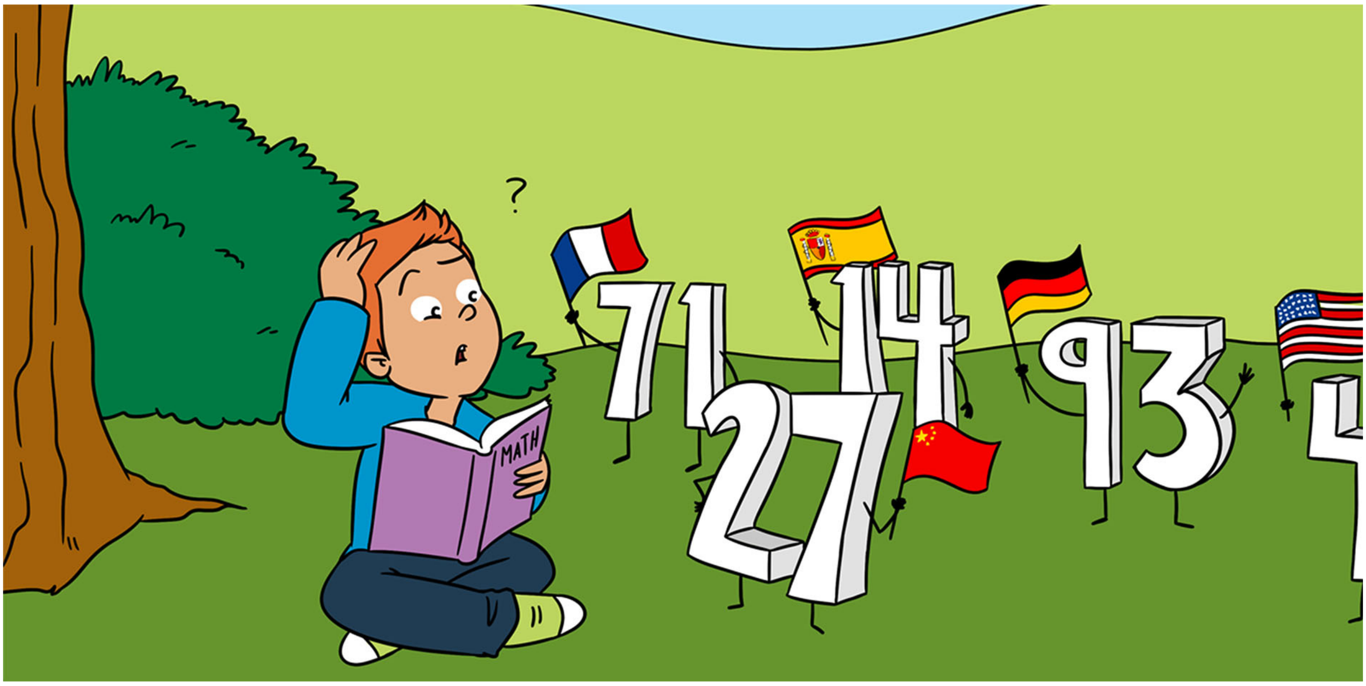


FORTY-TWO OR TWO-AND-FORTY: LEARNING MATHS IN DIFFERENT LANGUAGES

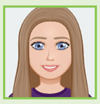
***Julia Bahnmueller*[1,2,3]*, *Hans-Christoph Nuerk*[2,4] *and Krzysztof Cipora*[1,2,4]**

[1] Centre for Mathematical Cognition, Loughborough University, Loughborough, United Kingdom
[2] LEAD Graduate School & Research Network, University of Tübingen, Tübingen, Germany
[3] Neuro-Cognitive Plasticity Laboratory, Leibniz-Institut für Wissensmedien, Tübingen, Germany
[4] Department of Psychology, University of Tübingen, Tübingen, Germany

YOUNG REVIEWERS:


THE BOMBAY INTERNATIONAL SCHOOL
AGES: 13-14


BRIDGET
AGE: 11


SIENA
AGE: 10

Doing basic maths seems to be a pretty common thing. 2 + 2 equals 4, both in France and in China. 7 × 8 equals 56, both in the United States of America and in Germany. Although most of us use the same symbols to write down numbers (1, 2, 3, 4, ...), we use very different words for these numbers simply because we speak different languages. In this article, we will give examples of what number words in different languages look like. We also show how the way multi-digit number words are built can make learning maths and dealing with large numbers easier or more difficult.

NUMBERS AND MATHS ARE PRETTY UNIVERSAL

Doing basic maths[1] seems to be a pretty common thing—you do it, I do it, even very young children do it before they go to school, for instance, when they count marbles. This is also true for calculations: 2 + 2 equals 4, both in France and in China. 7 × 8 equals 56, both in the United States of America and in Germany[2]. Most countries use the so-called **Hindu-Arabic numeral system** to write down numbers. The Hindu-Arabic numeral system uses exactly ten symbols that you are probably familiar with: 1, 2, 3, 4, 5, 6, 7, 8, 9, and 0. We use these ten symbols to write down single-digit numbers and we combine them when we write down multi-digit numbers.

Multi-digit numbers follow the **place-value rule**, which allows us to write down as many numbers as we want with only the ten symbols we already know. The place-value rule means that the value of each digit becomes clear when we look at the place of this digit within the multi-digit number. For example, the value of the 9 in 92 is 90 (9 × 10) and the value of the 2 in 92 is 2 (2 × 1). However, in 29 it is the other way around: the value of the 9 is just 9 (9 × 1) and the value of the 2 is 20 (2 × 10). This is why 92 is different from 29, although both are combinations of the same digits!

Having the same rules and symbols is great, because it makes it very easy to talk about numbers and calculations. It almost looks like we have one world-wide maths language and that learning basic maths in one country does the job, no need to learn it again in another country. 2 + 2 remains 4, no matter where you are.

LANGUAGES NAME NUMBERS DIFFERENTLY AND THIS CAN MAKE IT EASIER OR MORE DIFFICULT TO LEARN MATHS

There is just one tiny little problem. Although most of us use the same symbols to write down numbers, we use very different words for these numbers. This is because we speak different languages. In Table 1, you can find examples of number words for the numbers 1–10 in different languages. As you can see, the number words differ a lot between languages—just like most other words also differ between languages. Getting to know the names and the meaning of the numbers 1–10 in your own language is one of the earliest and most important steps in maths learning. However, learning ten number words is equally hard for children speaking different languages. In the end, they all need to learn ten new words; eleven, if we include 0 and 10.

Learning number words for numbers larger than ten differs much more between languages (try the quiz in the Figure 1). In some languages, the way people name multi-digit numbers is very clear and regular. Mandarin (the most popular language in China) is one of these languages. The Mandarin number word for 29 means "two-ten-nine"

[1] Maths is the abbreviation of mathematics used in the United Kingdom. In the United States of America, the abbreviation is math.

[2] The "×" in 7 × 8 is a symbol for multiplication. However, people also use " · " (7 · 8) or " * " (7 * 8) instead.

HINDU-ARABIC NUMERAL SYSTEM

A set of symbols that is used to write down numbers in most countries. The Hindu-Arabic numeral system uses exactly 10 symbols: 1, 2, 3, 4, 5, 6, 7, 8, 9, and 0. We use these ten symbols to write down single-digit numbers and we combine them when we write down multi-digit numbers.

PLACE-VALUE RULE

A rule that allows us to write down as many numbers as we want with only the 10 symbols we already know (1, 2, 3, 4, 5, 6, 7, 8, 9, and 0). The place-value rule means that the value of each digit becomes clear when we look at the place of this digit within the multi-digit number. For example, the value of the 9 in 92 is 90 (9 × 10) and the value of the 2 in 92 is 2 (2 × 1). However, in 29 it is the other way around: the value of the 9 is just 9 (9 × 1) and the value of the 2 is 20 (2 × 10). This is why 92 is different from 29, although both are combinations of the same digits!

Table 1

Number words in different languages. Do not worry, you do not have to look at all of them in detail. Maybe focus on the blue ones. All blue number words have something special compared with the very regular Mandarin number words. Below all two-digit number words, you can see how these number words would most likely be translated to English. The way some of these words are built is quite complicated. If you want to know how these number words are pronounced, you can listen to them on the internet. For Mandarin, French, German, and Hindi, go to bing.com/translator and insert the number word. For Basque, have a look at these YouTube videos: `https://www.youtube.com/watch?v=6eb0J4Vg5ys&feature` (numbers 1–19), `https://www.youtube.com/watch?v=wPbYCBzsw2A&feature` (numbers 20–39).

	Mandarin	English	French	German	Basque	Hindi	
0	ling	zero	zéro	null	zero, hutsa	shuniye	0
1	yi	one	un	eins	bat	ek	1
2	èr	two	deux	zwei	bi	do	2
3	sān	three	trois	drei	hiru	teen	3
4	sì	four	quatre	vier	lau	chat	4
5	wǔ	five	cinq	fünf	bost	panch	5
6	liù	six	six	sechs	sei	cheh	6
7	qi	seven	sept	sieben	zazpi	saat	7
8	bā	eight	huit	acht	zortzi	aath	8
9	jiǔ	nine	neuf	neun	bederatzi	nao	9
10	shí	ten	dix	zehn	hamar	das	10
11	shí yi *[ten one]*	eleven	onze *[oneteen]*	elf *[eleven]*	hamaika *[ten one]*	gyaarah *[oneteen]*	11
12	shí èr *[ten two]*	twelve	douze *[twoteen]*	zwölf *[twelve]*	hamabi *[ten two]*	baarah *[twoteen]*	12
13	shí sān *[ten three]*	thirteen	treize *[thirteen]*	dreizehn *[three ten]*	hamahiru *[ten three]*	tehrah *[thirteen]*	13
16	shí liù *[ten six]*	sixteen	seize *[sixteen]*	sechzehn *[six ten]*	hamasei *[ten six]*	saulah *[sixteen]*	16
17	shí qi *[ten seven]*	seventeen	dix-sept *[ten seven]*	siebzehn *[seven ten]*	hamazazpi *[ten seven]*	satrah *[seventeen]*	17
20	èr shí *[two ten]*	twenty	vingt *[twenty]*	zwanzig *[twenty]*	hogei *[twenty]*	bees *[twenty]*	20
21	èr shí yi *[two ten one]*	twenty-one	vingt et un *[twenty and one]*	einundzwnazig *[one and twenty]*	hogeita bat *[twenty and one]*	ikis *[one and twenty]*	21
29	èr shí jiǔ *[two ten nine]*	twenty-nine	vingt-neuf *[twenty-nine]*	neunundzwanzig *[nine and twenty]*	hogeita bederatzi *[twenty and nine]*	unatis *[one before thirty]*	29
48	sì shí bā *[four ten eight]*	forty-eight	quarante-huit *[forty-eight]*	achtundvierzig *[eigth and forty]*	borrogeita zortzi *[forty and eight]*	adtalis *[eigth and forty]*	48
75	qi shí wǔ *[seven ten five]*	seventy-five	soixante- quinze *[sixty-fifteen]*	fünfundsiebzig *[five and seventy]*	hirurogeita hamabost *[sixty and ten five]*	chiyahatar *[five and seventy]*	75
97	jiǔ shí qi *[nine ten seven]*	ninety-seven	quatre-vingt -dix-sept *[four-twenty-ten-seven]*	siebenundneunzig *[seven and ninety]*	laurogeita hamazazpi *[eigthy and ten seven]*	sataanave *[seven and ninety]*	97
100	yì bǎi *[one hundred]*	one hundred	cent *[hundred]*	(ein)hundred *[(one)hundred]*	ehun *[hundred]*	ek sau *[one hundred]*	100

Table 1

and the number word for 97 means "nine-ten-seven." Scientists call such languages **transparent**. This means that, in Mandarin, number words fit nicely to the way we write down the digits of multi-digit numbers and the number words clearly show the place-value rule: 97 $= 9 \times 10 + 7 =$ "nine-ten-seven."

Scientists found out that learning maths and dealing with multi-digit numbers is easier for children who speak a language with clear number words. However, the problem is that not all languages have clear number words. What do unclear number words look like? Have a look at some of the words for 97. In Basque (a language mostly spoken in a region in the north of Spain), they say "laurogeita

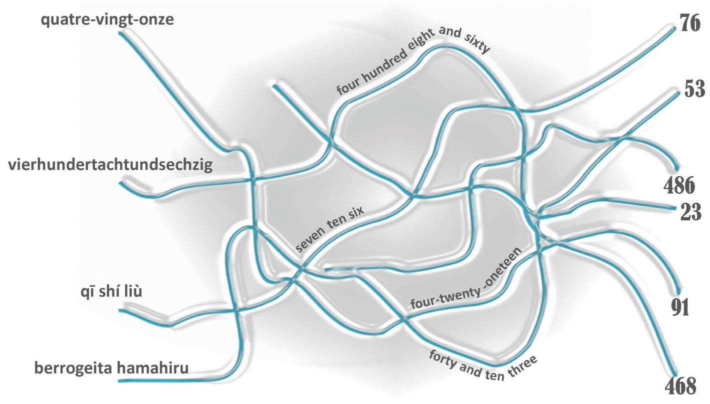


Figure 1

Figure 1

Which number word on the left belongs to which Hindu-Arabic number on the right? Try to figure it out on your own and then follow the line to check if you were correct. In the article, there are some hints that should help you to figure it out, and Table 1 might also help you make sense of the number words.

hamazazpi," which means "eighty-ten-seven" (80 + 17). In French, they say "quatre-vingt-dix-sept," which means "four-twenty-ten-seven" (4 × 20 + 10 + 7). The way these number words are constructed is really complicated. In Hindi (one of the most popular languages in India), there are a few numbers for which people use subtraction rather than addition to build the number word. For example, for the number 29 they say "unatis," which means "one before thirty" (30-1).

In Table 1, you can see the words for some multi-digit numbers in different languages. All the blue number words are somehow unique. The teen numbers are especially difficult to learn in many languages. Wouldn't it be clearer to say "one-ten-two" than "twelve" for 12? Twelve is a new word we need to learn, while for "one-ten-two" we can just use a rule. Saying "fourteen" instead of "teenfour" (or even "one-ten-four," like in Mandarin) is also not that helpful. Why do we sometimes switch the order of numbers and name the units first? Such switching is called **number word inversion**. In English, only a few teen numbers (thirteen to nineteen) are switched. In other languages, such as German, Dutch, Arabic, or Maltese, all two-digit numbers are switched (97 is "siebenundneunzig" in German, which means "seven-and-ninety"). For larger numbers, it gets even more confusing! The German number word for 234 means "two-hundred-four-and-thirty." Here, the digit on the left is named first, then the digit on the right, and finally the one in the middle. Complicated, isn't it?

It is not surprising that children who speak languages with switched number words have a hard time dealing with multi-digit numbers. German children (switching needed) make more than 5 times as many mistakes when they write down numbers than Japanese children (no switching needed) [1]. About half of the errors German children made involve mixing up the order [2]. For example, when they hear "five-and-forty," they often write down 54 rather than the correct number, 45. So, any child who grows up with a more transparent

TRANSPARENT

Transparent is another word for clear or well-structured. In the context of number words, the word transparent is used to describe languages in which number words fit nicely to the way we write down the digits of multi-digit numbers. In transparent languages the number words clearly show the place-value rule (e.g., 97 = 9 × 10 + 7 = "nine-ten-seven").

NUMBER WORD INVERSION

In some languages, the order of numbers in two-digit number words is switched. For example, instead of saying forty-two for the number 42, in some languages they would say two-and-forty. This switching is called number word inversion.

number word system can be happy that they have an easier time learning numbers.

HOWEVER, AFTER SOME TRAINING, MOST PEOPLE JUST LEARN HOW IT IS DONE

We already know that children speaking a language with non-transparent number words have a harder time with maths compared to children speaking a language with transparent number words. However, most older children and adults usually no longer have such problems. If learning non-transparent number words is only a matter of time or some extra practice, is it really a problem? Well, even though most children quickly deal with it, others keep on struggling. For instance, one study showed that children who struggle with number words at about 7 years old are more likely to have problems with maths 3 years later [3]. So, having problems with number words can show us which children might need some extra help with maths, so that they are not left behind. The earlier we help, the better!

... BUT THE PROBLEMS START ALL OVER AGAIN WHEN PEOPLE TRY TO DO MATHS IN ANOTHER LANGUAGE!

More and more people are now traveling and even living in other countries where they need to speak other languages. Sometimes, the new language has a different way of saying multi-digit number words and we must learn these new number words by heart. This can be a big problem, for example, if you come from Poland (no switching needed), and you want to live in Germany (switching needed). Krzysztof, one of the authors of this article, is one of these people. Every single time he does his groceries and tries to pay for them, he gets confused. When the lady at the cash desk says "Neunundzwanzig euro, bitte!" ["Nine-and-twenty euros, please!"], Krzysztof's first thought is "How on earth did I manage to spend almost one hundred euros for food I plan to eat in the next 3 days?" Despite knowing that he must do the switching, and despite doing research on this very topic, it usually takes him a while to calm down and pay the proper amount of money.

Learning number words in a new language is a good start, although this might already be tricky. However, even if you know all the number words in a new language it does not mean that you will want to do maths in this new language. Usually, people prefer to do maths in one language and, in most cases, they do not want to do maths in the language they have just learned to speak. It is more likely that people do maths in their main language, or the language in which they learned to do maths in school.

CONCLUSIONS

We use numbers and number words every day and for most of us they are not really special—at least not after some time and practice. However, when we look at number words more closely, it is fascinating to see how languages differ in naming multi-digit numbers. Although number words differ a lot, in most cases the way the number words are built is not random but follows specific rules. Have another look at the quiz in Figure 1. Now that you have learned some of these rules, see if you can decode some of the numbers more easily. Exploring the details of number words can help us understand why children speaking one language might struggle with maths more than children speaking another language. We might also be able to identify children having problems with maths early on and to find out how to support them. Of course, the rules for building number words are not the only thing that is important when learning maths, but it is certainly one piece of the puzzle.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

THE BOMBAY INTERNATIONAL SCHOOL, AGES: 13-14

We are the students of grade 8 at The Bombay International School (two sections of 20 students each) and are interested in the concept of reviewing articles for Frontiers for Young Minds. We enjoy testing our own skills as writers when coming up with feedback for a manuscript. Learning, exploring, and challenging our boundaries is fun. There is so much to learn at Frontiers for Young Minds!

BRIDGET, AGE: 11

Hi, I am Bridget, I enjoy the exact same things as Siena—learning is fun!

SIENA, AGE: 10

Hi, my name is Siena, I enjoy reading, writing, and cats, and I am in fifth grade.

AUTHORS

JULIA BAHNMUELLER

In my research, I am interested in how children learn basic maths but also how adults deal with numbers. I am especially interested in how different languages help or sometimes do not help maths learning. I also think it is very important to use the things I learn from research to support children that really struggle with maths, reading, or writing. My main language is German, but I also speak English and French and I am trying hard to learn to speak Spanish right now. *j.bahnmuller@lboro.ac.uk

HANS-CHRISTOPH NUERK

As a child, I was quite late in learning language. I only started talking a bit around 2 years old. On vacation that time, I met a little girl of my age who could already talk. However, I was quite early in learning numbers and calculations. Maybe this is one of the reasons why I am interested in how language influences number processing and maths. Is calculation easier in some languages than in others? Do we need language at all to deal with numbers? Is language especially important when maths problems get more difficult?

KRZYSZTOF CIPORA

I am a researcher working in Loughborough, UK and I originally come from Poland. I have also lived in Germany for a couple of years. Polish is my main language, and this may be the reason I struggle with German numbers! In my work, I am doing research on how the mind handles numbers and what kind of other information it uses to handle them. Apart from that, I am interested in many things about science in general. In my free time, I love to travel and to hike. My favorite animals are: penguins, giant pandas, alpacas, and koalas.

frontiers FOR YOUNG MINDS

NEUROSCIENCE
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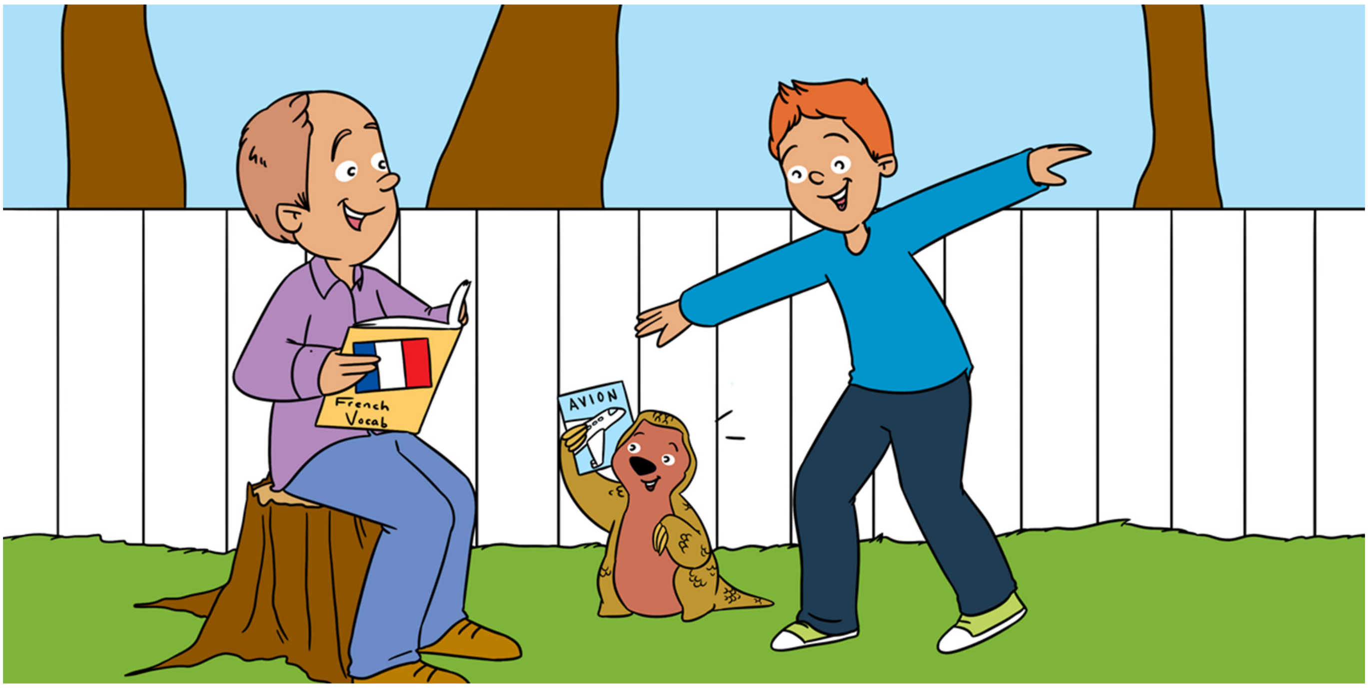

HOW CAN WE LEARN FOREIGN LANGUAGE VOCABULARY MORE EASILY?

Brian Mathias [1,2*], ***Christian Andrä*** [3,4], ***Katja M. Mayer*** [5], ***Leona Sureth*** [2], ***Andrea Klingebiel*** [2], ***Gesa Hartwigsen*** [6], ***Manuela Macedonia*** [2,7] ***and Katharina von Kriegstein*** [1,2]

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YOUNG REVIEWERS:


ETHAN
AGE: 10


JAIDEN
AGE: 13

Have you ever tried to remember a word in a foreign language? What strategy did you use? In several studies, we examined the beneficial effects of viewing pictures and performing gestures while learning foreign language words. Both pictures and gestures helped primary school kids and adults to better remember the meanings of foreign language words compared to learning by just listening. For kids, pictures and gestures were equally helpful. For adults, gestures were more helpful than pictures. Both visual and motor brain areas helped with learning the foreign language words. Our studies suggest that

learning foreign language words with pictures and gestures is helpful for learners, because pictures and gestures allow both kids and adults to experience the meanings of words through multiple senses.

HOW DO WE LEARN VOCABULARY IN A FOREIGN LANGUAGE?

Languages are important because they allow us to communicate with one another. People living on Earth today speak over 6,000 different languages [1]. Each of those languages has tens of thousands of words, or **vocabulary**, that refer to objects in the environment, people, places, feelings, and thoughts. Since you are reading this article, which is written in the English language, English may be your **native language (L1)**—the language that you started to learn at birth. You may also have learned English at school, from teachers or books, or by hearing English words outside of school. If this is the case, then you probably learned English as a **foreign language (L2)**. One of the most important steps for learning a new language is to learn the vocabulary of that language. This takes a lot of time and practice.

VOCABULARY

The set of words used in a language.

NATIVE LANGUAGE (L1)

A language that a person has been exposed to and started learning from birth.

FOREIGN LANGUAGE (L2)

A language spoken mostly by people in another area of the world than the speaker.

To learn an L2 word, we must hear how the word is spoken or see how it is written and learn the meaning of that word. Kids and adults use many strategies to learn L2 words. They might, for example, listen to audio recordings or study word lists. Recent research suggests that such techniques are less effective than strategies that use **enrichment** [2]. Enrichment refers to information presented during learning that allows us to experience the meaning of a word through multiple senses [3]. Instead of learning an L2 word by just listening to it, for example, we could see a related picture while listening to it. This happens when reading picture books and when learning vocabulary with picture cards. Another enrichment strategy could be to perform gestures that display the meaning of a word while listening to it. The word *airplane*, for example, could be displayed by moving our arms through the air as if they were wings.

ENRICHMENT

The presence of additional, complementary information during learning that helps to illustrate the meaning of a foreign language word.

Viewing pictures while listening to L2 words is a form of multisensory enrichment, because this technique uses information from multiple senses—seeing and hearing. Performing gestures while listening to L2 words is a form of sensorimotor enrichment, because this technique not only uses information from the senses, but also body movements. We tested which type of enrichment helped L2 learning the most [3, 4], and how the brain supported the L2 learning [3, 5, 6]. Both adults and kids were taught L2 vocabulary using three different methods: listening to the vocabulary while viewing pictures (multisensory enrichment), listening to the vocabulary while performing gestures (sensorimotor enrichment), and just listening to the vocabulary (no enrichment). Our **hypothesis** was that seeing pictures and performing gestures during

HYPOTHESES

Assumptions that can be tested by carrying out scientific experiments.

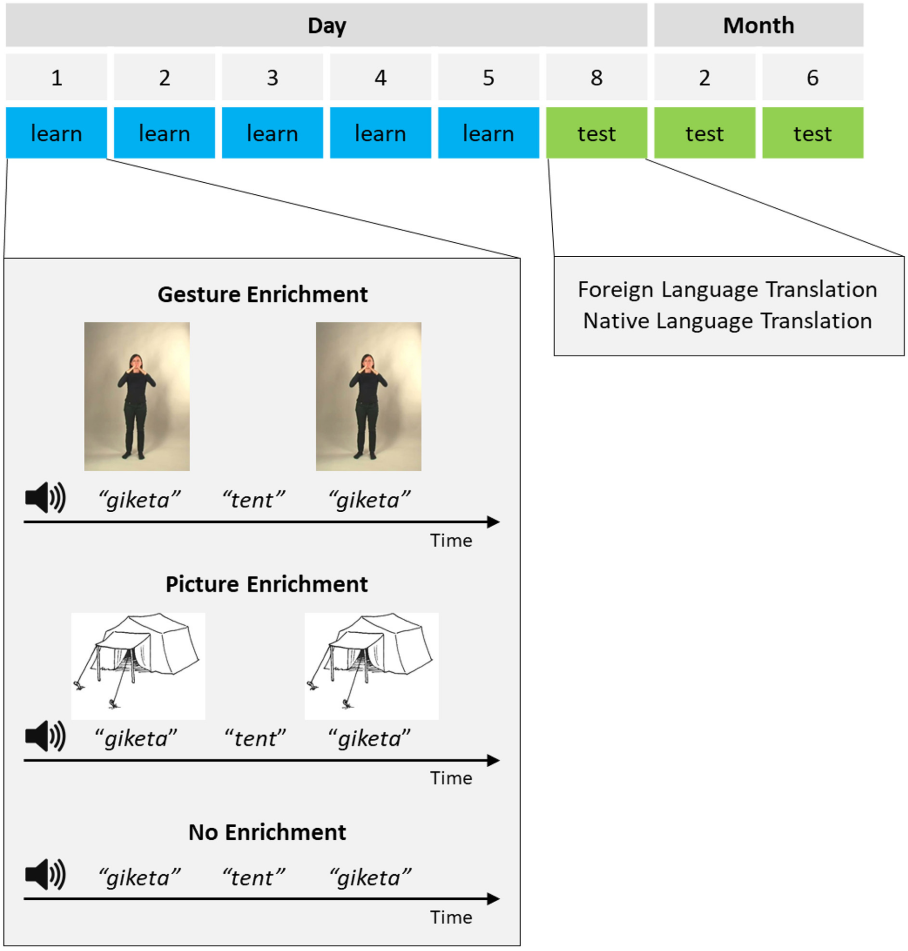

Figure 1

Figure 1

Foreign language learning procedure. Adults and kids learned foreign language words over 5 days. They learned the foreign languages words by performing gestures (gesture enrichment), by viewing pictures (picture enrichment), or by just listening (no enrichment). The adults and kids completed vocabulary tests 8 days, 2 months, and 6 months following learning, in which they were asked to translate a list of the native language words (native language translation) and a list of the foreign language words (foreign language translation).

learning would help kids and adults learn better than learning only by listening.

DO PICTURES AND GESTURES HELP ADULTS LEARN FOREIGN LANGUAGE WORDS?

We first tested our hypothesis in young adults [3]. Twenty-two adults heard L2 words and their L1 translations during 5 days of training. The adults were taught words that they had never heard before, such as *diwume* and *giketa*. A complete list of the words that the adults were taught can be found here. Some words were paired with pictures (Figure 1). For example, when the adults heard the foreign word that meant *tent*, they also saw a drawing of a tent. Other words were paired with videos of an actress performing gestures. For example, a video of an actress drinking from an imaginary bottle was paired with the word that meant *bottle*. The adults performed the gesture along with the actress. The rest of the words were learned only by listening to each L2 word and its L1 translation.

Figure 2

Translation test results. (Top) Scores for young adults (left) and kids (right) on the translation tests completed 6 months after the foreign language learning [3, 4]. Gestures (green bars) and pictures (purple bars) helped both young adults and kids learn the translations of the foreign language words more than non-enriched learning (black bars). The lines coming out of each bar represent estimates of how much variation there was in the test scores for all the young adults or kids. (Bottom) Scores for the non-enriched words were subtracted from scores for the words learned with enrichment, to see the enrichment benefit. For adults, the enrichment benefit for words learned with gestures was higher than the enrichment benefit for words learned with pictures, meaning that gestures were even more helpful than pictures.

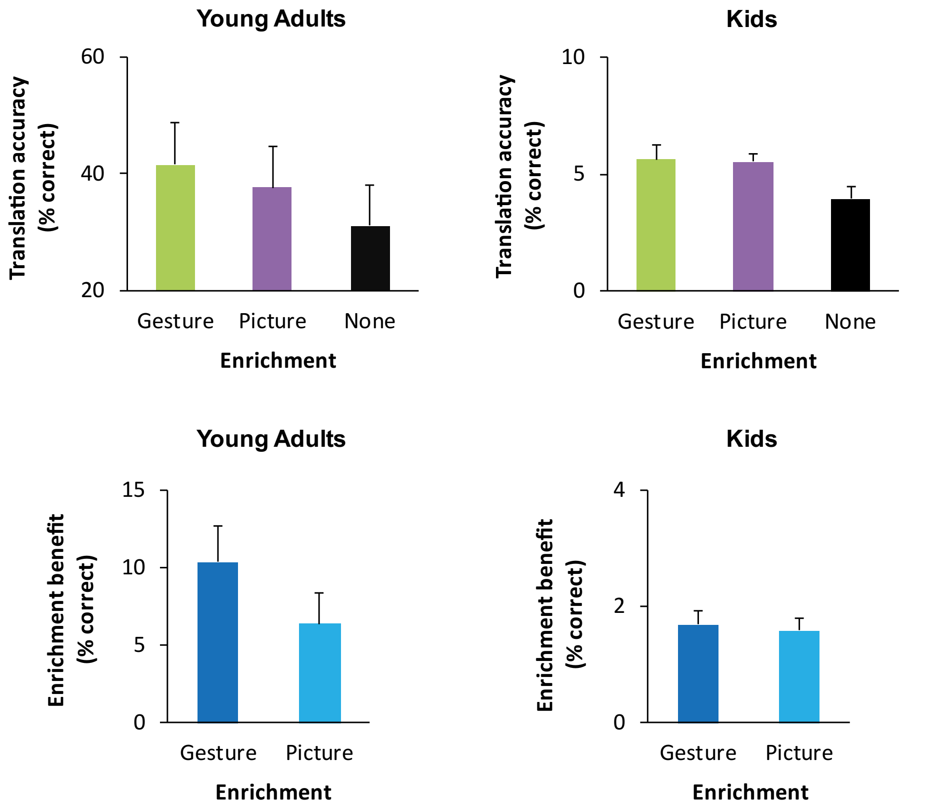

Figure 2

Vocabulary tests were completed 8 days, 2 months, and 6 months after learning. In one of the tests, the adults received a list of all the L1 words and wrote down their L2 translations. In another test, they received a list of all the L2 words and wrote down their L1 translations. We added up the test scores. We found that adults had higher test scores for words learned with both pictures and gestures compared to no enrichment, and that these benefits were still present after 6 months [3]. We also found that pictures and gestures were equally helpful in the short-term (at 8 days and 2 months after learning). However, over the long-term (6 months after learning), learning with gestures was even more helpful than learning with pictures (Figure 2).

WHAT ABOUT KIDS?

We next tested whether gesture enrichment would also help kids [4]. Ninety-seven 8-years-old German school kids learned English L2 words over 5 days. They learned the words using pictures, gestures, or no enrichment (Figure 1). The kids were taught English words that they had never seen or heard before in their English courses. The kids completed the same vocabulary tests as adults at 8 days, 2 months, and 6 months after learning. The kids gave their answers by speaking rather than writing.

We found that kids had higher test scores for words learned with both pictures and gestures compared to no enrichment at 8 days, 2 months, and 6 months after learning. Like the adults, pictures and gestures were equally helpful in the short-term (8 days and 2 months after the start of learning). However, unlike the adults, the kids' test scores following gesture- and picture-enriched learning were equivalent 6 months after learning (Figure 2). This result suggests that gestures and pictures were equally helpful for kids' L2 learning. The kids' scores were lower overall. This could be because the kids received less training than the adults.

WHAT BRAIN AREAS ARE INVOLVED IN LEARNING FOREIGN WORDS?

Our next step was to try to understand how multisensory and sensorimotor enrichment helped L2 vocabulary learning. To help answer this question, we turned to the brain. We know that seeing other people move can produce responses in a brain area called the **biological motion superior temporal sulcus (bmSTS)** [7], and that performing movements can produce responses in a brain area called the **motor cortex** [8]. We hypothesized that the bmSTS and the motor cortex would respond more when kids and adults heard gesture-enriched L2 words compared to picture-enriched L2 words. We made a similar prediction for the L2 words learned using pictures: we predicted that a visual brain region called the **lateral occipital complex (LOC)** would respond more when kids and adults heard picture-enriched L2 words compared to non-enriched L2 words.

BIOLOGICAL MOTION SUPERIOR TEMPORAL SULCUS (bmSTS)

A visual area of the brain that responds when people see body movements.

MOTOR CORTEX

The part of the brain that can initiate movements by controlling the muscles.

LATERAL OCCIPITAL COMPLEX (LOC)

A visual area of the brain that responds when people see objects.

So far, we have tested these **hypotheses** in adults [3]. To see which areas of their brains were active, 22 adults completed a brain scan after 5 days of L2 vocabulary learning. More information on how a brain scan measures brain activity can be found in this Young Minds Article [9]. We examined responses within the bmSTS, motor cortex, and LOC while the adults heard and translated the L2 words (Figure 3). We found that responses in the LOC told us if a word was learned with pictures, and responses in the bmSTS and motor cortex told us if a word was learned with gestures. These results tell us that specific brain responses are linked to the helpful effects of picture and gesture enrichment.

In scientific research, one method is usually not enough to prove that a conclusion is correct or not. The reason for this is that all methods have specific strengths and weaknesses. We therefore also examined whether the bmSTS and the motor cortex caused the benefits of L2 enrichment using a method called **transcranial magnetic stimulation (TMS)** [5, 6]. During TMS, small magnetic signals can affect brain activity and cause changes in behavior. We found using TMS that the bmSTS and the motor cortex helped adults to translate words learned with gestures.

TRANSCRANIAL MAGNETIC STIMULATION (TMS)

A neuroscience method in which the brain is affected by small magnetic signals.

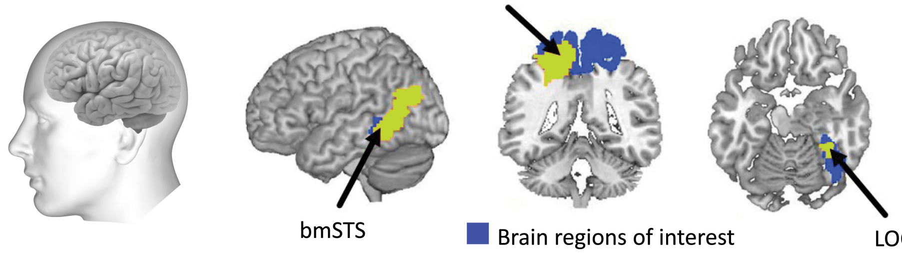

Figure 3

Brain imaging results. The two images on the left show the surface of the left side of the brain, and the two images on the right show two views of the inside of the brain. Areas of the brain that are known to process visual motion information (the bmSTS), motor information (the motor cortex), and visual object information (the LOC) are shown in blue. Areas of the brain that were seen by brain imaging to participate in the translation of foreign language words after learning enrichment with gestures or pictures, are shown in light green [3].

WHAT DO OUR FINDINGS MEAN?

Learning enrichment, with both pictures and gestures, helped kids and adults learn foreign language vocabulary. However, adults benefitted most from gesture enrichment, while kids benefitted equally from picture and gesture enrichment. This means that the types of enrichment that work for adults might not necessarily work for kids. In our studies, kids and adults received different amounts of training; future studies may investigate how different amounts of training may improve enrichment effects. We also found that the brain uses its visual and motor areas for remembering the translations of enriched L2 words. This means that enrichment teaching strategies may work because a network of visual and motor brain regions contributes to enhanced learning outcomes. In sum, enrichment benefits L2 learning because it allows us to experience the meanings of words with our own senses.

AUTHOR CONTRIBUTIONS

BM wrote an initial draft of the manuscript. CA, KMM, LS, AK, GH, MM, and KvK contributed to the writing of the manuscript.

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The authors would like to thank those who assisted in the translation of the articles in this Collection to make them more accessible to kids outside English-speaking countries, and for the Jacobs Foundation for providing the funds necessary to translate the articles. For this article, they would especially like to thank Nienke van Atteveldt and Sabine Peters for the Dutch translation. This work was funded by the German Research Foundation grant KR 3735/3-1, a Schulbezogene Forschung grant from the Saxony Zentrum für Lehrerbildung und Schulforschung (ZLS), and an Erasmus Mundus Postdoctoral Fellowship in Auditory Cognitive Neuroscience. BM is also supported by the European Research Council Consolidator Grant SENSOCOM 647051 to KvK.

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YOUNG REVIEWERS

ETHAN, AGE: 10

I am fascinated by all topics in STEM, especially 3D-printing, robotics, and astronomy. My hobbies include Legos, playing card games, learning magic tricks, and watching the Office on Netflix.

JAIDEN, AGE: 13

I have been interested in science since age 7. My favorite journal to read is Scientific American. My academic interests include chemistry, economics, and entrepreneurship. My hobbies include equestrian show jumping, playing board and card games, puzzles and riddles.

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Christian Andrä works at the University of Leipzig as a lecturer and researcher in teacher training. His research focuses on learning in motion. In several projects he develops teaching content that can be presented by means of sensorimotor enrichment. Since 2008 he is also member of the research group “School in motion,” which aims to reduce sitting time and utilize the numerous benefits of physical activity during everyday school life.

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Katja M. Mayer received her diploma in psychology from Tübingen University in Germany and wrote her diploma thesis at the Max Planck Institute for Biological Cybernetics. She then moved to Newcastle University for her Ph.D. in neuroscience, and later held post-doc positions at the Max Planck Institute for Human Cognitive and Brain Sciences and Münster University. Her research interests are multisensory perception and learning. She currently works as a psychotherapist.

LEONA SURETH

Leona Sureth is a medical student at the University of Leipzig, Germany. The mysteries of the human brain fascinate her, so she is interested in how the brain works and how science can be used to understand that. Besides her interest in medicine and neuroscience, she enjoys playing any sport that involves a ball and knows how to juggle.

ANDREA KLINGEBIEL

Andrea Klingebiel is a medical student studying at the University of Leipzig. During her studies she was fascinated by neuroscience and always curious to experience and participate in research. So she was very happy to have found this wonderful and exciting project. She enjoyed studying the human brain and doing her little part to help understanding it a better.

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Gesa's research group at the Max Planck Institute for Human Cognitive and Brain Sciences is interested in cognition and neural plasticity, especially in the language network. How does the language network adapt to neuronal challenges, e.g., induced by neurostimulation, noise, or training? How does the brain recover and repair function after a lesion? These and other questions drive our research.

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Dr. Manuela Macedonia is a senior scientist at Linz Johannes Kepler University in Austria and a guest scientist at the Max Planck Institute for Human Cognitive and Brain Sciences in Germany. Manuela's scientific interests reside in embodiment of language. In her base research, she investigates the effects of gestures on memory for foreign language words in the short and long term. In her applied research, she develops and tests virtual environments and virtual teachers for mobile devices that allow ubiquitous embodied learning of foreign language.

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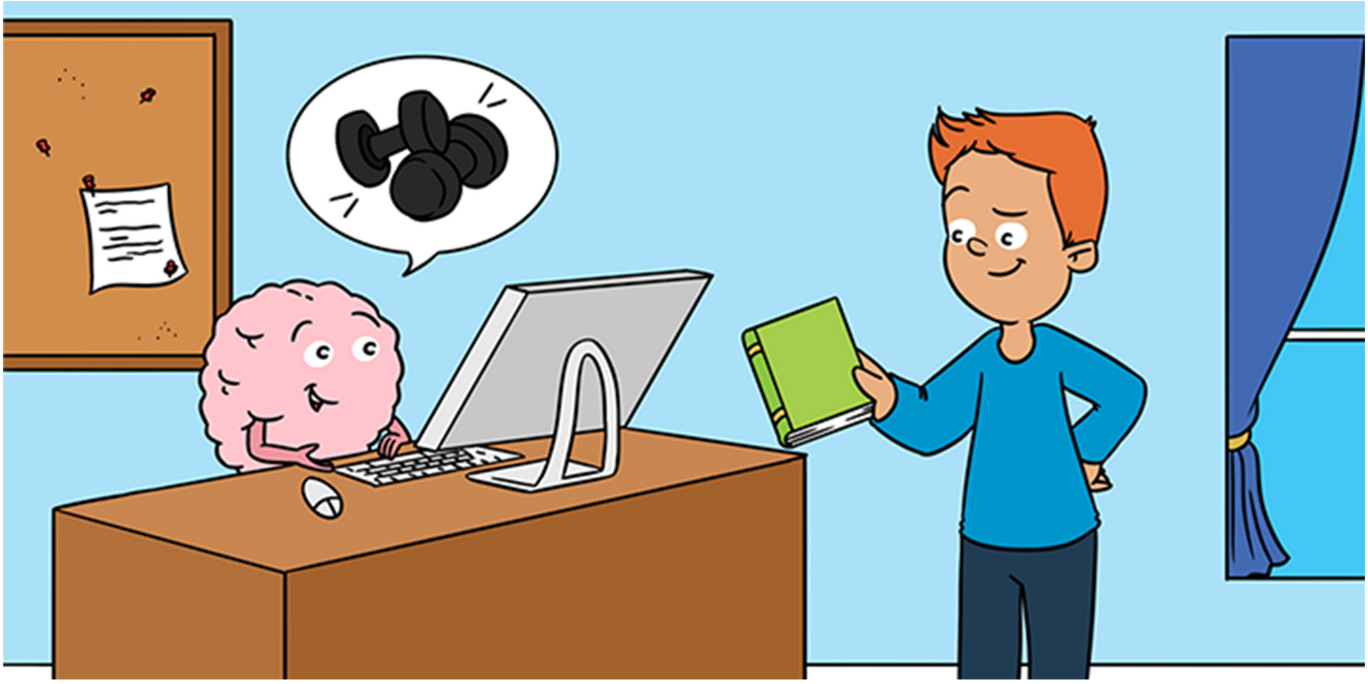

WANT TO TRAIN YOUR BRAIN? READ THIS ARTICLE!

Dietsje Jolles [1,2*] ***and Linda Van Leijenhorst*** [1,2]

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YOUNG REVIEWER:

VELIANA

AGE: 11

Imagine that you could make yourself smarter simply by playing games. Wouldn't that be awesome? You spend a few hours at the computer every week, and you will be able to concentrate better, learn faster, and remember more. Your grades will skyrocket, you will finish school without any trouble, and life will be perfect. Wouldn't it? If you search the internet, it is not difficult to find games and apps claiming to boost your brain, allowing you to use its full potential. In this article, we will discuss the science behind these so-called brain-training games. We will argue that, in theory, it should be possible to make yourself smarter. However, the evidence that brain training will help you do so is mixed, at best. We will speculate about the next-generation brain-training programs and discuss alternatives for improving your thinking skills. Why not simply read a book?

Many kids dream of being smarter or more creative. If you search the internet, you will find games and programs claiming to help you with just that: boosting your brainpower. But is it really possible to make your brain work better? And are these so-called brain-training games

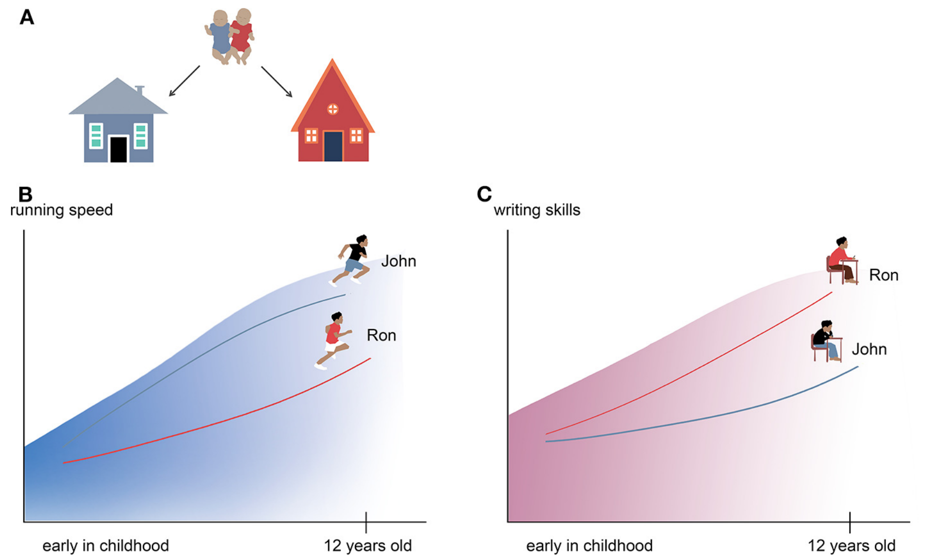

Figure 1

Figure 1

Development is influenced by genes and the environment. **(A)** Imagine two boys, John and Ron. They are identical twins, which means that they have the exact same genes. For some reason, John and Ron grow up in different families. John's family members are all avid soccer players and like to go for runs on the weekends. Ron's family members love to stay inside to read and write stories. When John and Ron are twelve, they meet each other. **(B,C)** Although they are amazed by some of their similarities, they also notice that they have some significant differences. John is a sports enthusiast, who plays soccer and is the best runner in his class. Ron loves to read and write and takes great pride in getting good grades in school. Thus, although John and Ron have the same genes, their environments determined to what extent their talents were expressed.

worth your valuable time? After reading this article, you can decide for yourself!

YOUR FLEXIBLE BRAIN

Have you ever thought about why some children excel in sports, whereas others are better at playing the guitar or performing mathematics calculations? Can you blame your genes for not being able to concentrate, or should you just try harder? For many years, scientists have tried to find out which parts of our talents and abilities are determined by our genes and which parts are influenced by the environment. It turns out that there is no simple answer to this question, because genes and the environment always work together [1]. Although your genes may influence the upper limits of your performance and your capacity to learn, your environment determines how your abilities actually develop. Thus, there is some built-in flexibility in the way your brain develops. This helps you to adjust to the environment that you grow up in. To explain this idea, we would like to introduce (fictional) John and Ron (Figure 1). John and Ron are identical twins, which means that they share 100% of their genes. Let us imagine that, for some reason, John and Ron are separated right after birth and raised in separate families. John grows up in a very athletic family, whereas Ron grows up in a family that is fond of reading and writing. It turns out that, although John and Ron have the same "runner" and "writer" genes, their different family environments influence the way their abilities develop. Whereas, John grows up to be an avid runner, Ron becomes a writer when he is older.

But what about being smart or talented in school? Research has shown that excelling in school has a lot to do with what are called **executive**

EXECUTIVE FUNCTIONS

Brain abilities that help you control your thoughts and behavior. Executive functions are also called cognitive control by some researchers.

WORKING MEMORY

The ability to hold information in mind for a short time, so you can work with it.

INHIBITION

The ability to resist distractions and temptations.

COGNITIVE FLEXIBILITY

The ability to switch back and forth between different tasks.

functions [2]. Executive functions are a set of abilities that help you do complex tasks, such as planning your schoolwork, completing assignments, and having control over your emotions and frustrations. One of the most important executive functions is called **working memory**. Working memory allows you to hold information in mind and perform mental operations, for example, adding large numbers in your mind (Figure 2A). Another important executive function is **inhibition**, which helps you to resist distractions and temptations, for example, the temptation to eat the entire jar of cookies (Figure 2B). A third executive function is **cognitive flexibility**, which helps you to quickly shift your attention back and forth between different tasks, like switching back and forth between your homework and your YouTube feed (Figure 2C). To measure executive functions, researchers have designed a number of games that can be played on the computer (Figures 2D–F). It turns out that children who do better at these games also do better at school. Moreover, poorer executive functions have been associated with undesirable conditions, such as mental health problems, obesity, and social problems [2]. You might think that executive functions are hardwired in your brain, but that is not entirely true. Just like any other ability, executive functions are influenced by your genes and by your environment. That is good news, because it means that you have at least some control over the development of these functions. Childhood might even be the best time for boosting your brainpower. The same way that it is easier to shape a developing tree compared to a full-grown tree (Figure 3), it might be easier to train a developing brain than an adult brain [1, 3]. Finally, it is important to note that although children's brains are more malleable than mature brains, children might not be as efficient and strategic when processing new information. This may hamper training effects a little bit.

TRAINING YOUR BRAIN

The internet is full of tips and tricks for optimizing your brain function, and numerous self-help books have been written about this topic. The advice includes getting enough sleep, eating healthy food, and exercising. But there is also something called brain training. According to the companies that offer such training, you can "train your brain in minutes a day," and users report impressive changes, ranging from improving their concentration to getting better at bowling [4]. Brain training usually refers to practicing the brain's executive functions. By performing complex mental tasks, your brain is working very hard, hence the name brain training. Moreover, research has shown that the brain changes with training [3], however, this is less impressive than it may seem. Everything you do makes small changes in your brain, whether it is walking your dog, meeting friends, or reading this article. Thus, brain training is a little bit of a misnomer. A more accurate name would be training of executive functions.

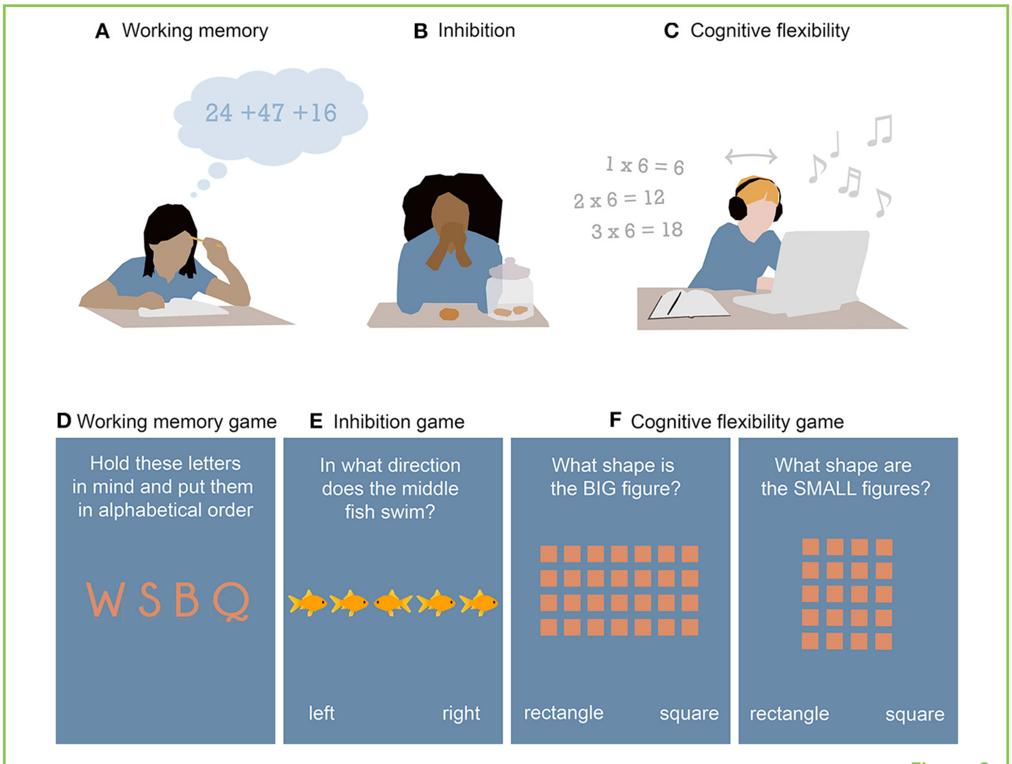

Figure 2

Figure 2

Executive functions and associated brain-training games. **(A–C)** Everyday activities that require executive functions: working memory, when you are adding large numbers in your mind; inhibition, when you are trying not to eat too many cookies; and cognitive flexibility, when you shift your attention between your homework and your YouTube feed. Games are often used to test and to train these executive functions. **(D)** In this working memory game, you have to hold several letters in mind and put them in alphabetical order. **(E)** In this inhibition game, you have to indicate the direction that the middle fish swims, and ignore the fish swimming in the opposite direction. **(F)** In this cognitive flexibility game, you go back and forth between a task where you have to indicate the shape of the big figure (rectangle), and another task where you have to indicate the shape of the small figures (squares).

TRANSFER

Using skills that you learned in one situation to improve your performance in a different situation.

But does brain training work? Because executive functions are closely related to intelligence, school performance, and all sorts of other real-life outcomes, researchers have suggested that games that train the brain's executive functions might also lead to improvements in all these domains. In other words, because the everyday activities shown in Figures 2A–C require the same brain abilities as the games depicted in Figures 2D–F, you might improve in the everyday activities after training with the games. This is what researchers call **transfer**. Over the past 20 or so years, numerous scientific studies have been conducted to test whether transfer actually happens [4]. Results indicate that brain-training programs often improve performance on the tasks that are being trained. In other words, participants who practice reordering letters in working memory get better at reordering letters in working memory. There is also good evidence that participants get better at closely related tasks, for example, reordering digits in working memory. However, based on current evidence, we cannot yet conclude that brain training improves more distinct tasks, such as performance on math or reading assignments [4]. Thus, although you might improve tremendously on the games that you are using for training, this does not necessarily mean that you will notice any improvement in your daily life. It is often the case that the skills that you have learned apply only to the specific games that you were playing. To have more far-reaching effects, the next generation of brain-training programs might include a greater variety of activities, integrated into real-life situations. For example, activities to train your

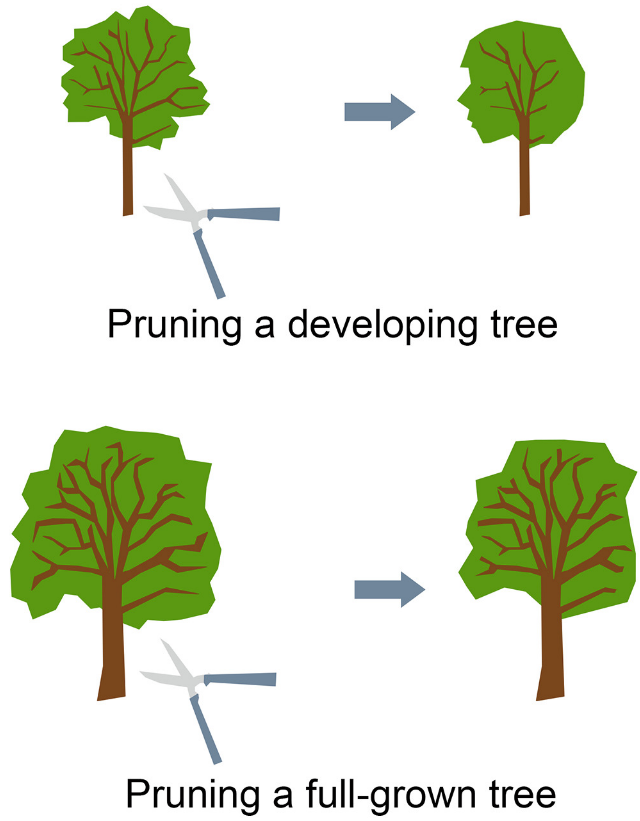

Figure 3

Figure 3

Pruning a developing tree is easier than pruning a full-grown tree. Researchers have argued that children have a greater capacity for learning and adapting to environmental circumstances than adults do, because children's brains are still in development. In other words, the same way that it is easier to prune a developing tree compared to a full-grown tree, it might be easier to train a developing brain than an adult brain.

executive functions could be incorporated in complex video games or into school subjects.

YOUR BRAIN ON BOOKS

We know that the things you do every day help shape your brain, and we also know that it should be possible to train your brain. However, researchers are still trying to find the best ways to train the brain. Would you be willing to spend your valuable time on a brain-training program that might not have substantial effects? Or would you rather spend your time doing something fun, like playing sports or reading books? Interestingly, research has shown that physical activity is not only good for your body, but also for your brain. The effects of regular physical activity might even be more important for school performance than the effects of a brain-training program. Similarly, reading books appears to have more general effects on your thinking skills. Research suggests that regular reading helps make you smarter by building your vocabulary and increasing your background knowledge [5]. The cool thing is that, with every new memory you create, new connections are built in your brain and existing connections are strengthened. The more knowledge you have, the easier it becomes to learn even more [5]!

Moreover, reading books might even train your thinking skills. Have you ever noticed how the rest of the world seems to disappear when you are absorbed in a story? This is possible because your brain is hard at work. When you read a book, you need to keep track of different characters, their backgrounds, goals, and details about their personalities and behavior. Moreover, you frequently need to read between the lines to understand what a book is about. To do these things, you use both your background knowledge and your executive functions. Without background knowledge you would not understand the words that are used, and without your executive functions you could never create a full story in your mind. Research has shown that children get better at these skills the more they read. Finally, besides increasing your memory and comprehension abilities, reading might help you to take the perspective of and sympathize with different characters, which is also an important skill for real life [6].

CONCLUSION

Even though your developing brain is super flexible, and it should be possible to make yourself smarter, the evidence that brain training will help you do so is mixed at best. Future brain-training programs will probably include multiple activities that are integrated into real-life situations. But do not wait for new programs! If you want to do something today to optimize your brain functions, stay active, eat healthy foods, get enough sleep, and keep on learning new things by doing lots of reading. Congratulations, you are doing it right now!

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YOUNG REVIEWER

VELIANA, AGE: 11

I am Veliana and I am 11 years old. I love going to school. My favorite subjects are mathematics, English, and sports. In my free time I like playing sports, painting, and reading.

AUTHORS

DIETSJE JOLLES

During my early school years I always wanted to be a detective. Instead, I became a scientist. But being a scientist is a little bit like being a detective. My main subject: the miraculous workings of the developing brain. I am particularly interested in the way children, adolescents, and adults learn and how their learning is influenced by their brain development. I hope that my research will contribute to a better understanding of the brain and its development, and that it provides new insights that can help to improve education. *d.d.jolles@fsw.leidenuniv.nl

LINDA VAN LEIJENHORST

I am an assistant professor studying developmental cognitive neuroscience at Leiden University, The Netherlands. I am fascinated by the changes our brain goes through as we grow from child to adolescent to adult. I hope to some day understand how these changes influence the way we make sense of the world around us. Isn't it amazing that our brain allows us to experience the world, to dream and to imagine things? To learn more about this I study how children and adolescents make decisions and how they understand stories they read.

frontiers FOR YOUNG MINDS

NEUROSCIENCE
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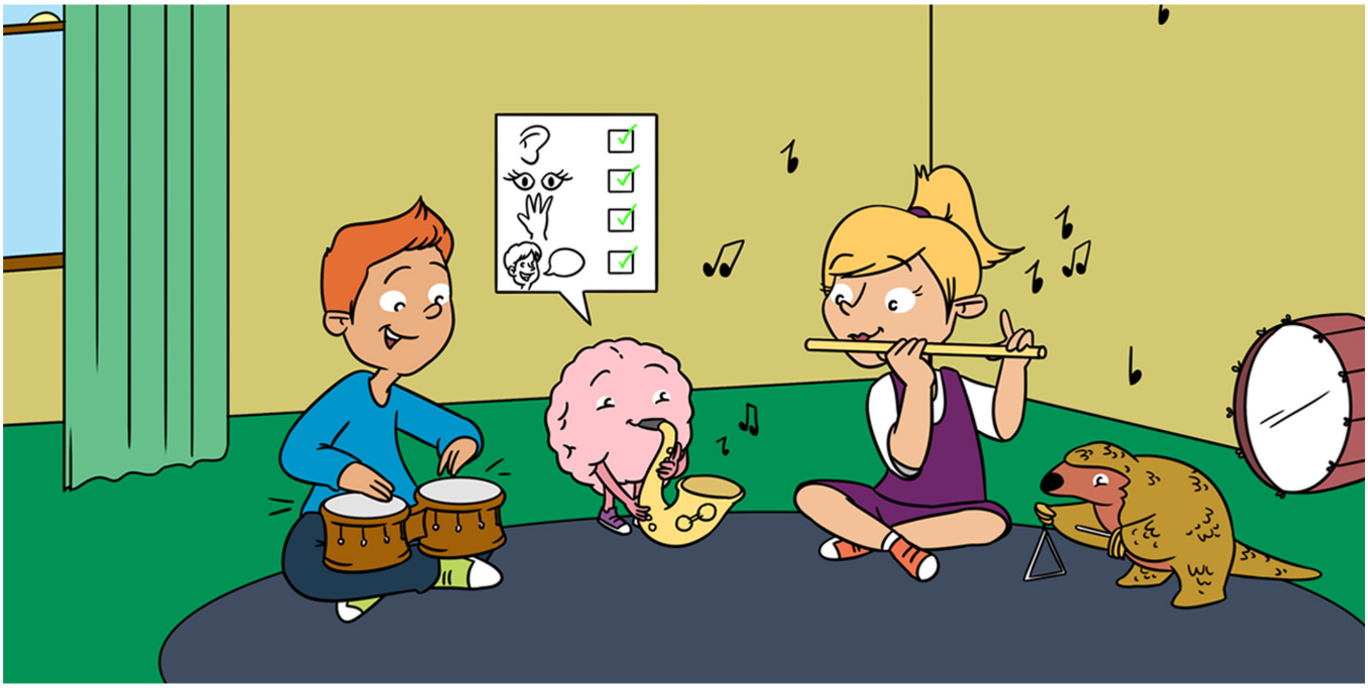

MUSIC AND LEARNING: DOES MUSIC MAKE YOU SMARTER?

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YOUNG REVIEWER:

SHIVANI

AGE: 15

What is music and why do people think it is important for learning? Musical sounds fill our lives: from the music you share online to the songs playing in shops and restaurants, we are rarely far from music. Playing music gives the brain a multisensory "workout" that can strengthen memory, help us pay attention, and perhaps even improve reading ability. In this article, we highlight how various brain functions, including hearing, sight, movement, and social awareness, are impacted by music training. You do not have to be a Mozart to get the brain benefit of playing music, because music is so accessible and is more than just songs. Whenever you communicate without words (the way you say something instead of what you say) you are engaging in musical behavior. In this article, we explore research on learning and music to help us understand why music promotes brain development and how music can be a central part of our lives, in and out of the classroom.

MIND THE MELODY

What is music and why do people think it is important for learning? While people of every culture around the world make something that could be called music, not so many of them give it a name or think of it as separate from other activities, like dance or storytelling [1]. Because of this, we can only define music in a general way, as a form of communication through sound. Unlike speech, however, music is not generally considered **semantic**. This means that music does not use words to explain things. Think how difficult it would be to say something relatively simple like, "your left shoe is untied," using only **melody** and **rhythm**. At the same time, music can convey profound emotions that would be difficult to describe in words. In addition to music being an art form, any form of communication is partly musical and can be said to have **musicality**. Think of the different ways that you might say "huh." Each of those ways communicates something different. That is musicality. It is not a musical performance, but a musical aspect of communication. While not everyone is a master of the violin, everyone is a master of their own communication style.

SEMANTIC

Relating to meaning in language or logic.

MELODY

A sequence of single notes that is musically satisfying.

RHYTHM

A strong, regular, repeated pattern of movement or sound.

MUSICALITY

Musical talent or sensitivity.

At first, some scientists thought that the brain could benefit just by listening to music. They showed that people's scores on **IQ tests** improved when they listened to classical music by Mozart [2]. This led people to believe that listening to music makes you smarter. But this was an oversimplification and an overstatement of the results. Subsequent studies showed that listening to music does not actually make you smarter, but rather raises your level of enjoyment and decreases your feelings of stress, which sometimes result in better focus and improved test scores. This means that, while music in your home or classroom would not automatically improve your performance, it could be useful to help you to focus on a new task or in situations when increased attention and decreased stress are necessary. Further, just listening to music may have a different, or perhaps smaller, effect than actually playing music. This is much the same as the way that playing sports will improve your physical condition more than simply watching sports. Therefore, the focusing power of music could be amplified by playing along.

IQ TEST

Intelligence quotient, a standard measure of an individual's intelligence level based on psychological tests.

MUSIC FOR BRAIN POWER

Just like your muscles, your brain gets stronger the more you exercise it. The process of changing the brain through our experiences is called **neural plasticity**, because the brain is easily shaped, like plastic. Scientists measure neural plasticity with special brain-imaging techniques, like magnetic resonance imaging (MRI) or electroencephalogram (EEG), to find out exactly how playing music changes the way our brains work. Research with these machines, as well as studying the brains of people who have died, shows that

NEURAL PLASTICITY

The capacity of the nervous system to modify itself in response to experience or deprivation.

auditory (hearing), visual (sight), and motor (movement) areas of the brain are specialized in expert musicians [3]. The specialization includes not only increased size of each brain area, but also the way each area functions. The science tells us that music is so much more than just a source of entertainment; it is an important part of our lifetime of learning. Here are some of the important things that happen in the brain when we play music (for review, see Zatorre [4]):

Auditory: The auditory system processes sound more effectively after musical training. People can detect smaller differences in frequency (the number of sound waves per second), making both speech and music easier to hear [5].

Motor: Brain areas that control instrument-related muscles and body parts (such as the fingers, the mouth, etc.) grow in size. More neurons in the brain are devoted to fine-tuning muscle movement in these areas.

Reading: Studies show that better musical ability is related to higher reading scores, suggesting a link between how well we hear speech and how well we can map speech sounds to letters.

Socio-emotional awareness: Playing music together can enhance socio-emotional awareness, which is the ability identify, manage, and express emotions constructively. A good example of this is that very young children are more likely to interact positively with people they play music with.

MAKING THE MUSICAL CONNECTION

How can music change anything other than what you hear? The reason music can reach so many parts of the brain is that the auditory system is highly interconnected with other sensory areas [6] (Figure 1). Think of your earliest school days and you will probably remember singing songs. Many of us still sing the alphabet song when trying to remember the position of a given letter. If you do not believe us, what letter is four letters after "M"? Now tell us you did not hear the alphabet song in your mind as you looked for the answer! Songs, with repetitive melodies and rhythms, help us memorize lists, stories, and even processes.

Figure 1 shows the pattern of connections between the main auditory area in the brain and the other areas of sensation and perception. When we learn to play music, our senses actively interact, including sight, touch, hearing, balance, movement, and proprioception (body awareness). There are two things that make music fairly unique in this process. First, when you play music, you are using all of your senses. For example, you feel the instrument in your hands, hear the sounds you play and see the notes on the music sheet. Since each different

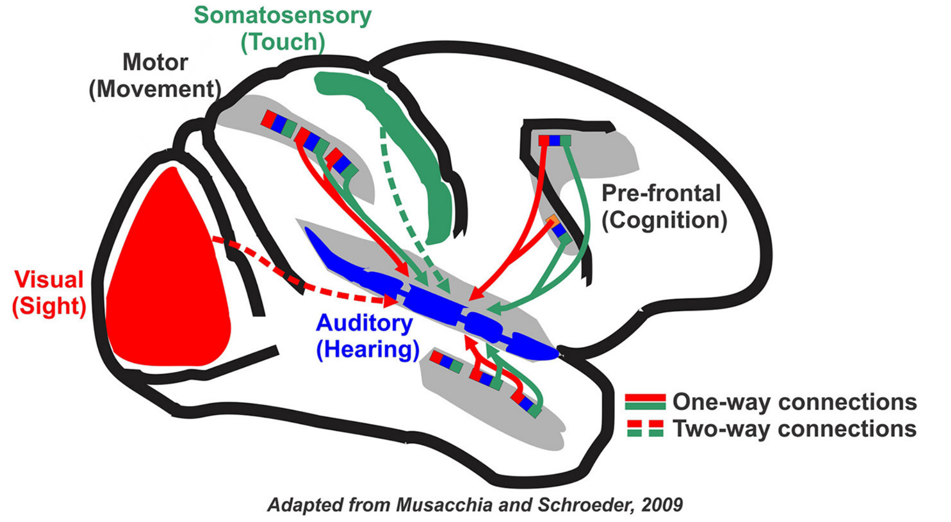

Figure 1

Other sensory areas of the brain provide input to the auditory (hearing, in blue) area. Multisensory areas, such as the pre-frontal cortex (cognition), motor cortex (movement), and complex auditory cortex are shown in gray and contain small boxes colored to show the senses they interact with. Strong connections to and from auditory and visual areas are considered to be two-way highways, because sensory information is shared between brain areas in both directions (dashed orange lines). Similarly, somatosensory (touch) areas are shown in green and also have two-way connections that share information. Adapted from Musacchia and Schoreder [6].

type of sensory information reaches your brain at a different time, your brain must work to synchronize all of this information. Second, when playing music, things happen at different speeds and time scales and must line up precisely. For example, a guitarist must know where s/he is on a beat, in a rhythm, in a melody, in a song, and in a concert, precisely lining up all of these things. While our understanding of how the brain keeps track of all these things remains unclear, it is likely that there are different timekeeping mechanisms ("clocks") for different timescales (speeds). Some of our research is based on the idea that synchronization between these brain "clocks" could help us analyze other sounds streams like speech.

A LIFETIME OF MUSIC

Music is also a way that we express our identities: the music we play, or even listen to, can be a way of telling the world, our peers, our parents, and our friends something about who we are. In cultures that do not use writing, singers often hold an important place in society, because they memorize important things like history and family relationships. While musical expression of identity is usually positive, there have been times when one group of people found another group's music threatening, or even dangerous [7]. For example, in the late 1980s rap music artists were arrested for performances that authorities thought were hostile and disrespectful.

While you might think of singing a song or playing an instrument as a special activity that you do only at certain times, you should also notice that music and musical sounds fill our lives. Music is played on speakers and sometimes played live, and we can hear music in most public places, on buses, in elevators, and in restaurants. Many of us listen to music through our phones or in our cars as well. Our lives are truly full of music, and so our relationship to music can have a big effect on a lifetime of learning.

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YOUNG REVIEWER

SHIVANI, AGE: 15

Hi! My name is Shivani and I am a high school student athlete living in San Jose. In the classroom, I love learning about math and science, and outside of the classroom, I love swimming as well as playing volleyball and golf. When I am not busy with school, I enjoy volunteering, spending time with my friends, and discovering new music.

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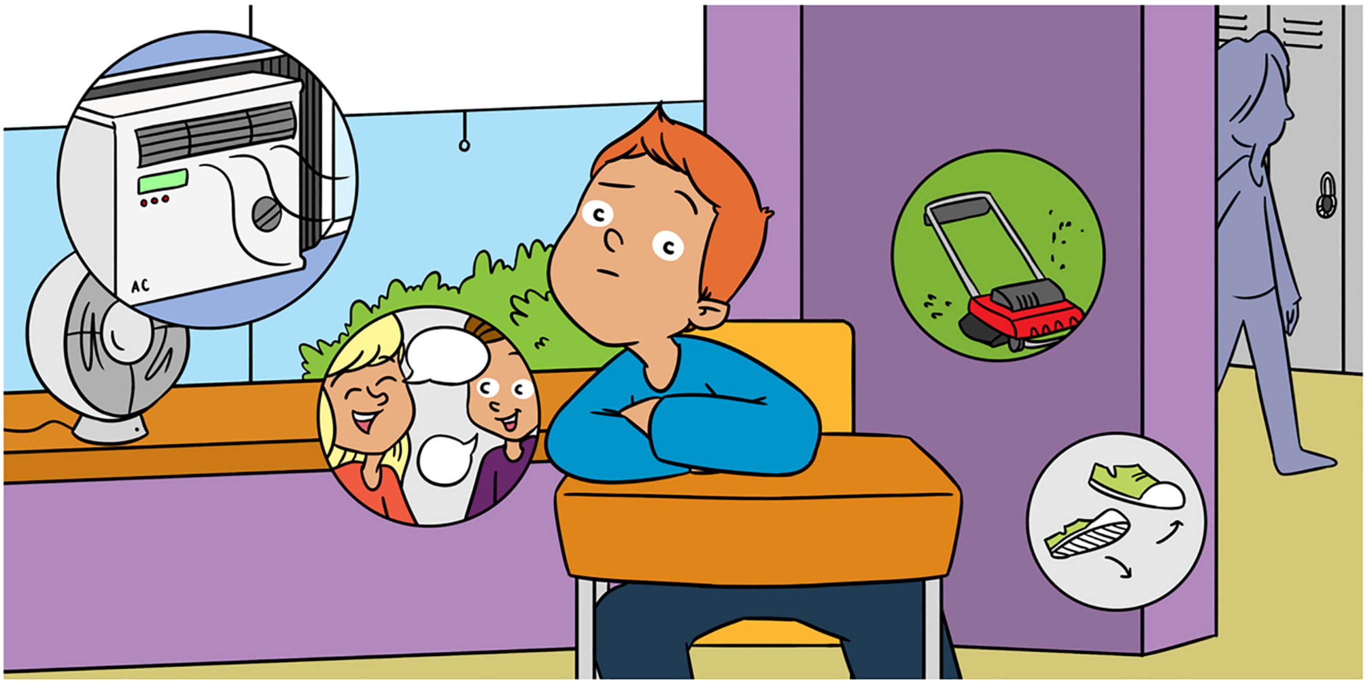

WHEN CHOOSING NOT TO LISTEN HELPS YOU HEAR AND LEARN

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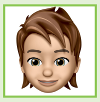
YOUNG REVIEWERS:



IAGO
AGE: 13

ROADRUNNERS & COBRAS
AGES: 10–11

Listening to important sounds will help us learn. However, it can be hard to separate the important sounds from the not-so-important sounds, or noise. Different parts of our brains are impacted by different kinds of noise, making it hard to learn. As our brains grow, we get better at separating the important sounds from the noise. However, there are a few listening tricks that both children and adults can use to listen and learn in noise.

AUDITORY SYSTEM
The body system responsible for hearing. It includes machine-like pieces and neurons which carry information about sound from the ear to the brain.

Adults often expect children to learn in noisy classrooms. Chairs scrape across the floor. Lawn mowers cut grass outside. Other students talk at the next table. In fact, we recently measured sounds in 157 classrooms; even with no students in the room, 137 classrooms had enough noise to interfere with listening [1]! It might seem like a short trip for sounds to travel from our ears to our brains. Still, there are many ways for noise to disrupt learning along the way. What can be especially frustrating is that sometimes noises do not bother adults as much as they bother kids. This is partly because a child's **auditory system** is still growing and changing (Figure 1). Also, adults have skills

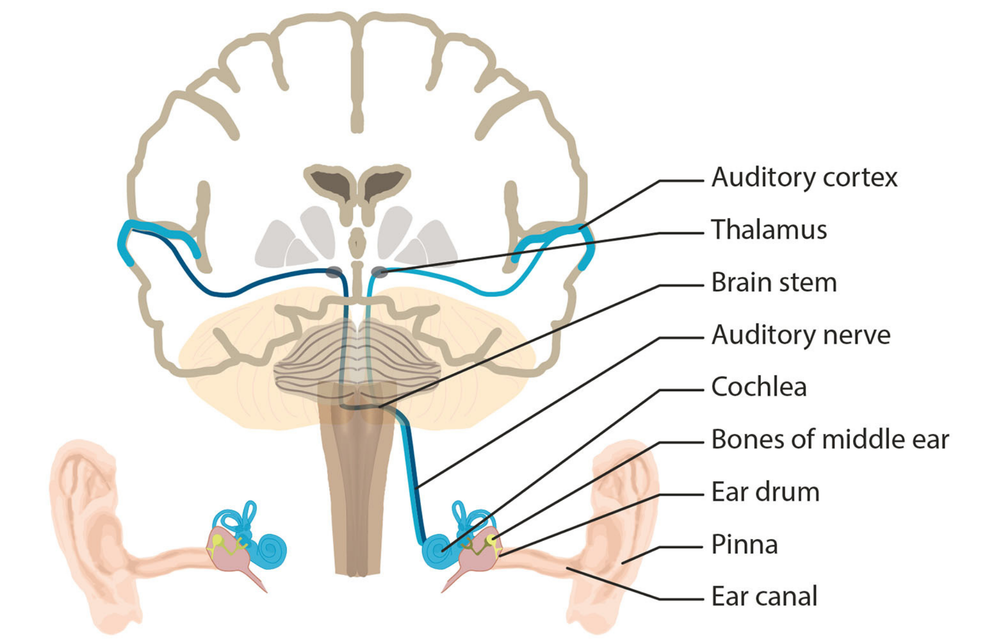


Figure 1

Figure 1

Here we see the machine-like structures and neurons of the auditory system. The parts most involved in hearing and ignoring noise are labeled. The pinna funnels sounds into the ear canal. We should look at important sounds because the pinna is best at funneling sounds in front of us. The cochlea turns sounds into electricity which travels down the auditory nerves to meet in the brainstem. Then electric signals travel through the thalamus on their way to auditory cortex in the temporal lobe of the brain.

for dealing with noise. We will discuss how sounds that do not seem important still make it hard to understand other things we hear and see. Then we will give you tricks for listening and learning through the noise.

CATEGORIES OF NOISE

Different noises affect our auditory system in different ways. We will focus on three kinds of noise. First, there is noise that changes over time. This would be the kind of noise from two of your classmates having a conversation. Another example of changing noise would be listing to jazz music while you are studying. When noise changes, sometimes the noise has a high pitch, like a trumpet; sometimes, it has a low pitch like a tuba. Sometimes the noise is loud and sometimes it is quiet. We measure the loudness of sounds in decibels (dB). Soft sounds, like leaves rustling, are around 20 dB, and loud sounds like airplane engines are over 100 dB. Second, there is steady noise. This is noise that sounds mostly the same from start to finish. This type of noise includes the whirring of a computer, the roar of a lawn mower, and the babble in the cafeteria as everyone talks at once. The third type of noise is sudden and short. Noises in this category are often surprising. These noises might be loud like a slamming door, but they do not have to be loud. They just need to be louder than nearby sounds. A softly buzzing cell phone would be in this category if the rest of the room were very quiet.

SEPARATING SOUNDS FROM NOISE

When one place has many sounds, those sounds mix together as they travel to our ears. Your "ears" are more than those curvy soundwave-catchers on the sides of your head which are called the **pinnae**. Each of your ears also includes the ear canal to your ear drum, your ear drum, some very small bones on the other side of your ear drum, and a structure called the **cochlea**. The cochlea is where sound waves turn into signals that neurons in your auditory system understand. The cochlea is also one place sounds mix together. Imagine that your cochlea is like a pond. The sounds coming into your cochlea are like rocks leaving ripples as they are thrown into the pond. If every student in the cafeteria tossed rocks into our pond, there would be ripples everywhere. Eventually, the ripples would run into each other. After the ripples get mixed up, it is hard to pick out exactly which ripples came from which students. This is the first reason it is hard to learn when it is noisy: two sounds are not very good at being in the same place at the same time. Instead, two sounds will mix into one messy, confusing sound. All three kinds of noise mix with important sounds, but steady noises mix with other sounds the most. Unlike sudden noises, steady noise lasts for a long time. Unlike changing noise, steady noise never gets quieter. When changing noise gets quiet, even for just a moment, the important sound has the cochlea all to itself. One trick is to use those moments of quiet to "glimpse" the important sound. Our cochleae are fully developed before we are born, so sounds mix in the cochleae the same for adults and children. However, adults are better able to use tricks like "glimpsing" to hear important sounds. This is because our brains' ability to process sounds gets better as we get older.

PINNA (PLURAL: PINNAE)

The part of the auditory system attached to the outside of the head, and what people usually call the "ear." Scientist call everything from the pinna to cochlea the "ear."

COCHLEA (PLURAL: COCHLEAE)

A spiral-shaped structure that turns sound waves into nerve signals that leave the cochlea on the Auditory Nerve—one of 12 special "cranial nerves" that bypass the spinal cord.

In order to make sense of what is happening around us, we need to divide the mixed sounds back into separate bits. A trick to help us separate sounds is to make the important sound louder. Imagine our pond full of ripples from the students' rocks. Now, imagine your teacher throwing in a huge boulder. The boulder's ripples might still mix with the ripples from the students' rocks. However, the boulder's ripples are so big they are easy to separate. We invited children with typical hearing and children with hearing loss to listen to important sentences in background noise. Very few children in either group could understand the sentences when the sentences were quieter than the noise or when the sentences and the noise were the same loudness. As soon as the sentences became even a few decibles louder than the noise, most children with typical hearing were able to separate sounds from noise and understand the sentences. However, some children needed the sentences to be much louder than the noise in order to separate them (Figure 2).

Making the important sounds louder is a useful trick because there are lots of ways to make your teacher louder. You could ask your teacher to raise his voice, or you could move closer to your teacher.

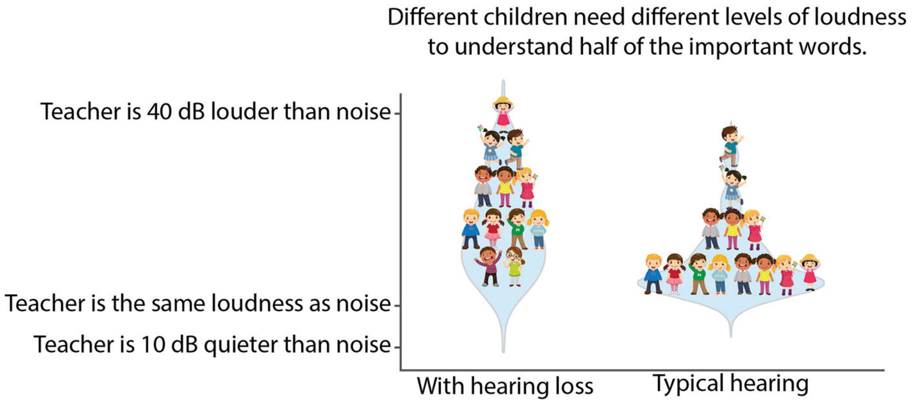


Figure 2

Figure 2

Very few children understand half of what they hear when the talker is quieter than the noise. For example, the bottom of the graph would be like the teacher talking (most people talk at about 60 dB) next to a lawn mower (70 dB). A noisy classroom is about 90 dB! Most children with typical hearing need the talker to be at least as loud as the noise (right side). Children near the top of the graph need the talker to be louder than the noise. Notice that almost all children with hearing loss are near the top of the graph (left side). This illustrates how much harder listening in noise is for children with hearing loss—even when they use hearing aids [6].

You could also try to make the noise quieter. If the noise is outside, ask to close the window. Our brains also have a useful trick for making the not-so-important noises seem quieter. This trick is called **habituation**. Habituation is when the same thing is presented over and over and we stop responding to it. Habituation occurs for sounds, sights, smells, and touches. Have you ever made popcorn that smelled really good? After a while, you stopped noticing the smell. Then you went to the bathroom, and when you came back, you could smell your popcorn again. This is an example of habituation to a smell. The popcorn smell is still there, but your brain stopped noticing it. The same thing can happen with sounds—especially steady noises. Even though the steady noise does not actually get quieter, it produces a smaller brain response over time which makes the important sound seem louder in comparison. Unfortunately, even children as old as 9–11 years take longer than adults to habituate to sounds [2]. Adults' ability to habituate to steady noises may be one reason that they are better than children at understanding important words even when there is noise [3].

HABITUATION

A decrease in responding when the same sound, sight, smell, or touch is presented for a long time.

We also separate sounds by figuring out where each sound is coming from. This is possible because we have two ears. A sound on your right will be a tiny bit louder to your right ear than your left ear (Sound Demo). A sound on your right will also get to your right ear just a tiny bit faster than it gets to your left ear. The difference is so small (half of one millisecond) that you would not ever notice it. Your auditory system notices, though! After sound information leaves each cochlea, it travels along a special nerve called the auditory nerve directly to the brainstem. The brainstem gets nerve signals from both cochleae and can tell which cochlea heard a sound first and louder. By the time we are adults, our brainstems have figured out exactly how much more time it takes (and how much the loudness changes) as sound travels around our heads. Our heads are still growing very quickly until we are 6 years old, which makes finding sounds harder for very young children. Knowing where each sound comes from helps our auditory system unmix sounds.

We can also separate mixed sounds is by paying attention to one sound while ignoring the other sounds. We do not entirely understand how our brains are able to do this. Sometimes, we seem to decide what we pay attention to, but other times it seems like our brains decide for us. If your class was working when a door suddenly slamed, the students would look at the door. Your auditory system heard the sound, figured out where it was coming from, and decided it might be important enough to pay attention to. One idea is that the **thalamus**, a structure deep inside the brain, helps prioritize information [4]. The thalamus gets information about sounds as well as sights, tastes, and touch. The thalamus can monitor our environment and detect when a sound, sight, or touch changes. Sounds are more likely to get our attention if they come on or change unexpectedly. This means that changing sounds might get our attention even when we do not want them to.

THALAMUS

A structure deep inside the brain that sends information about sound, sight, taste, and touch to the rest of the brain. It may alert our brains to changes in our surroundings.

NOISE MAKES IT HARD TO LEARN WHAT WE SEE

Not only does noise make it difficult to pay attention to important sounds, but noise also makes it difficult to pay attention to important information we see. Until children are about 9 years old, even steady noises, like air conditioners, can hurt their memory [5]. Steady noises do not seem to bother adults very much, probably because they habituate to them. However, both children and adults struggle to remember words when changing noises play in the background—especially if the changing noise also has words. This means that that you are less likely to remember what you have read if the TV is on. Even children as old as 12 have trouble remembering when the changing sounds do not have words—like jazz music. In other words, all noises disrupt memory when we are young, but different noises become easier to ignore as we get older. This suggests that as we get older, our brains become better at controlling which sounds get our attention. Once we control what our brains pay attention to, we are better at listening and learning through noise.

USE YOUR EYES TO HELP YOU HEAR

A very important listening trick is to look at important sounds. Looking at something helps us pay attention to it. This will help us separate the important sound from the noise. We can also use the shape of someone's lips as a clue to the sound they are saying. Ask your friend to say the words "dark" and "mark" without making sound. Notice how their lips come together to make the "m" sound? People who are good at using these lip-reading clues are also better at understanding speech in noise.

CONCLUSION

Noise makes it difficult to listen and learn. Children have an especially hard time listening and learning in noise because their auditory systems are still developing. However, scientists have discovered some tricks that help us hear better: (1) make important sounds louder and noise quieter, (2) find out where the important sounds are coming from, and (3) look at the important sounds.

SOUND DEMO

Listen to this sound demo without headphones. Can you tell what story the teacher is reading? Now put on headphones. Do you notice how the teacher moves around the classroom but the noise stays still. Locating the teacher helps us pick out her voice and understand the line from "Jack and the Beanstalk."

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YOUNG REVIEWERS

IAGO, AGE: 13
My name is Iago and I am in seventh grade. My favorite subjects are writing, math, social studies, and science. My hobbies are acting, D&D, and fake-sword fighting. I think it is important for scientists to write for children, so that kids can learn how to think critically and ask questions about how the world works. My mom and dad are "mad" scientists because they stuck a playing card in a brain for a magic trick—good thing the brain was made of Jell-O!

ROADRUNNERS & COBRAS, AGES: 10–11
We are a creative class of fifth graders who are eager to learn more about the world. We have thoroughly enjoyed thinking creatively about this article, and learning more about something that we encounter every day: noise. We have had a fun experience being part of Frontiers for Young Minds!

AUTHORS

ANGELA M. AUBUCHON

Angela AuBuchon's research goal is to understand how people remember important information (and ignore not-so-important information) in order to solve a problem. To learn more about Angela's research, follow her lab @BoysTownWMLL on Facebook. When Angela is not doing research, she visits local schools to teach students about neuroscience. Her favorite lesson is to help students dissect sheep brains. She is also the cheerleading coach at Platteview High School in Springfield, Nebraska. Go Trojans! *angela.aubuchon@boystown.org

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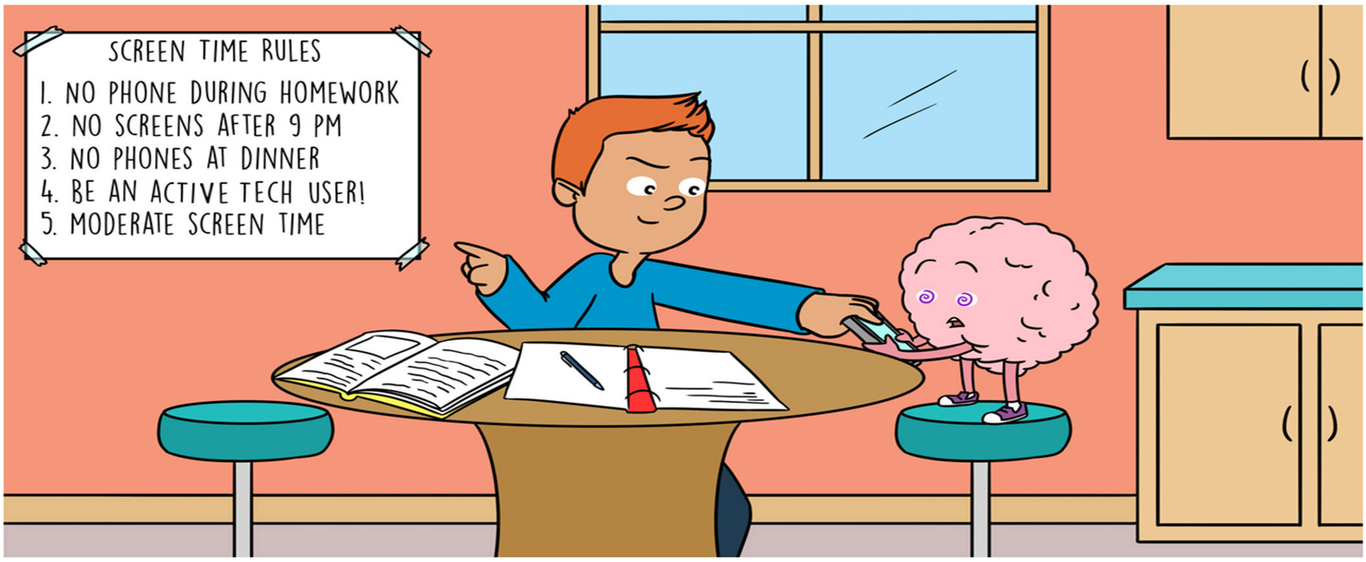

MIND GAMES: TECHNOLOGY AND THE DEVELOPING TEENAGE BRAIN

Lucía Magis-Weinberg* and Estelle L. Berger

Adolescent Research Collaborative, Institute of Human Development, University of California, Berkeley, Berkeley, CA, United States

YOUNG REVIEWER:

SCOTTY

AGE: 10

The brain has regions that react to things that are exciting or rewarding, and regions that help you plan and control your impulses. Both systems work together to help you learn. As children and teens develop and their brains change, the balance between the reward regions and control regions changes. These brain changes make children and teens more willing to explore, take risks, and learn from friends. However, these brain changes also make it hard for kids to regulate their behavior, especially when friends are around or when there is a lot of excitement. Technology can enhance learning by tapping into the balance between reward and control. However, some technological features can also promote unhealthy social interactions or make it very hard to control impulses online. In this article, we show how the control and reward areas of your brain influence learning. We also discuss how understanding how your brain works can help promote positive learning and empower you to make your own decisions about how to spend time online.

TEENAGERS GROW UP ONLINE AND OFFLINE

When it comes to technology, children and teens are the ultimate experts. Ninety-five percent of teenagers between the ages of 13 and 17 in the United States have a smartphone, and 94% report that they use the Internet at least once a day [1]. As children grow older and become teenagers (or adolescents), they start to gain independence and begin using—and owning—devices, especially as they move into secondary school [2]. Technology provides many opportunities to connect, learn, and have fun, inside and outside the classroom. But technology also carries risks, such as distraction from other activities and relationships, too much screen time, or hasty posting. Both the positive and negative aspects of technology can be amplified by some key features of the developing teenage brain.

THE IMPACT OF TECHNOLOGY DEPENDS ON THE QUALITY OF ONLINE ACTIVITIES

Research on technology use is difficult for a few key reasons: (1) it is hard for people to accurately report on how much media they use; (2) it is difficult to know whether technology use causes kids to get bad grades and feel upset, or if kids who are already getting bad grades and feeling upset tend to use more technology; and (3) we need to wait until users grow older to measure long-term effects. Despite these challenges, this research is important, and we will share with you what we do know about the links between time online and well-being.

Researchers are finding that using technology in moderation is key (Figure 1): people who spend too little or too much time using digital devices experience the most problems [3]. However, spending a moderate amount of high-quality time on digital devices might be associated with positive experiences, such as feeling happy and connected to friends. High-quality activities are those that require you to be actively engaged, such as chatting with friends and family, working on a project, creating content, or learning through videos. Low-quality activities are associated with feelings of depression, envy and loneliness, and might include scrolling passively, comparing yourself to others on social media, or using your devices late into the night or when you need to finish other tasks. Also, it is important to use technology purposefully and avoid multitasking and distraction. For example, if you do homework while chatting with friends, the quality of both activities is affected. While we want to know the effect on adults as well, the fact that kids are still developing makes children and teenagers particularly exposed to certain potentially negative features of technology (See Box 1).

Figure 1

Moderate use of screens (computers, tablets, videogames, and smartphones) is associated with the highest well-being, while both extremes, low and high use, are associated with lower well-being (figure adapted from Przybylski and Weinstein [3]).

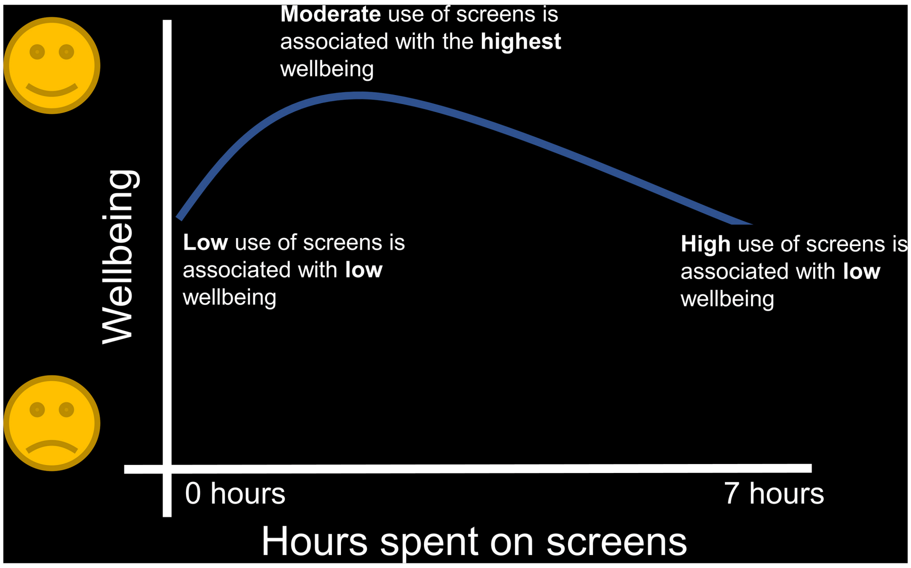

Figure 1

Box 1 | Tech Tips for Teens

1. Pay attention to the quality and content of what you do online instead of total screen time
2. Use technology actively (creating videos, writing stories, chatting with friends and family, using videos to learn a new skills) instead of passively (like scrolling through a celebrity's account)
3. Avoid multitasking: when you are doing homework, turn off your phone
4. Make sure that using your devices is not taking time away from exercise, getting enough sleep, doing homework and interacting with friends and family
5. When you go to sleep, keep your device outside of your bedroom: use an alarm clock instead
6. Turn off all the defaults in apps that might make it hard to control their use, like video autoplay and notifications
7. Take responsibility for your own engagement with digital media, and create a technology use contract that makes sense for you and your family

SOCIAL MEDIA AND THE SOCIAL BRAIN

The teenage years (**adolescence**) are a period during which kids are learning a lot both inside and outside the classroom, exploring their interests, and figuring out who they are and how they feel about themselves [4]. Between the ages of 10 and 24, there are big changes in the body and the brain. During these years, we become particularly sensitive to what is happening around us, because our brain networks that control **socio-emotional development** (Figure 2, in blue and green) are socio-emotional maturing faster than our **cognitive control** network (Figure 2, in red). The cognitive control network is in charge of mental processes like attention, memory, and decision-making that guide thoughts and behaviors to help us achieve our goals. This means that our capacity to make decisions and learn is affected by how exciting or social the situation is [2, 5].

ADOLESCENCE

Period of development between childhood and adulthood; also known as the teenage years (roughly between 10 and 24 years of age).

SOCIO-EMOTIONAL DEVELOPMENT

The ability to understand, express, and manage emotions and feelings in order to build and maintain relationships with others.

COGNITIVE CONTROL

Mental processes like attention, memory, and decision making that guide thoughts and behaviors to help us achieve our goals.

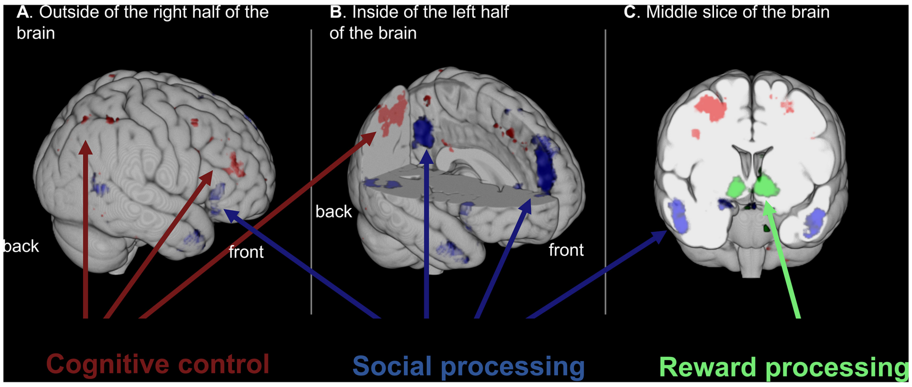

Figure 2

Figure 2

Brain areas that participate in cognitive control, social processing and reward processing are shown from different angles. **(A)** Surface of the right half of the brain, showing regions that are involved in cognitive control and regions involved in social processing. **(B)** Middle surface of the left side of the brain (the right side has been removed), showing key areas of the social brain. **(C)** Middle of the brain (imagine that the person is facing you and a slice has been cut), showing regions that are involved in processing rewards.

Teenagers have very important socio-emotional **developmental goals**—like discovering who they are and developing relationships with others—which might be influenced by social media. Teenagers are prone to pay a lot of attention to the number of likes or follows on social media because it feels especially important to be liked by peers and to feel popular and admired during this time [4, 5]. This need to get **extrinsic rewards**, specifically positive feedback from friends, might be one of the reasons why the majority of adolescents use social media constantly [6]. Social media can be a great tool to connect with friends when used in a positive way (like learning more about what a friend likes or giving them encouragement). Another key positive aspect of social media is that it creates opportunities to develop many identities: who you are as a student, friend, sibling, or fan of your favorite band [2]. This exploration will help you understand who you are, what and who you like.

DEVELOPMENTAL GOALS

Set of abilities that people are typically expected to achieve during a period of life (like learning to walk, for children, or becoming more independent from parents, for adolescents).

EXTRINSIC REWARDS

Doing something for external motivation, like getting points, likes, money, or encouragement.

However, the desire to be popular might also drive the need to post about risky activities, make mean comments, or send revealing pictures to get attention. Digital drama, cyberbullying, and exposure to inappropriate material can also make adolescents stressed or upset and may harm a person's reputation. When emotions are running high, it is particularly challenging to make good decisions, since cognitive control abilities are still maturing (Figure 2) [4, 5]. Therefore, as you craft a response to a friend who hurt your feelings or consider which picture to post, take an extra moment to cool off and think about whether your future self will regret or benefit from this permanent trace of your opinions and behavior. Drama can really distract from your well-being and your school experience, so consider which social media strategies work best for you.

Some features of social media, such as the fact that you can like, share, and openly comment on posts, can make people do things to get extra attention, impress a virtual audience, and compare themselves with others. In our research, we have found that adolescents in middle school who compare themselves with others and seek feedback through social media also reported more depressive and anxious symptoms. In addition, spending a lot of time scrolling through the feeds of others can affect a person's self-esteem. However, one question researchers are trying to answer is whether online activities cause problems or whether people who already have these problems tend to use social media in ways that might be harmful. Keeping these socio-emotional changes in mind, how can you use technology to make your friendships stronger and avoid the social pitfalls of devices?

GETTING "HOOKED" ON DEVICES

When you are having fun online, it can be especially difficult to monitor your time and you may find yourself "hooked" on your devices–spending much more time online than is good for you. It can even feel that you cannot control how much time or attention you want to give your device. Although the maturation of the cognitive control network (Figure 2, in red) allows you to pay attention for longer periods and avoid distractions, there are limits to your ability to self-regulate, especially in exciting or emotional moments. Remember, during adolescence there is also a surge in activity in regions of the brain that respond to all kinds of rewards, including social rewards (Figure 2, in green). Some rewarding activities can be beneficial to you, such as making friends or getting good grades. Then again, other activities that activate your reward centers can also be bad for you, like eating sugary treats, playing videogames all night, or taking part in dangerous activities. Being more sensitive to rewards makes teens more likely to try out new things, explore, and act in ways that will make them feel good immediately [4]. When you are online, this need to experience immediate rewards might then override your ability to control and think about the long-term future. Gaming, chatting, or streaming late at night might make you feel good in the moment, but be mindful of the consequences the next morning when you are tired and cranky in school (See Box 1).

EFFECTS OF TECHNOLOGY ON SLEEP

What is the last thing you did before closing your eyes last night? You probably replied to one last text message or fell asleep while watching a show you were streaming. We know that technology use affects sleep, which in turn impacts your brain, body, and health. This has negative effects on your ability to pay attention, learn, and remember. Lack of sleep can also make you feel anxious or sad. Using your devices in bed at night makes it harder for you to go to sleep and is probably making you stay up later than you should. Notifications can also wake you up in the middle of the night! It is very important that your technology use does not interfere with healthy sleep habits, particularly at a time when your brain and body are developing. It is a good idea to keep your devices outside your room when you go to bed (See Box 1).

TAKE BACK CONTROL!

Luckily, we know of some useful skills that can help you to disengage from social media, games, and videos and take back control of your valuable time. If you enjoy watching videos online, turn off "auto-play," which is often the default setting on many platforms. This will make it easier for you to choose when to stop watching. Before you activate a new account, ensure that your profile is protected and deactivate push notifications. Oftentimes, default settings might be designed to keep you hooked, because companies are competing for your attention and time. Take control by choosing settings that help you to use technology in a way that feels right for you. You can also consider leaving your device outside your room at night, or perhaps turn WiFi off completely while you are doing your homework, to avoid temptation and distraction. You can even set reminders on your phone to take breaks and do different activities, like playing sports or spending time with friends and family (See Box 1).

Given what you now know about how your brain responds to social media, computer games, online videos, and other forms of digital media, think about an after-school and weekend schedule that allows you to maintain control of how you spend your time. You know which afternoons you have after-school commitments and the number of hours it takes to do your nightly homework. You also know that it feels important to stay connected to your friends via social media, to post to your channel, and to play your favorite online games. By creating your own guidelines for technology use, presenting them to your parents or teachers, and then benefitting from rules that you have created for yourself, you will be motivated by **intrinsic reward**. Put simply, an intrinsic reward is that sense of pride or fulfillment that you experience when you have completed something meaningful to you. A system that you design yourself, in collaboration with the adults that care for you, might work better than one that is imposed upon you. Maybe even create a technology use contract with your entire family. Parents struggle with how to manage their devices too, so you can share what you know about how to maintain a healthy digital media balance.

INTRINSIC REWARDS

Doing something for internal motivation, like feeling accomplished or pleased with yourself.

MAKING THE MOST OF TECHNOLOGY

The teenage years are an exciting time when you will figure out who you are, make sense of what and who you like, and develop the tools you need to pursue your passions. Using your devices purposefully and with intention can help you succeed. There might even be positive mental health benefits to chatting with your friends, posting pictures of your creative work, or connecting with a group of people who share a common interest. Monitor the quality and content of what you do online rather than fixate on the number of hours. When using technology, be active rather than passive, and avoid multitasking in order to make the most of your time. Make sure that using your devices is not taking time away from exercising, getting enough sleep, doing your homework, or interacting with your friends and family. While scientists continue to research technology use and the developing brain, it is very important that you take responsibility for your own engagement with digital media. Be in charge of your device, instead of letting your devices be in charge of you.

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YOUNG REVIEWER

SCOTTY, AGE: 10

My favorite color is red. My favorite movies are Space Jam and the Goonies. My favorite thing to do in my free time is play sports and video games. My favorite sports are basketball and football.

AUTHORS

LUCÍA MAGIS-WEINBERG

I am a doctor and scientist investigating how technology impacts the development of children and adolescents and their brains, particularly in countries in Latin America. I use technology all the time—to do my work, to run our projects in other countries, and to communicate with my family and friends that live far away—so I realize the power that comes with online interactions. Through my research, I want to help adolescents thrive in a world of accelerated technological change. *l.magisweinberg@berkeley.edu

ESTELLE L. BERGER

I am a post-baccalaureate psychology student, and I explore the intersection of adolescent development, social context, and technology use. Through my research, I am continually inspired by young people's power to inspire and create meaningful change in the world. Outside of the lab, you can find me hiking, attempting the Sunday crossword puzzle, or taking care of my plants.

frontiers FOR YOUNG MINDS

NEUROSCIENCE
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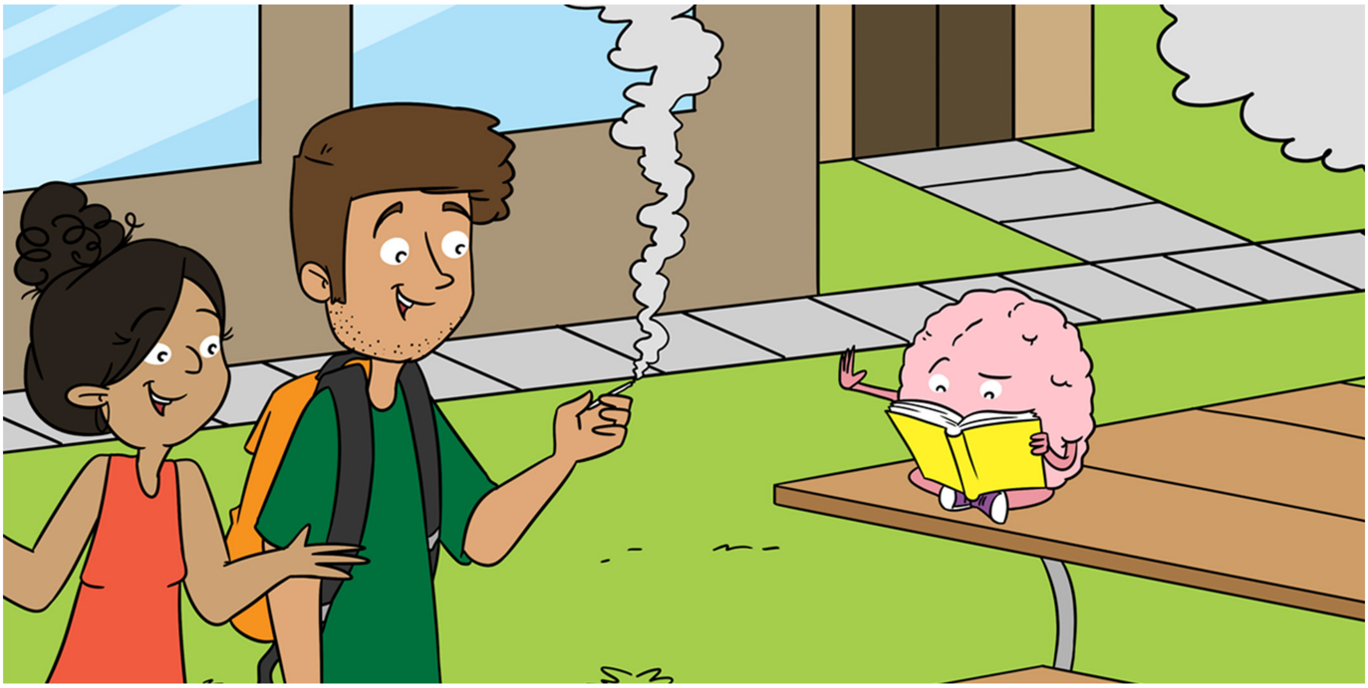

CANNABIS AND THE LEARNING BRAIN

Lana Vedelago [1,2*], ***Jillian Halladay*** [1,3], ***Catharine Munn*** [1,4], ***Katholiki Georgiades*** [5,6] ***and Michael Amlung*** [1,6]

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YOUNG REVIEWER:

GREESHMA

AGE: 13

How does cannabis (marijuana) affect the developing brain, learning, and academic performance? Research tells us that the brain continues to develop through the teenage years into the mid-20s, and during this time the brain is especially sensitive to the effects of drugs like cannabis. This article will give an overview of the research on the short- and long-term effects of cannabis on thinking, learning, and academic success. We will also provide a window into brain imaging research, which allows researchers to see what is happening in the brain over time when youth use cannabis. We hope to leave you with more answers than questions, but will finish by highlighting some of the unanswered questions about the potential negative effects of cannabis use in youth.

INTRODUCTION

As a teenager, you are faced with an overwhelming number of choices and pressures. One choice you may face is whether or not to try cannabis or other drugs. You may hear different things about the risks of trying cannabis or using it regularly. Recent public debate, changes in the laws around cannabis, and its use as a treatment for some medical conditions have led some people to believe that cannabis is safe and without any risks to health or learning. This article is not here to tell you what to do, but to share the most up-to-date research about the effects of cannabis on the learning brain and to challenge some of the stereotypes and myths about cannabis use.

Cannabis is also known as marijuana, weed, or pot, and has psychoactive effects, meaning it can temporarily change brain function to alter mood, thinking, and behavior. After tobacco and alcohol, cannabis is the most commonly used drug in the world and is most often consumed by smoking, vaping, or in edible form. In North America, recent changes in the laws have legalized cannabis use for those over 18 or 19 in Canada, and over 21 in most U.S. states. People say that they use cannabis for a number of reasons, including for the "high" feeling that happens, to "experiment," to help with socializing, or for medical purposes. Initially, it may seem like cannabis is helping—for example, by improving mood or making social situations a little easier—but with repeated use, cannabis tends to be related with making things worse. Cannabis can also have negative consequences on physical and mental health, especially when it is used while you are a teenager or young adult, used very often, or used in large amounts. Cannabis can also impair your judgment and ability to make decisions, and can lead some people to do risky things they might not do otherwise, like driving a car while high [1].

Advances in technology allow researchers to look closely at how the brain looks and works. Brain imaging techniques, like magnetic resonance imaging (MRI), have shown that adolescence through young adulthood is a time of dramatic change, especially in two major parts of the brain. The first part, called the endocannabinoid system, helps to develop and streamline the connections between different parts of the brain [2]. As you might be able to tell from the name, this system is affected by cannabis. The second part of the brain that changes a lot during this time, the prefrontal cortex, is the command center or "boss" of the brain, responsible for functions like making decisions, solving problems, and controlling our own behavior (Figure 1) [2]. Research tells us that the endocannabinoid system and the prefrontal cortex are still developing until we are in our mid-20s. Until this age, these parts of the brain are especially sensitive to the effects of chemicals like alcohol, cannabis, and other drugs [2].

Figure 1

The prefrontal cortex. The area of the brain colored yellow in this image is known as the prefrontal cortex. It is the command center of the brain and is responsible for things like making decisions, solving problems, and controlling our behavior (illustrated by Madelyn Vedelago).

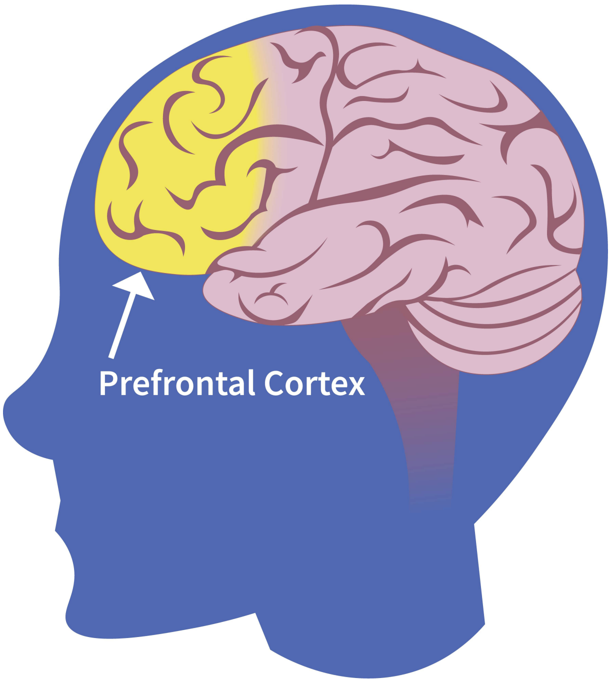

Figure 1

QUESTION 1: WHAT ARE THE SHORT-TERM EFFECTS OF CANNABIS ON THE BRAIN AND LEARNING? HOW DO RESEARCHERS KNOW THIS?

The short-term effects of cannabis on the brain include a variety of negative consequences that can impact grades and success at school in teenagers (Figure 2). Researchers have found that adolescents who use cannabis did not do as well as their peers who were not using cannabis on tasks requiring attention, learning, memory, and reaction time [3]. This held true even if the cannabis users stopped using for 1 month before the experiment. Teenagers who start using cannabis at a younger age (under 15) perform even more poorly on these tasks than those who start using at an older age [2]. So, what is happening in the brain to cause this decreased performance?

As mentioned above, the endocannabinoid system in the brain is still developing throughout adolescence. While its role in the brain is not yet entirely understood, we know that the endocannabinoid system strengthens important connections and weakens unimportant ones in areas of the brain that are critical for learning and memory [2]. Using cannabis while this system is still developing may explain the problems with thinking, paying attention, and learning that are seen in teenagers who use cannabis [2].

Using MRI images, researchers found that a specific area of the prefrontal cortex was smaller in adolescents who use cannabis heavily compared with adolescents who do not use cannabis [4]. The cannabis-using group also tended to be more impulsive, that is,

Figure 2

Figure 2

The negative effects of using cannabis during adolescence. Since the brain is still developing while you are a teenager, certain skills necessary to succeed in school like thinking, memory, learning, and attention can be negatively impacted by using cannabis (illustrated by Madelyn Vedelago).

to do things without thinking [4]. In a memory task, cannabis users showed less activity in the prefrontal cortex compared with non-users [3]. Overall, it appears that cannabis use can interfere with both the size and the activity of the prefrontal cortex, which is very important to learning.

QUESTION 2: WHAT ARE THE LONG-TERM EFFECTS OF CANNABIS USE ON SCHOOL SUCCESS?

Research suggests that people who are heavy cannabis users in adolescence do not go as far in school, that is, they are less likely to achieve higher levels of education. A study that observed people from their teenage years into adulthood found that individuals who use cannabis as teenagers and continue to use throughout life tend to be in school for fewer years than those who did not use cannabis during the teen years [5]. Why might this be the case? More research is needed to be certain about how cannabis use impacts school success, but it is possible that the changes in the brain that occur when cannabis is used in the teenage years may explain this. Or, it could be due to the short-term negative effects of cannabis on memory, attention, and motivation, which could lead to lower grades in high school and reduced chances of getting into university or college.

QUESTION 3: CAN THE NEGATIVE EFFECTS OF CANNABIS ON LEARNING BE REVERSED?

The good news is that, because of the rapid changes and reorganization happening in the teenage brain, adolescents may be better able to bounce back from the effects of toxins like alcohol, cannabis, and other drugs. For example, researchers have found that when cannabis users stopped using for 3 months, most of their problems with memory, learning, and attention returned to normal [3].

CONCLUSION

Overall, the research suggests that cannabis may have negative effects, particularly when use starts in the teen and young adult years. However, the research findings are also unclear in some studies and much remains unknown, because not enough good research has been done yet. Additionally, most of the research that has already been done focuses on links (or correlations) between cannabis use and differences in the brain. This means that we do not know yet whether cannabis is the cause of these differences, or if these differences existed before cannabis use started. While we still have a lot to learn about the effects of cannabis use, most doctors, researchers, and governments recommend not using it during adolescence.

If you are thinking about trying cannabis, it may be helpful to ask yourself a few questions:

- Why do I want to use cannabis? Am I trying to escape something or to cover up a problem?
- How would I know if cannabis is impacting my ability to learn or go to school? How would I recognize if cannabis use was becoming a problem for me?
- Who could I talk to or where could I find help if I or one of my friends started having problems with cannabis?

Considering these questions will help you to make the best decisions for you and your learning brain.

AUTHOR CONTRIBUTIONS

LV, JH, CM, KG, and MA contributed to the conception and design of the manuscript. LV wrote the first draft of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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YOUNG REVIEWER

GREESHMA, AGE: 13

My name is Greeshma and I am 13 years old. Both of my parents are software engineers and my favorite subjects in school are mathematics and science. Outside of school, I love to play volleyball and participate in science clubs.

AUTHORS

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I am a graduate student studying addictions and related mental health problems. I am interested in improving the lives of people struggling with these issues. When I am not in the laboratory, you can find me volunteering at the animal shelter, dancing, and cross-stitching! *vedelagl@mcmaster.ca

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I am a mental health nurse and a researcher. I am interested in trying to figure out how youth can be successful and happy while they are young and when they grow up. Much of my research focuses on if and how substances (mainly cannabis and alcohol) and mental health concerns co-occur. In my free time, I like to lift weights, play board games, and hike!

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MICHAEL AMLUNG

I am an Assistant Professor of Psychiatry at McMaster University in Ontario, Canada. I am interested in understanding the brain basis of alcohol and drug use and how they relate to other mental health problems. We hope that our research will improve treatments for people who are struggling with addictions. I enjoy working with my students and colleagues on many exciting research studies using brain scans and other types of technology. In my spare time, I enjoy cooking, traveling, and spending time with my family.

NEUROSCIENCE
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A GOOD NIGHT'S SLEEP: NECESSARY FOR YOUNG MINDS

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YOUNG REVIEWERS:


JACOB
AGE: 12


ST. BERNARD REGIONAL CATHOLIC SCHOOL
AGES: 11–14

During your lifetime, you will spend almost 250,000 h asleep. Why do we need so much sleep? Sleep is not just rest from the day, but also necessary for your body and brain to be healthy, particularly as you grow up. For example, a good night's sleep enables you to pay attention and learn the next day. When and how long you sleep will change as you get older. So, how do you know how much sleep you should get, or when you should go to bed at night? Here, we will share answers to these questions and more. We have studied the science of sleep and we now understand a little more about what your brain does throughout the night: keeping you healthy, alert, and ready for school and fun the next day. If you read this right before bed, you will be sure to get enough ZZZ's tonight.

Of all the things you do, which do you do the most? It is not eating or drinking, it is sleeping! We spend a third of our lives sleeping. Scientists have worked for decades to understand why we sleep. While your body lies still in your bed, your brain is processing the day's information to get you ready for tomorrow. Here, we will explain the what, when, why, and how of sleeping and how it changes as you grow up.

WHEN DO YOU SLEEP?

If we asked, "When do you sleep?" you might say, "at night!", or "when I am tired!" Turns out, both are right. Humans prefer to sleep at night, which makes us diurnal, as opposed to nocturnal animals that sleep during the day. This preference is hard-wired. Deep in your brain sits the **suprachiasmatic nucleus (SCN)**. The SCN is your biological clock. It tells time for every part of your body. We call this the **circadian rhythm** (circadian is Greek for "about a day," because the rhythm of sleeping and waking repeats once every 24-h). Like any clock, the SCN can be reset, based on when we see sunlight. When we travel, our bodies adjust to the new pattern of light. This is why people who travel from North America to Australia can adjust to a new pattern of sleep within a couple of days.

SUPRACHIASMATIC NUCLEUS (SCN)

A small region deep in the brain that forms the "biological clock" and generates the circadian rhythms.

CIRCADIAN RHYTHMS

One of the two ways we know when to sleep. The naturally occurring pattern of sleeping and waking that repeats every 24 h in response to light.

Saying, "I sleep when I am tired," is also true. Have you ever taken a nap in the middle of the day? Another system in the brain keeps track of how much time you have been awake and how much you slept the night before. We call this the **sleep homeostat**. Homeostat sounds like another word: "thermostat," which is a good way to think about this. Just like a thermostat turns the air conditioning on when it is too hot and turns it off when it is too cool, the sleep homeostat listens to how long you have been awake. Your need to sleep grows throughout the day, and when it reaches a certain point, you fall asleep. Once you have rested, the sleep homeostat turns off and lets you wake up, and the process repeats every day. The sleep homeostat, however, does not know if it is daytime or nighttime outside, only whether you have been awake or asleep. If you force yourself to stay awake all night, the need for sleep will continue to grow throughout the night until you finally go to sleep. If you skip a night's sleep, you might be very tired and it will take longer to pay back that sleep need (just like it would take longer for the A/C to cool a super-hot room). The circadian rhythm and the sleep homeostat ultimately work together, which is why you may feel alert in the middle of the day, even if you did not get much sleep the night before, or why you suddenly feel tired at night, even if you woke up late that day.

SLEEP HOMEOSTAT

One of the two ways we know when to sleep. Sleep need increases as we stay awake and decreases as we sleep.

HOW DOES YOUR SLEEP CHANGE AS YOU GET OLDER?

Think about your own sleep. You probably sleep differently now compared to when you were a baby or a young child. The SCN and the sleep homeostat change as we grow up (Figure 1). When you hit puberty, your SCN acts as if it shifted time-zones. Your body wants

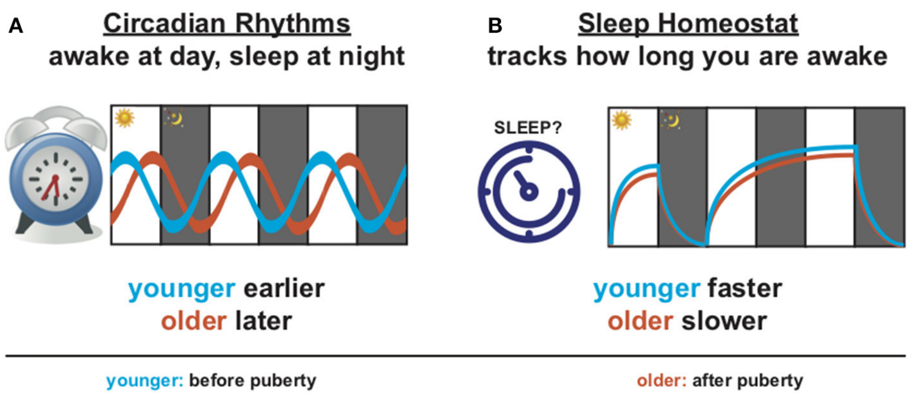

Figure 1

Figure 1

Why do you sleep when you do? In each graph, the sleep of younger children (6–13 years) is plotted in blue and that of older children (14–17 years) is plotted in orange. Dark bars indicate nighttime; light bars daytime. **(A)** Circadian Rhythms: the biological clock, organized by the SCN, keeps us awake during the day and asleep at night. It is affected by light, cycles every 24 h, and shifts during adolescence. **(B)** Sleep Homeostat: the thermostat for sleep and wakefulness. It tracks how long we have been awake. The need for sleep increases throughout the day as we remain awake and decreases during the night as we sleep. If we skip sleep, the homeostat tracks that we are awake, until we are able to sleep again. As we get older, this process is slower, allowing us to stay up longer before we need to sleep.

to wake up later and go to bed later. Eventually, somewhere in your twenties, the SCN starts reversing again (Figure 1A).

As for the sleep homeostat, during puberty, your need for sleep builds a bit more slowly than it did when you were young. Put another way, if we remember the thermostat example, you have slowed down how quickly the room heats up, so that the A/C waits longer before turning on (Figure 1B). As both the SCN and the homeostat change during puberty, it becomes easier to stay up late.

HOW MUCH SLEEP DO YOU NEED?

The National Sleep Foundation recommends that school-aged kids (6–13 years) sleep between 9 and 11 h a night. Teens are recommended to get 8–10 h a night and adults about 7–9 h [1]. If you are a student, particularly in the United States, you may find it difficult to get this amount of sleep on school nights. As you go through puberty, your body wants to go to bed later and sleep later. But school (particularly in the U.S.) often starts too early! This makes it hard for teenagers to get enough sleep on school nights [2]. By the weekend, you probably have missed so much sleep that you feel particularly sleepy, and you may dramatically oversleep as your sleep homeostat works hard to recover the sleep you need. If you oversleep all weekend, however, this can make waking up on Monday morning a miserable experience.

WHY DO YOU NEED SLEEP?

Sleep is critical for both your body and your mind. In your body, your metabolism (how you digest and use food), your immune system (how quickly you get over being sick), and your physical fitness (how exercise impacts your body) all benefit from a good night's sleep. We will focus on one organ in your body: your brain. All the functions of your mind depend on your brain's different regions. For example, your

Figure 2

Regions in the brain affected by sleep. A side view of the brain, as if looking in from the ear. Two regions are impacted by a good night's sleep and support brain health: The prefrontal cortex (blue) is critical for paying attention in school; and the amygdala (pink) is a key center for regulating emotion and mood.

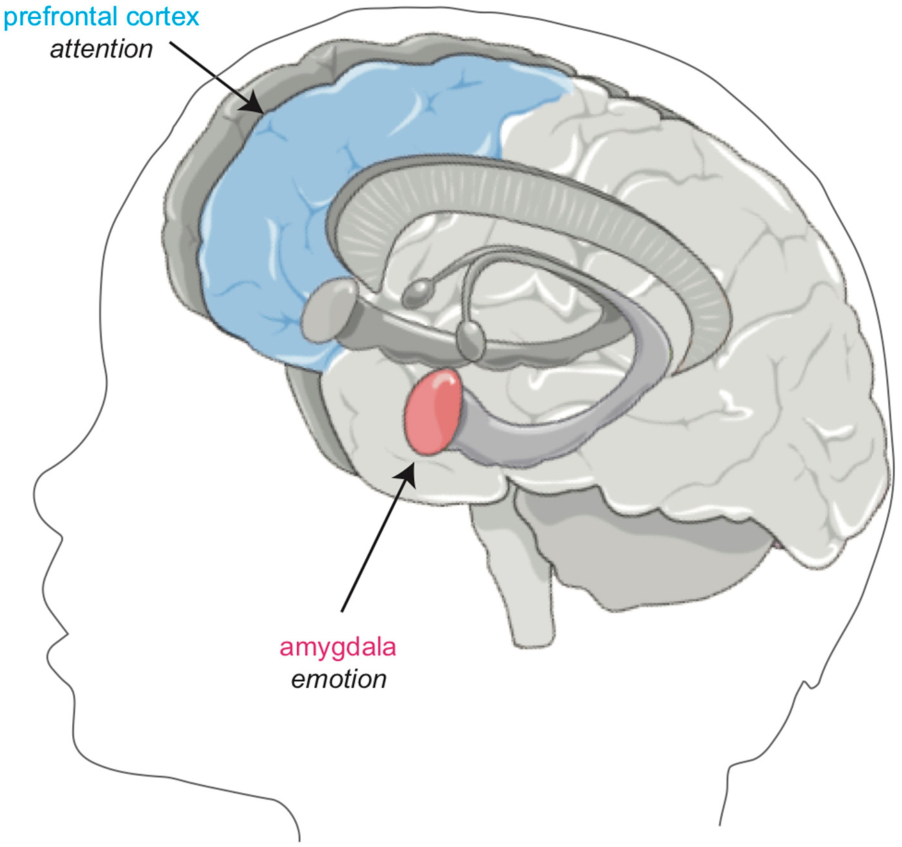

Figure 2

brain controls your ability to pay attention (such as staying focused in class), to learn and remember (when taking a test, for example), and to process emotions (like not getting too grumpy if things do not go your way). We will focus on attention and emotion, and how they are aided by sleep (Figure 2).

Attention

Have you tried paying attention in class after a bad night's sleep? It is hard. The last part of the brain to fully develop, the **prefrontal cortex (PFC)**, sits at the very front of the brain. This special region is critical for paying attention, planning, and switching between tasks. If you do not sleep the night before, or only sleep a little bit, the PFC cannot function efficiently the next day [3], making it extra hard to concentrate without getting distracted. If you do not get enough sleep, studying in the evening becomes hard as well. Students often ask if it is better to go to bed or stay up late to study. We hope by this point you can guess the right answer. Data shows that sleep is important for grades! An extra hour of sleep was associated with 3–5 point improvement on standardized test scores [4].

PREFRONTAL CORTEX

The front portion of the brain, critical for paying attention and planning.

Emotion

After a night without good sleep, we often feel more irritable. Sleep is involved in keeping you happy and keeping your emotions in check.

AMYGDALA

A small region deep in the middle of the brain responsible for processing emotions.

Sleep directly refreshes the emotional centers of our brain, like the **amygdala** [3]. This means that not only is your mood more stable after a good night's sleep, but you are also better able to respond to emotional things in your life. When looking at your friends' faces, you can tell if they are mad, sad, or happy. But when sleep deprived, we lose the ability to tell the difference between these emotions. A good night's sleep helps us process these complicated signals so that we are better able to detect, process, and react to emotions.

SLEEP AND MENTAL HEALTH IN CHILDREN

We all have some bad nights of sleep that can affect us the next day. The good news is that restoring healthy sleep habits will often fix these issues right away. However, some children may experience prolonged sleep difficulties that can impact their mental health in the long run. Because of all the ways sleep impacts the brain, sleep problems and mental health issues [like attention-deficit/hyperactivity disorder (ADHD), autism, anxiety, or depression] often go hand-in-hand. Children and adolescents struggling with mental health can also experience trouble falling and/or staying asleep, or difficulty waking up. We are still working to understand the connection between sleeping and mental health, to determine whether helping children sleep better can help children with mental health issues [5].

HOW CAN YOU HAVE HEALTHY SLEEP?

We hope you are convinced that sleep is important. But, what can you do to sleep better?

Good sleep begins with good sleep habits (Figure 3). First, go to bed around the same time each night, to keep the SCN and sleep homeostat properly functioning. Second, build a bedtime routine to make going to bed easier, like reading a book or dimming the lights. Third, try to limit the amount of digital screen time right before bed. This is for two reasons: (1) the light from your devices might trick your SCN into thinking it is still daytime, and (2) the excitement from games, TV shows, and the internet can keep you from settling down to sleep. Fourth, keep your bedroom simple, cool, dark, and free of distractions like TVs and devices (try not to take your phone to bed). Fifth, when possible, try not to do your homework in bed; keep your bed for sleeping. Finally, try to limit caffeine (soda, energy drinks, coffee/tea) during the day and avoid these drinks after 4 p.m. Caffeine essentially tricks your sleep homeostat, making you feel less sleepy, but without decreasing sleep need, which is not helpful when school starts at the usual time the next day.

Speaking of school—it is important that teachers and principals understand that sleep is critical for learning and health. Scientists are

Figure 3

Figure 3

Tips for good sleeping habits. Good sleep begins with good sleep habits. Working on each of these tips will help you get the best sleep you can each night, and to feel rested and ready for school the next day.

working with schools and governments to make school start later for teenagers. If you feel your school starts too early for you to get a good night's sleep, tell your teachers or write a letter to your mayor, governor, or congressperson. Tell them why it is important for schools to help protect everyone's sleep health.

SLEEP: WHAT IS IT ALL FOR?

Sleep is one of the strongest predictors of health, yet why we sleep is a mystery to us. We hope that we have shed light on that mystery and that you, your teachers, and you parents may better understand and apply the power of sleep to support learning success, emotional health, and brain health. We hope you sleep well tonight.

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YOUNG REVIEWERS

JACOB, AGE: 12

Hi, I am 12. Sleep is the foundation of life, so pay attention in class kids. I am a sporty guy. I play sports like baseball, basketball, and American-and-the-rest-of-the-world football. My love of reading is very extensive. I have love for food just like the other 7.8 billion people in the world. I especially have a love for Asian and American foods.

I have two siblings, two parents, and hopefully I am funny... So are you, so keep on trying.

ST. BERNARD REGIONAL CATHOLIC SCHOOL, AGES: 11–14

Eclectic group of middle school students and future engineers, teachers, politicians, dancers, musicians, doctors, and armed forces. We enjoy asking questions and inquiring about the world. Many of us look forward to assignments and future jobs that require creativity and problem solving. In the meantime however, we enjoy our over goofy and over caffeinated teacher, and interrupt our classes with witty comments and animal noises. A perfect balance of learning and fun!

AUTHORS

M. ELISABETH KOOPMAN-VERHOEFF

Elize is a psychologist and a researcher at the department of Child and Adolescent Psychiatry/Psychology at the Erasmus Medical Center in Rotterdam, The Netherlands. She studies sleep and mental health in the Generation R Study, a study following the development of around 7,000 children from Rotterdam. In her free time Elize loves to hike, read a lot of books, and to cook for her friends and family. Fun fact: she loves to go to bed early and get out of bed before 7 a.m. (also on the weekend).

JARED M. SALETIN

Jared is a sleep researcher and an Assistant Professor of Psychiatry and Human Behavior at Brown University in Providence, RI, USA. He studies how sleep helps children and adolescents, and their brains, learn and pay attention. He hopes his research helps young people succeed in school after a healthy night's sleep. In his free time, he likes to spend time with friends, family (and his cat), cooking traveling, playing board games, and attempting to bake bread. *jared_saletin@brown.edu

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FROM ZZZs TO AAAs: WHY SLEEP IS AN IMPORTANT PART OF YOUR STUDY SCHEDULE

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YOUNG REVIEWERS:

HATHAWAY BROWN SCHOOL

AGES: 14-15

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT

AGES: 14-15

All of us sleep. While adults spend about one-third of their time asleep, the younger you are, the more you sleep. However, this does not mean that children and teenagers are being lazy by spending too much time in bed. In fact, not getting enough sleep usually makes people feel tired, less effective, and unable to concentrate. Not only should you avoid these consequences of bad sleep, but you should also prioritize good sleep. Good sleep restores your body and brain, and offers an opportunity for your brain to reorganize itself after a busy day. In this article, we consider why sleep is especially important for supporting memory. Your ability to learn, remember, and refine your brain is extraordinary during childhood and adolescence, so sleep is particularly important during these stages. We explain the links between brain and sleep changes as you grow older, and why sleep should be an important part of your study schedule.

As you get nearer and nearer to a test at school, sometimes it feels like there is so much to learn in so little time. So why waste time in

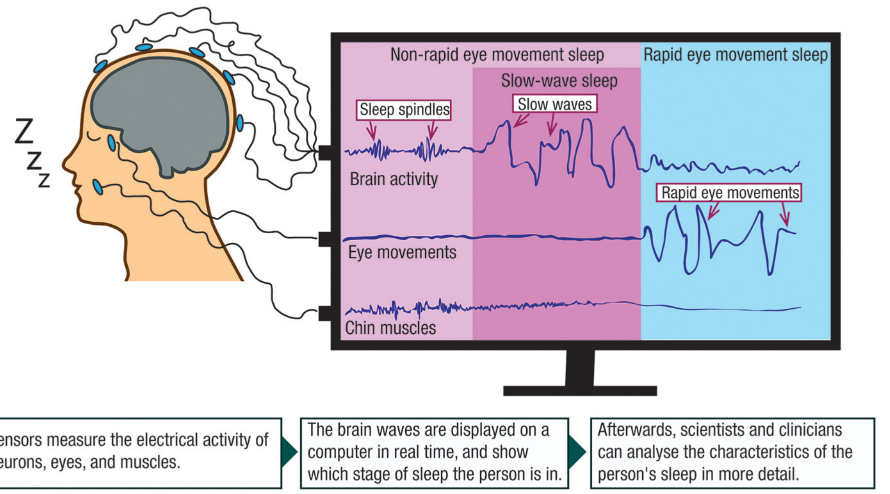

Figure 1

Figure 1

How we measure sleep. (Left) We measure the activity of neurons, eyes, and muscles using little sensors. (Right) The activity is displayed on a computer screen as wiggly lines. During light non-REM sleep (pink area) we detect sleep spindles in the brain activity. During deeper non-REM sleep—otherwise known as slow-wave sleep—chin muscles relax (the line gets flatter) and the curves representing brain activity get really slow and big (slow waves). During REM sleep (blue area) the muscle activity is the lowest, brain activity gets faster, and the eyes start making rapid zigzag movements.

bed when you could use that time to study? Staying up late to cram in some extra learning time might seem a tempting thought, but sleep is vital for your body and brain. It keeps you healthy and restores your energy so you feel alert and active the next day. Sleep also provides a time for the brain to remodel and refine its structure and function to your individual needs and experiences. The sleeping brain is not only important for general brain development but—fortunately—also does some pretty important work on your memories. Scientists have shown that the brain's activities during sleep help to save new knowledge to memory as well as prepare for new learning the next day. This means that spending time asleep is much better than trying to pull an "all-nighter" in the run-up to exams. While this is important throughout life, the ability to reshape your brain and your capacity to learn is extraordinary across childhood and adolescence, and so is your sleep across this period.

THE SLEEPING BRAIN

The sleeping brain is not always doing the same thing. A good night's sleep cycles through different sleep stages, determined by muscle and eye movements, and the activity of tiny nerve cells in the brain (called **neurons**). Scientists can measure this activity by placing small sensors beside a person's eyes, on the chin, and on the head while the person sleeps (see Figure 1). Sometimes the neurons act very quickly and chaotically, similar to when the brain is awake and busy. This is the case during **rapid eye movement sleep** (REM), a sleep stage during which the eyes are moving very quickly, muscles are extremely relaxed, and the brain is engaging in very vivid dreams. The remaining sleep stages are referred to together as non-rapid eye movement sleep (non-REM). During light non-REM sleep, we see short bursts of brain activity called **sleep spindles** (see Figure 1). During deep non-REM sleep, neurons in the brain show slow rhythmic activity similar to gigantic waves in the

NEURONS

Tiny nerve cells in the brain that store and transfer signals and information.

RAPID EYE MOVEMENT (REM) SLEEP

Sleep stage in which the eyes move quickly and the muscles are extremely relaxed, often associated with vivid dreams.

SLEEP SPINDLES

Short periods of increased activity in the brain that we believe help with efficient communication between different parts of the brain.

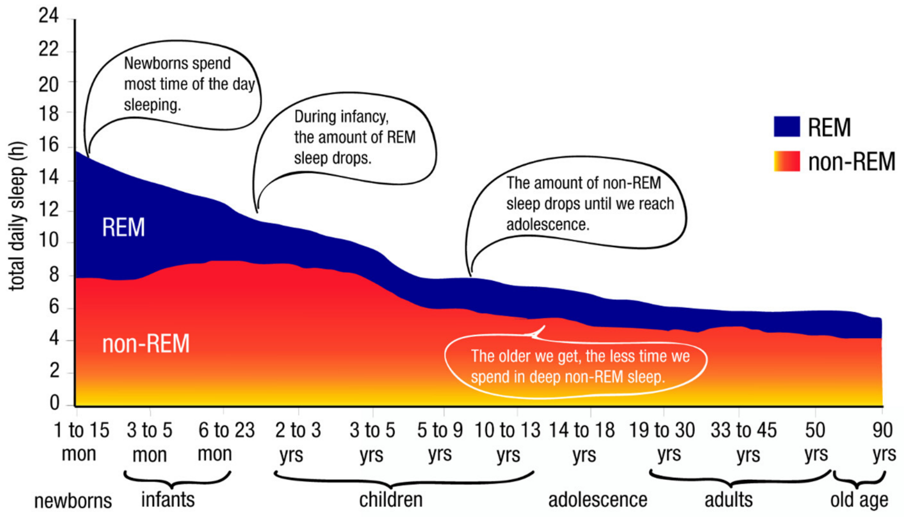

Figure 2

How sleep changes across the lifespan. The older people get, the less time they spend asleep. Moreover, the balance between REM and non-REM sleep changes during childhood, and as children get older, less time is spent in deep non-REM sleep, so-called slow-wave sleep (Adapted from Roffwarg et al. [1]. Reprinted with permission from AAAS).

SLOW-WAVE SLEEP

The deepest phase of non-REM sleep, during which the neurons in the brain show slow rhythmic activity (slow waves), thought to be important for the storage of lasting memories.

ocean (Figure 1), called slow waves. Because of this, deep non-REM sleep is often referred to as **slow-wave sleep**. Both sleep spindles and slow waves are specialists in remodeling the brain, meaning that the more they are present, the more the brain is being shaped.

THE BRAIN UNDER RECONSTRUCTION

As a newborn, you spent more time asleep than awake. But the older you get, the less you sleep. It is not just the amount of sleep that changes during development but, importantly, the balance between different sleep stages also changes. Generally, as you grow older, you get less and less slow-wave sleep, while the proportion of light non-REM sleep increases (Figure 2). Scientists believe that these changes in sleep may tell us about the brain's potential to reconstruct itself.

From infancy to adolescence, your brain undergoes major reorganization and optimization to deal with your daily needs and experiences. New connections between brain cells are built, connections you do not need are removed, and the communication of information along important neuron tracks speeds up. Crucially, when a specific part of the brain is under reconstruction, the neurons in that region show more slow rhythmic activity during slow-wave sleep. For example, scientists in Switzerland recorded the sleep of 40 children and young adults, and also measured their performance on certain tasks [2]. Interestingly, they found that sleep slow waves were most powerful in the brain region responsible for the skills participants were learning at each age, and the slow waves in those brain regions got weaker once the skill was better developed. For instance, in late childhood when children get really good at performing complex movements, like riding a bike—maybe even hands-free—slow waves

NEOCORTEX

The outer layers of the brain that are thought to store knowledge for the longer term.

were most powerful in the brain region responsible for performing movements. The scientists also saw this optimization in the brain's structure when the participants went in the brain scanner: the brain's outer layer, the **neocortex**, was thinner in these regions, reflecting "fine-tuning" of the brain to perform tasks more efficiently. These relationships between slow waves, skills, and brain structure lead researchers to think that looking at slow rhythms during sleep might help us to learn how the brain is developing.

Unlike slow waves, which decline as the brain matures, the sleep spindles that characterize light non-REM sleep get more numerous and faster throughout childhood and adolescence. Some scientists think that the speeding up of sleep spindles during childhood and adolescence reflects faster and more efficient communication between different parts of the brain. In one of our studies, we found that children who showed the biggest increases in the number of spindles over a seven-year period performed better on tests of general mental ability at ages 14–18 [3]. Unfortunately, we do not yet know exactly how spindles are helping brain development, and this is an exciting area that scientists are still trying to understand.

SLOW AND STEADY WINS THE RACE

By looking at sleep, we can understand how the brain changes as children grow older and learn new skills, like riding a bike. However, sleep performs another important task. It helps you to form long-lasting memories of new facts, like information you learn at school.

Lots of experiments have shown that sleep can help you to remember the new things that you learn. Some studies have even shown that memories can get better with sleep, without any extra studying! For example, researchers at the University of York taught 7- to 12-year-old children new words in either the morning or the evening [4]. When the researchers tested the memory of the children 12 hours later, those who had learned in the evening and then gone to sleep could remember more words than the children who stayed awake all day. In fact, they could recall more of the words than they could before they went to bed. How can that be?

Scientists believe that the brain has two different learning systems, a fast one and a slow one. These two learning systems can be thought of like the slow tortoise and the speedy hare in the old fable. In the tale, the hare speeds off very rapidly in his race against the tortoise. Pleased with his progress and confident of winning, he takes a nap midway that allows the slow and steady tortoise to overtake and win the race. One learning system in the brain works like the speedy hare: it helps you to learn new information very quickly during the day and gives the information a head start in memory. However, the

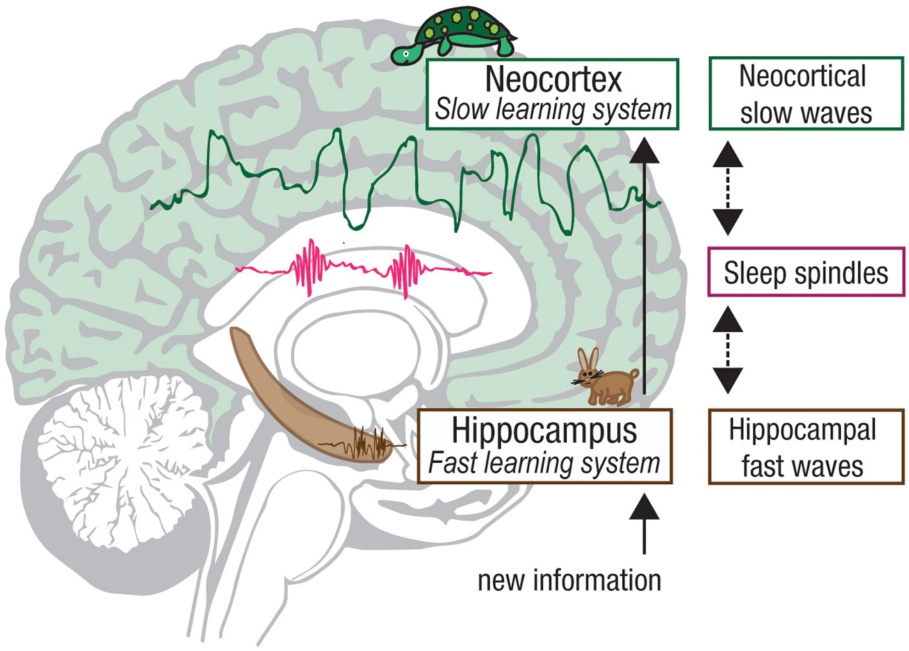

Figure 3

Figure 3

How slow-wave sleep helps with memory storage. The hippocampus (brown), a small structure deep in the brain, is the fast learning system that helps to quickly acquire new knowledge. To make sure that these new memories are safely stored in the brain, the hippocampus communicates them to the slow-learning neocortex, the outer layers of the brain (green), during sleep. By acting out a sequence of slow waves (green line), sleep spindles (pink line), and fast waves (brown line) the two regions talk to each other, allowing new information to become strengthened and linked to older knowledge already present.

second learning system is much slower and wiser, like the tortoise, and carefully links the new information to things that we already know. This slower learning system wins out in the long-term, helping you to remember new information in the future. Much like in the tale, the "tortoise" memory system can take over when you give your brain an opportunity to sleep.

HIPPOCAMPUS

A brain structure deep inside the brain that helps to support fast learning of new information.

Studies show that a region deep in the brain (the **hippocampus**) gets the head start in learning like the speedy hare, while the outer layers of the brain (the neocortex) act like the slow tortoise (see Figure 3). During slow-wave sleep, the speedy hippocampus repeats the information it has learned during the day and communicates it to the slow-learning neocortex. Many scientists think that the brain is acting out a very specific sequence of slow waves, sleep spindles, and very fast waves in the hippocampus, which allow the two learning systems to talk to each other. This communication strengthens fragile memories for the longer term and links them with older knowledge already stored in the neocortex [5]. Scientists in Belgium showed that this memory-strengthening process can happen even during a nap [6]. They taught children aged 8–12 some "magical" meanings for made-up objects (for example, one object could see through doors, another object could stop the rain), and then tested their memory for these associations while measuring brain activity. Immediately after learning, the hippocampus responded to the learned meanings. Half the children then took a 90-min nap, whereas the other half stayed awake. In a second memory test, only children who had slept showed greater brain activity in the neocortex when remembering the meanings. So, even after a short nap, the slow tortoise system can win the memory race.

SO SLEEP TIGHT, WAKE UP BRIGHT!

Now you know that sleeping definitely is not a waste of time. Rather, sleep allows your memories to become as good and long-lasting as possible. Sleep is essential for allowing your brain to reorganize as you grow up and experience the world, and for helping you to remember all the new things that you learn. In the long run, children who get more sleep perform better at school, and even do better in exams than children who stay awake late to do extra studying [7]. So, be sure to make sleep an important part of your study schedule, and let your brain do the hard work while you relax for the night.

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

HATHAWAY BROWN SCHOOL, AGES: 14–15

We are students from the Science Research & Engineering Program at Hathaway Brown School. We enjoy learning about the peer review process, learning how to communicate science to different audiences, and offering our suggestions. We are helped by our Science Mentor, Crystal Miller.

THE SCHOOL FOR SCIENCE AND MATH AT VANDERBILT, AGES: 14–15

We are a class of students from all over Nashville, who come together once per week at Vanderbilt to learn more about science, technology, engineering, and mathematics. We conduct experiments in our classroom and in labs on campus!

AUTHORS

EMMA JAMES

In the run-up to school exams, I would insist to my parents that I had not learned enough to go to bed early. I hate to admit it, but my research has taught me my parents were right: I am amazed at what sleep does for memory. I am particularly interested in how sleep helps us to learn new words, and why some children find this learning more difficult than others. I work at the University of York (UK), but have also lived in Bristol, Oxford, Lancaster, London, and in America. In my spare time, I like running, cooking, and playing the piano. *emma.james@york.ac.uk

ANN-KATHRIN JOECHNER

I love sleep—not only because I personally like to sleep, but because I think it is amazing how active the brain is during a time where we seem inactive and have no conscious experience. Since I was a student at university, I have been fascinated by how sleep helps the brain to restructure and thus to retain new memories, and I have tried to understand it ever since. As childhood is a time of massive brain and cognitive changes, I am especially interested in how sleep supports memory across childhood and how the development of the brain is related to this. *joechner@mpib-berlin.mpg.de

BEATE E. MUEHLROTH

When I was 6 years old, I could beat my parents when we were playing the matching pairs game. Of course, at that time I did not know how special a child's brain is. In my research, I want to find out what the brain is doing when we are learning and remembering and how sleep supports these tasks. Most of the time, I am trying to understand if bad sleep, as we might observe in our grandparents, could explain why older people forget more of the things they learned throughout the day. *beatemuehlroth@gmail.com

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