Mathematics and the Learning Cycle: How the Brain Works As It Learns Mathematics

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Fernando, a third-grade teacher, regularly engages his students in exploring mathematical concepts by providing them with problem-solving activities that build on and extend the knowledge they currently possess. Fernando's class has been working on counting sets of objects and has briefly worked with the idea of equal sharing. Today Fernando poses a problem about pennies in hopes that working on it will enable his students to use the learning cycle to further develop the concept of division. The problem presented goes like this:

> Four children were walking to school. They found a sack full of pennies like this one *[Fernando holds up a clear, resealable bag with plastic pennies in it.]* The children brought the sack of pennies to their teacher, who suggested they give it to the principal because whoever lost it would most likely come looking for it. After a week, the principal called the students back to

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> her office and said no one had claimed the bag. She told them they could have the pennies if they shared them equally. The children counted and found fifty-four pennies in all. How many pennies should each child receive? (adapted from Burns 1995)

Because Fernando's students regularly engage in problem-solving activities, they eagerly begin working on the problem. Gabrielle, Robert, and Justin rush to the manipulative corner and begin counting plastic coins. After they have counted fifty-four pennies, Gabrielle remarks that this problem is like one she encountered last week: She received four candy bars divided into eight squares each, which her mother made her share with her two brothers.

After a few more minutes of discussion, the children get quiet, and each of them becomes engaged in their thoughts. Gabrielle tries to assimilate the pennies problem into her prior experience with the candy bars. Robert's mind is abuzz with an algorithm he used previously to solve a similar problem. Justin focuses on the pennies he helped count. After time spent thinking, each child begins to act. Gabrielle and Justin draw four squares on a sheet of paper and begin placing the fifty-four pennies one by one into each square, while Robert begins to calculate with numbers. As the children work, Fernando walks around the room and poses questions to encourage them to reflect on their actions and their thoughts. As he visits with each group of students, he encourages them to consider their actions, explain things to themselves and one another, and make predictions about what will happen if they try a particular strategy.

This brief glimpse into a classroom reveals the learning cycle of the brain as students develop the concept of division. The students' brains take in sensory experiences, integrate this information with what they already know, reflect on this information, and formulate plans to put ideas into action. As students engage in the learning cycle, their brains are building structures and making neural connections that they will use to understand mathematical concepts and procedures (Berninger and Richards 2002). Their brains are influenced and changed by the experiences they encounter in a classroom.

Now consider mathematical learning and understanding from a constructivist view, which states that children do not merely absorb information but rather construct knowledge from the things they experience. Knowledge is built on existing structures as children assimilate new information into existing schemes (Piaget and Inhelder 2000).

The National Council of Teachers of Mathematics (NCTM) poses constructivist ideas in its *Principles and Standards for School Mathematics* (2000). NCTM supports mathematics instruction that takes a developmental perspective; starts and builds on what children know; and leads children to construct relational understanding, problem-solving abilities, and the ability to reason logically. In this context, learning is change, and development of mental associations and these associations are influenced by the quality and quantity of experience (Van de Walle 2007). Understanding grows as webs of interrelated ideas become more complex, and this happens in classrooms like Fernando's, which contain rich experience, time for integration and reflective thought, and opportunities to take action and use what is known.

Our aim in writing this article is to merge information about the learning cycle with NCTM's constructivist view to help teachers of mathematics understand their students' brain cycle as they develop mathematical concepts and competencies. We believe this is an important focus because other professionals who work with children—such as pediatricians, psychologists, and speech pathologists—all receive information about the brain, its development, and its structures and processes, but educators often do not. It seems logical that teachers, whose main role is helping children learn, should have the same information (Wolfe 2001). Merging this information adds another layer of understanding of the way students learn, environments that promote learning, and why NCTM's recommendations are the best way to teach mathematics.

Mathematics in the Brain

The brain is a complex organ, and to understand it, we will examine information about a few basic structures and the cycle of learning the brain uses as it learns mathematics. We rely on the work of James Zull, a biology professor and the author of *The Art of Changing the Brain* (2002). This book is unique because it is written from a biology teacher's perspective and examines learning from a physiological view. To Zull, the learning cycle occurs because of the way the brain is built. Tracks of fibers in the brain connect, and these fibers are the paths that information takes through the stages of learning. This is not to say these paths are the only ones in the brain; brain wiring and connections are very complex. However, learning generally about how information flows through the brain can help teachers begin to understand why a constructivist view aligns with how the brain learns naturally.

The learning cycle occurs in four parts of the cerebral cortex, the brain structure responsible for much of the thinking and learning that occurs when children are engaged in problem solving and higher-level mathematics. The cerebral cortex is important to the learning and processing of mathematics because it is where executive functions such as interpreting, reasoning, communicating, decision making, and planning occur in the brain (Berninger and Richards 2002). The cerebral cortex is divided into four regions, and each section is dedicated to performing one of three functions:

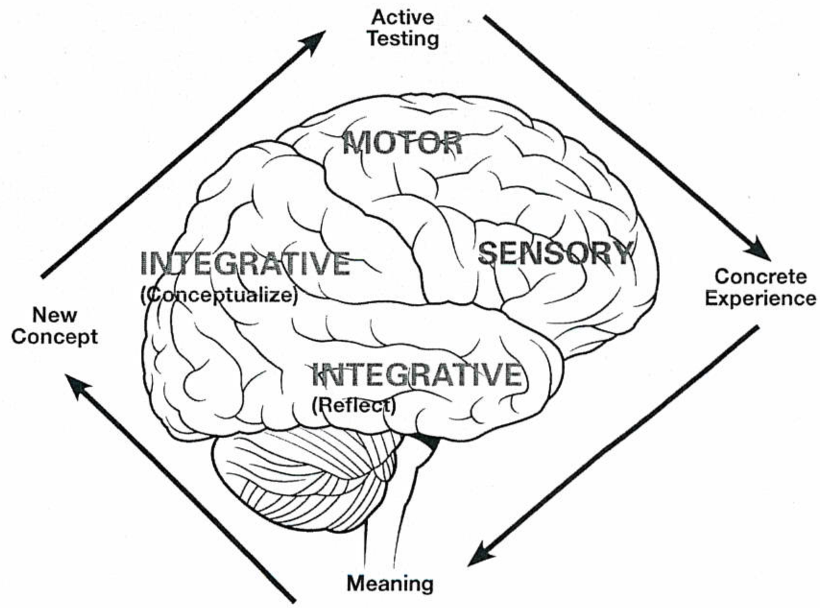
- To sense information (sensory cortex)
- To reflect on and integrate new information into what is already known (integrative cortex)
- To create mental or physical movement (motor cortex)

In essence, the learning cycle (consisting of sensing, integrating, and acting) is based on how the brain is structured. The illustration of the learning cycle (see **fig. 1**) depicts the four structures the brain uses in the learning cycle and how the cycle moves from the back, to the middle, to the front of the brain. Many similarities and overlaps exist between the ideas we pose and the physical structure of the brain, but we are taking a more holistic-functional approach (not a structural one). The *big* idea is not so much specific regions processing specific information but brain function—what the brain does: how information enters, flows, gets integrated, and then changes into action or new knowledge.

The following sections of this article explain each of these structures, the learning cycle, and specific strategies teachers can use to begin the cycle and build mathematical structures and connections in the brain.

Figure 1

A simplified diagram of the brain and the learning cycle



Brain: John Woodcock/iStockphoto.com

The Sensory Cortex: Concrete Experience and Representation

In the opening scenario, Fernando activated his students' sensory cortex when he posed the problem orally and held up the pennies in the bag. The sensory cortex is the brain structure receptive to sensory input. The sights, sounds, touches, smells, tastes, and muscle sensations children experience all go to this part of their brains. The sensory cortex is the place where processing begins; so, it seems reasonable to use it as a starting point to help students learn mathematics. NCTM's Representation process standard promotes this idea by encouraging the use of various models to interpret physical, social, and mathematical phenomena. It encourages the use of sensory experiences like manipulatives, field trips, projects, and role playing to achieve this goal. Visual representations can come from pictures and manipulatives that help children see mathematical ideas. Sharing ideas with others and listening to ideas provide auditory input and opportunities to advance verbal reasoning skills. The sensory cortex can be activated by touch as students manually explore the shapes of pattern blocks or count pennies. The sensory cortex seeks and needs these experiences to begin to construct mathematical concepts (see **fig. 2**). Teachers need to observe and talk with students as they are engaging in these experiences. Chatting with students, as Fernando did in the opening scenario, helps students make connections between the experience you are providing and the concepts you want them to learn. Rich sensory experiences lead to the next step of processing—making connections to what is known.

The Integrative Cortex: Personal Connections and Reflection

Experience, even if it is rich in sensory information, is insufficient for learning unless children are able to make sense of the input and bridge the gap between that experience and what they already know. The integrative cortex is the part of the brain that does this because it takes information from the sensory cortex, searches it for meaning, and integrates it with what is already known. In the opening scenario, the students were searching for connections to their prior knowledge. Robert connected the problem to the pennies he saw and relied on those pennies to solve the problem. Gabrielle demonstrated that her integrative cortex had taken the problem and connected it to her prior experience with candy bars, and Robert's prior knowledge prepared him to transform the problem into an algorithm using abstract symbols. Child psychologist Jean Piaget (1970), referred to this process as *assimilation.* Assimilation happens when a new experience can be easily understood because it fits into what is already known. This idea aligns with the NCTM Connections process standard and also fits with how the brain processes information. When children make links between new information and what they already know, physical connections take place between brain cells. Forging connections in the early years is accomplished by having students associate mathematics they are learning in the classroom with the intuitive, informal mathematics they have gained through life experience. As students construct knowledge and their neural networks grow, they become able to tie various mathematical concepts together both within mathematics and across domains. Instruction that emphasizes connections assists the integrative cortex to fit new experiences into what is already known.

Children's understanding grows in classrooms with rich experiences, time for reflective thought, and opportunities to act on what they know

Assimilating information takes time and effort and is enhanced through reflective thought (Fosnot 1996). Reflection is an inner process that entails private speech, or talking to oneself, about what is known and what one needs to learn in order to fill in gaps in knowledge (Vygotsky 1978). Reflection leads to reasoned thinking and is an important process recognized by NCTM. In the opening scenario, Fernando encouraged his students to become reflective thinkers by encouraging them to consider their actions, explain things to themselves, and make predictions about what will happen if they try a particular strategy. He likely used questions such as, "Think about why you think this is true" and "Explain to me how you went about finding that answer." Such questions encourage a deeper processing of material. Encouraging students to wonder why, explain things to themselves, justify ideas in their mind, and make predictions or estimates before they act—all promote reflection and reasoned answers. Avoid telling students the answer; teaching them to wrestle with ideas helps them understand that reflection and reasoning should undergird their ideas (Van de Walle 2007).

When learning is rote and dry, the brain will habituate—that is, become used to—the input and tune it out. Brain cells fire less frequently when the

Figure 2

Sensory Cortex

Sensory Cortex	Concrete Experience
Sensory experiences come in many forms (sights, sounds, touches, smells, and tastes).	Use sensory experiences in mathematics (e.g., manipulatives, field trips, projects, and role playing). Observe and talk with children as they are engaged in these to help them make the connection between experience and concepts. Have students use their senses (and multiple senses) when they learn (e.g., have them draw, write, and explain ideas).

Figure 3

Integrative Cortex

Integrative Cortex	Personal Connections and Reflection
The brain wants to understand where new information fits (to add it up). It tries to form relationships to what it already knows.	Make sure students have the prior knowledge they need. Provide experience when lacking.
The brain wants to understand and identify what it is learning (comprehension).	Reflection entails inner speech, or talking to oneself. Encourage students to explain things to themselves, justify ideas in their minds, make predictions or estimate, and make a best guess before they act. Let students do the thinking; don't hand them solutions.
Learning rote calculation is a passive activity that does not take advantage of the integrative cortex.	Challenge students to think at a higher level. Encourage them to wrestle with options, explore multiple paths, and see relationships among ideas.
This part of the brain is responsible for problem solving, making judgments, and evaluating ideas.	Higher-level thinking comes from life's experiences that are probable, improbable, variable, and random. The brain experiences this way of thinking every day, so use real life scenarios in the classroom and pose problems of chance and probability.

same problems are given over and over or when the same voice is heard over and over. The integrative cortex is designed to wrestle with the complexities of life, explore options, assess alternatives, and struggle with contrasting ideas. To engage the integrative cortex, a problem-solving approach to mathematics is needed. In the opening scenario, Fernando gave his students the opportunity to work together to solve the problem he posed. Events that are improbable, variable, and random have always been a part of life, and it is reasonable to use them to keep the integrative cortex engaged. Classrooms where mathematics is taught as anything less bore this part of the brain. NCTM supports this type of environment because it promotes a problem-solving environment where students propose mathematical ideas and conjectures, evaluate their thinking, and develop reasoning skills. **Figure 3** contains ideas for reflection along with ideas presented previously about the sensory cortex.

The Motor Cortex: Active Testing

It is one thing to have sensory experiences, make connections, and reflect on them, but it is another to put ideas into action. Up to this point in the process, learning has been receptive and internal, but to truly learn, the motor cortex must move ideas from the inside out or to the next stage. No matter what type of knowledge has been constructed in the integrative cortex, it is useless until the motor cortex tests ideas in an active and meaningful way. Asking children to bring their ideas outward, to express them so others can see, hear, and experience what they now know, helps their brains consolidate what they have learned. Asking children to write, draw, and model their ideas encourages them to actively test their new understandings with their motor cortex. The brain creates ideas, and the body is designed to bring them into reality. However, action need not be physical; active listening, gathering opinions, and moving ideas forward, even within one's own mind, are all ways to create mental movement and growth. The mind can advance thinking even while the body is perfectly still. Movement happens in the motor cortex as ideas are created, tested, and used to formulate a new cycle of ideas and plans. Such movement is extremely important for the growth of knowledge and for the emotional satisfaction it provides. Movement toward understanding, whether physical or mental, triggers positive emotions and helps children feel less anxious about mathematics. NCTM recognizes the connection between mental movement and the satisfaction that this movement

Figure 4

Motor Cortex

Motor Cortex	Active Testing
This area controls coordinated, voluntary muscle contractions to produce movement.	Encourage students to convert their ideas into actions and to talk, write, draw, and move (role playing, group work, etc.). Have them live mathematics by doing mathematics.
Remember that students can be actively testing ideas and performing mental operations even when they are physically still.	Encourage students to listen actively to what others think and say.
	Provide think time; recognize that movement toward a problem's solution can sometimes look very still.
Emotions matter.	Make mathematics pleasurable. Give students challenging tasks at their level.

brings when it proposes that students who wrestle with ideas and gain understanding experience a special feeling of accomplishment. **Figure 4** presents ideas for active testing.

Concluding Thoughts

As teachers of mathematics, we live in exciting and challenging times. The need to raise proficiency and understanding in mathematics has never been greater or more important. Children must develop an understanding of mathematics that will empower them to solve problems effectively, make reasoned judgments, and be reflective in their thoughts. NCTM recognizes this in its *Principles and Standards for School Mathematics* (2000), which provides strategies and direction for teachers of mathematics to meet these needs. We suggest that these Principles and Standards are powerful because they align with the learning cycle and provide insight into the types of experiences and input that a brain needs to learn. We believe the time has come for this information to be made available for teachers because there is now credible and reliable information as to how the brain learns and what the brain needs in order to learn effectively (Wolfe 2001). Blending the constructivist perspective with the learning cycle offers teachers another reason why ideas posed by NCTM truly help children learn and become mathematical thinkers. Insight into the learning cycle is also inspiring—because what teachers of mathematics do every day in their classrooms is nothing less than the art of changing the brain.

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