

Imagine that you are unable to move your arms. Maybe they're tied down, you've lost them, or you have intractable epilepsy like the seven patients that J. D. Wander and colleagues worked with. Wander et al. worked with these seven patients as they studied adaptations across multiple cortices (areas in the outer layer of the brain), while the patients learned how to perform a task in a brain-computer interface (BCI). Imagine

that through this BCI, you are suddenly able to move a cursor across a screen with just your mind—a bit challenging at first, of course. To do this, you have to imagine moving the cursor as if you were moving it with your hand (Ming, Dong, et al.). You might feel like a magician or a Jedi. You move the cursor, manipulating your physical environment, without actually

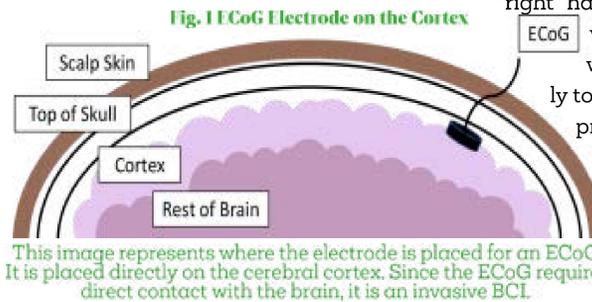
moving your body. Normally, when you manipulate your physical environment, you do so by sending a signal from your brain to your body. For example, this signal tells your arm to reach out for a doorknob. While you move and after you successfully reach the doorknob, your brain is receiving sensory feedback from your arm about where your arm is relative to your body, if it successfully reaches the doorknob, if it's on the correct trajectory, and so on (Tsay, et al., 1037–1049). This feedback is very important for learning a motor skill, as it gives you detailed information on how to correct the motion or do it better.

However, you do not receive this feedback when you are using or controlling a BCI (Wolpaw, 613–619). The only feedback the seven participants in Wander et al.'s study received was visual feedback as they moved the cursor across the screen. Behind the scenes, a researcher and doctors have placed an electrode directly onto your brain to measure the signals. This process is called electrocorticography (ECoG). Wander et al. placed the electrode grid on the surface of the brain, which measures activity across the cortex. The researchers of this study were measuring the patient's modulation of a specific range, 70–100 HZ, of the

high gamma (HG) band which encompasses 70–200 HZ.

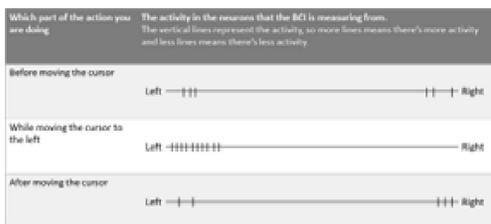
Essentially, you think about moving the cursor as if you were moving it with your hand. Inside of the brain, a specific group of neurons would grow more active and the HG would modulate across the cortex (Ray, et al., 11526–11536). As discussed earlier, Wander and their colleagues were monitoring this HG modulation and then using it in the BCI calculations. These BCI calculations are what enable you to move that cursor across the screen simply by thinking about it without moving your body, as if you are, to continue my Jedi metaphor, “one with the force.”

But how could Wander et al. do this? How exactly do they turn your brain's HG signals (representing neuron firing rates) into an action, a movement of something outside of your body? Generally, BCIs measure and utilize firing rates within groups of neurons in the sensorimotor cortex. Based on these firing rates, the BCI calculates the motion that you want to make. For example, when you think about moving the cursor, a group of neurons will grow more active and another will grow less active; if the group of neurons representing “left” has increased firing rates and the group representing “right” has decreased firing rates, the BCI will be able to predict that you want to move the cursor relative to the left (Bandara, Kiguchi). This process can be a little messy and is a difficult computation and interface because computers and biology don't always play perfectly well together. Part of learning how to use the BCI in-



cludes learning how to get the BCI to accurately move the cursor the way you want; as with many skills in life, you have to practice to get better.

**Fig 2. Neural Activity While Manipulating the BCI**



This image illustrates the changes in neural activity that might occur when you think about moving a cursor to the left. The neuron that represents the "left" movement in your brain will grow more active. The one that represents the "right" movement will grow less active. Note: This image is mock data, generated to be used only as an example.

Taking a step back, let's return to the fact that people can learn to control the BCI and get better at it with practice. Participants have described the experience of learning to control the BCI as very similar to how they would normally learn a physical action: they are cognitively focused on each part of the movement initially and over time, the specific steps of the movement become more automatic and they focus on the goal (Fitts, 381-391). You may have experienced this phenomenon while learning a new action: at the beginning, you have to focus on each step and part of the action, but as you practice it, you don't have to think about the individual steps any more than you do when you put your clothes on in the morning. So how does this change normally happen?

First, there are three distinct motor skill learning stages: cognitive, associative, and automatic (Fitts, Posner). Fitts and

Posner first described these three stages in their book *Human Performance* in 1967.

In the first stage, the cognitive stage, you are learning a new motor skill. Your movements are slow and irregular, and you have to think intentionally about not only the end goal of your movement, but also each step in the movement. For example, think about learning how to shoot a basketball. You don't instantly know the proper form and can't consistently sink a shot. First, you have to learn and practice the individual steps that combine together to get you that perfect form and get off that perfect shot. You have to actively think about how to properly pick up the basketball from your dribble, how to plant your feet, how to ensure your elbow is properly pulled in next to your body, how to hold the ball on one hand while balancing the ball with the other, and so on. You often have to narrow in on just one step of that movement, practicing properly planting your feet over and over until you get used to it.

As you get more used to some steps of the movement and can do those without thinking, you transition into the associative stage—stage two.

In stage two, some steps or parts of the movement become automatic and movements become smoother. When shooting the basketball, you don't have to focus as much on each individual step, yet you aren't consistently getting the whole movement quite right. You still have to think about some of the harder steps in the movement (such as properly aligning your arm and shoulders to get that perfect shot off), but you're getting better.

Finally, in stage three, movements are consistent and smooth, controlled mostly automatically rather than you having to consciously think about each step (Weaver). At this stage, you can sink a shot without having to focus on the individual steps of the movement. You do not have to devote so much attention to properly pick up your ball from the dribble, plant your feet, and align your arms as you pull the basketball up into position.

As you progress through these motor skill learning stages, different parts of your brain will be more or less active. In the first two stages (cognitive and associative), the prefrontal, premotor, and parietal brain regions are more active. In the last stage, the prefrontal, premotor, and parietal brain regions become less active. Instead, brain activity is predominantly in the cerebellum, which controls and manages more automatic movements, such as breathing and food digestion (Weaver).

**Fig 4a. The Lobes Related to Motor Skill Learning**

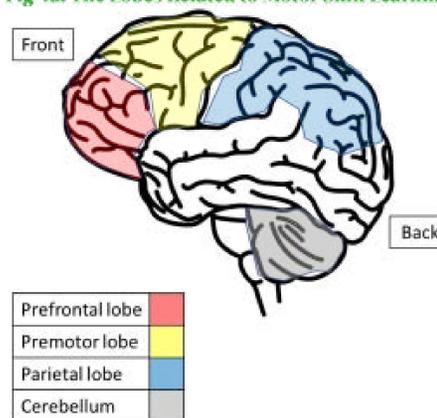
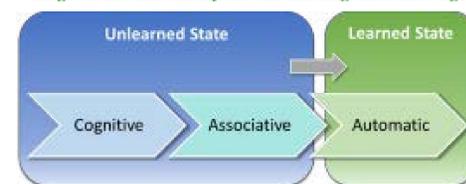


Image 4a visually represents the approximate location of the brain areas that are important in motor skill learning.

But does this, or a similar process, also happen during BCI motor skill learning? BCI motor skill learning is different from standard motor skill learning, of course, because it involves a computer and moving something without your body. Will the underlying neurological and cognitive processes, however, remain the same since they are similar processes?

That's what Wander et al. were investigating. They tracked participants' performance to note when they transitioned between unlearned to learned states; the unlearned state incorporates the cognitive and associative stages (stages 1 and 2) and the learned state is the automatic

**Image 3b. The Relationship Between Learning States and Stages**



In this image, you can see an illustration of the relationship between the states (learned and unlearned) and the stages (cognitive, associative, and automatic).

stage (stage 3). Wander et al. also recorded activity from across the cortex, not just the sensorimotor cortex whose signals they measured and analyzed to control the BCI. Wander et al. measured the primary motor cortex (MC), primary somatosensory cortex (SC), dorsolateral prefrontal cortex (PFC), dorsal/ventral premotor cortices (PMd/PMv), posterior parietal cortex (PPC), temporal parietal junction, inferior temporal gyrus, and supplementary motor area (SMA).

Let's refer to those first five areas—the MC,

SC, PFC, PMd/PMv, and PPC—as “Learning Areas,” since those areas were more active while participants were manipulating the BCI during the unlearned state, while they were still learning how to properly perform the movement. During the learned state, Wander et al. found that activity lessened significantly in those Learning Areas. There are three general brain areas that incorporate those Learning Areas: the frontal cortex, the superior

cortex during BCI learning. Those changes correspond both to Fitts’ stages of motor skill learning and to the areas of the brain previously known to be more active during motor skill learning. These results both support previous work and suggest that BCI learning is neurologically a very similar to, or possibly even the same process as standard motor skill learning. This link doesn’t make BCIs any less impressive or exciting, but it does illustrate that we can utilize our existing knowledge of neurological processes when we’re using BCIs to perform a similar task. We have a starting point of understanding what’s happening neurologically while learning how to move a cursor properly with your hand. We can use that knowledge to better understand moving a cursor without moving your body, just by thinking about it.

Wander et al. proposed that, based on their findings, more research can be done into changes in brain systems in living organisms—in vivo—using a BCI. What brain processes and changes would you be interested in learning more about? One potential exciting area for future research, especially when utilizing non-invasive BCIs, would be exploring brain activity while learning a first or second language. There are limitations in current BCI technology, especially for speech BCIs. Brain signals must be measured from across many cortical regions to figure out what you want to speak through a BCI (Rabbani, Qinwan, et al., 144–165). Speaking a language is more complicated than moving a cursor on a screen. Still, we might be able to use BCIs to study hearing or first language learning

at a young age, though non-invasive BCIs would be especially crucial to use in those studies. Invasive BCIs, like the ECoG, give the researchers cleaner brain measurement data, but are also riskier and can have more complications than a non-invasive BCI. Because of this complexity, invasive BCIs are often used with caution and with volunteers who will benefit from the BCI.

As well, there are some exciting current BCI applications that are benefiting the volunteers who are using them. For example, BCIs have been used in attempts to work around motor disorders or disabilities, such as a loss of motor control from a stroke or Parkinson’s disease (McFarland, Dennis, et al., 37–52). The BCI can enable people who have lost some motor control to briefly regain that ability and enjoy manipulating their environment in a way that many of us take for granted each day. Additionally, we can learn more about the details of these and other diseases through studying the BCI learning in these situations or even from understanding the natural progression of a disease over time in the cortex.

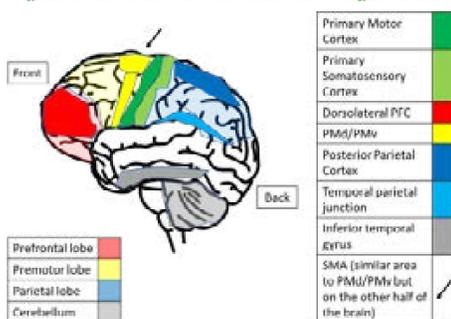
Another exciting potential area of research would be combining BCIs and Exergames. Under Dr. Anna Fisher at Carnegie Mellon University, PhD Candidate Cassandra Eng is currently researching the effects of Exergames on executive function in children. Exergames are cognitive games that incorporate an exercise that is related to that game. A fun example of an Exergame is one similar to the Virtual Reality (VR) game Beat Saber, but it incorporates a stroop-like element where you have to hit the blocks in the opposite direction than

you usually would (Eng). BCIs that incorporate a similar multidimensional task could illuminate both movement-related and cognitive systems as well as the systems related to the combination of the movement and cognitive systems (Exergame). Furthermore, they could provide insight into executive function, whose exact definition is currently the subject of discussion (Doebel, 942–956), but whose importance is widely accepted. Wander and colleagues also proposed that BCIs offer the opportunity to study the effects of sensory deprivation on the learning processes. For example, imagine that you were trying to move a cursor across a screen with your mind as you train to become a jedi, but you could not visually see how well you were performing. This lack of visual feedback will likely affect your learning, as you often use sensory input to learn and improve such movements.

We can see an example of this through a study by T A Martin and their colleagues. Their study was researching the changes on the participant’s ability to throw an object while looking through prisms that shifted their visual field slightly to the side. Essentially, imagine you were wearing a pair of glasses that shifted everything you were seeing over to the right. The blue solo cup sitting on the table in front of you would appear to be a few inches to the right of where it actually was with respect to your body. Now, imagine trying to throw a ping pong ball into that cup. It would take you a little while to physically adjust to that change.

An important nuance in this study is that you aren’t supposed to think hard

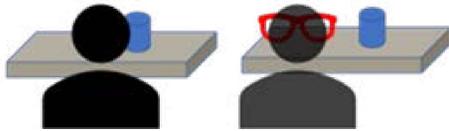
Fig 4b. The Areas of the Brain that Wander and Colleagues Measured



Labeled above are the areas that Wander and colleagues measured from. Note the overlap of the first 5 brain areas on the right table (the Learning Areas) with the first 3 areas on the left table (the areas important in motor skill learning).

parietal cortex, and the posterior parietal cortex. This lines up with what happens in your brain when you learn a standard motor skill. Think back to when you read about the three stages of learning a motor skill: cognitive, associative, and automatic. During those first two stages, which align with the unlearned state, the frontal and parietal cortex are more active. In the third stage, the learned stage, those cortices are less active. Wander showed that a similar process happens during BCI learning. In other words, Wander et al. found that there were changes in activity across the

**Fig 5. The Shift in the Visual Field from the Prisms (Glasses)**  
Before Glasses      After Glasses



In the image above, nothing has physically moved; you've simply put on the glasses. To you, it appears as if everything you can see (including the table and cup) has moved, because the glasses have shifted your perception of reality.

about trying to get the ball in the cup. Martin and their colleagues were interested in seeing the more “subconscious” correction, rather than a conscious attempt to correct for the shift that the participants knew is happening to their vision because of those glasses. Overall, this study demonstrated that visual and sensory feedback is important for learning and fine-tuning of motor movements. Behind the scenes, participants’ brains were over time “subconsciously” accommodating for that visual shift based on how accurate the throw was; when a movement wasn’t quite right, the brain would take note of that and try a new, slightly different movement, over time narrowing in on the updated motor movements necessary to successfully throw that object to the target (Martin, et al.).

While BCIs often don’t have most of your normal sensory feedback, they do still have visual sensory feedback on how well you’re performing. Martin and colleagues have demonstrated how important visual feedback is in learning motor skills. With that in mind, it would be fascinating to study motor skill learning without this visual or any other sensory feedback to further uncover if the brain learns in other ways.

In summary, BCIs are an exciting

technology that has many applications, some of which involve better understanding of the brain and its processes, systems, and changes over time. Because of BCIs, we can now study brain systems in vivo, and research suggests that learning BCI “motor skills” involves the same neurological processes as normal motor skill learning with our body. When you think about SciFi or ways we can use the advances in our society’s technology, keep in mind that budding jedis and magicians are out there, training right now, learning to move cursors across screens with just their minds or even speaking synthetically, just as you would do through using your own body.

## KEY TERMS

- Brain-computer interface (BCI): an area of technology which measures brain signals and utilizes those signals to control some computer-controlled action. BCIs can be invasive or non-invasive depending on which brain measurement technique they use.
- Invasive BCIs utilize techniques that measure brain activity from inside the body.
- Non-invasive BCIs utilize techniques that measure brain activity from outside the body, such as an EEG.
- Cognitive (difference from neurological): mental processes or matters such as memory, language, learning, etc. Generally, cognitive science is more abstract than neurological science; it is closer to the softer sciences such as psychology.
- Cortex/Cortices: often shorthand for the cerebral cortex, which is the outer layer of the brain. The word “cortex” can also refer to sub-parts of this area (such as the motor cortex).
- Electrooculography (EOG): a brain imaging technology similar to EEG that measures electrical signals in the cortex via an electrode grid placed directly on the surface of the brain.
- Electrode: a device which can measure and record electrical activity in biological tissues (such as the brain).
- Executive Function: a set of cognitive processes that are important for behavior control, including inhibitory control. Its importance is due in part due to findings suggesting that executive function in childhood predicts important life outcomes, such as academic achievement and long-term health (Blair & Razza).
- Exergames: physical activities that are driven by cognitive games provided technology, such as video games on Virtual Reality (VR) which involve some exercise related to the game.
- Hertz (HZ): a unit of measurement that represents one cycle per second. In the brain, there are waves of activity that are measured in hertz.
- In vivo - in biology, this phrase often refers to research or work done on living organisms.
- Intractable Epilepsy: a condition where there are seizures that cannot be controlled with treatment. People with intractable epilepsy may be unable to stop shaking, have stiff muscles, or have other difficulties with movement. BCIs can be an exciting opportunity for people with intractable epilepsy or other disabilities that affect movement; through BCIs, they can sometimes perform movements that they were unable to perform with their own body.
- Modulate: vary or change the intensity of a resting state.
- Neural: matters relating to a nerve or the nervous system.
- Neurological (difference from cognitive): matters relating to the biology, chemistry, and neural parts of the nervous system. Generally, neurological science (neuroscience) is less abstract than cognitive science; it is closer to the hard sciences.
- Neuron: a type of cell also called a “nerve cell” that makes up the brain and nervous system. Some of these cells are how your body gathers information about the world around you and your environment. Other cells send motor commands from your brain to the muscles in your extremities. Other cells help make up the “circuit board” of our brain that perform computation and process information, from identifying what that strange smell is to doing college algebra to stroking that brush just right to make a painting come alive on canvas.
- Nervous system: a system of nerve cells and fibers that, for humans, includes our brain, spinal cord, and other nerves throughout the body connecting to the brain or spinal cord. Through this system, our body communicates to our brain and our brain communicates to our body.
- Sensorimotor Cortex: the area of your brain that processes most of your sensory (“sensori”) and motor information. For example, this area helps control your movement when you reach out to open a door. It helps you both physically move your arm and also perceive (sense) where your

arm is in space to ensure that you're properly moving it.

- Stroop effect: an effect where a basic task has stimuli or elements that are mismatching (or incongruent). For example, in the standard Stroop task, one reads words of colors that are written in different colors (e.g., "red" written with blue ink). You then have to say the color of the ink, rather than the word. This task can be cognitively difficult since normally, you would automatically read the word.
- Subconscious - relating to "background" parts of the mind that you are not fully aware of. In this paper, this term is used rather loosely to describe the general idea of processes happening in your brain that you aren't actively paying attention to; it is not used strictly scientifically.

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