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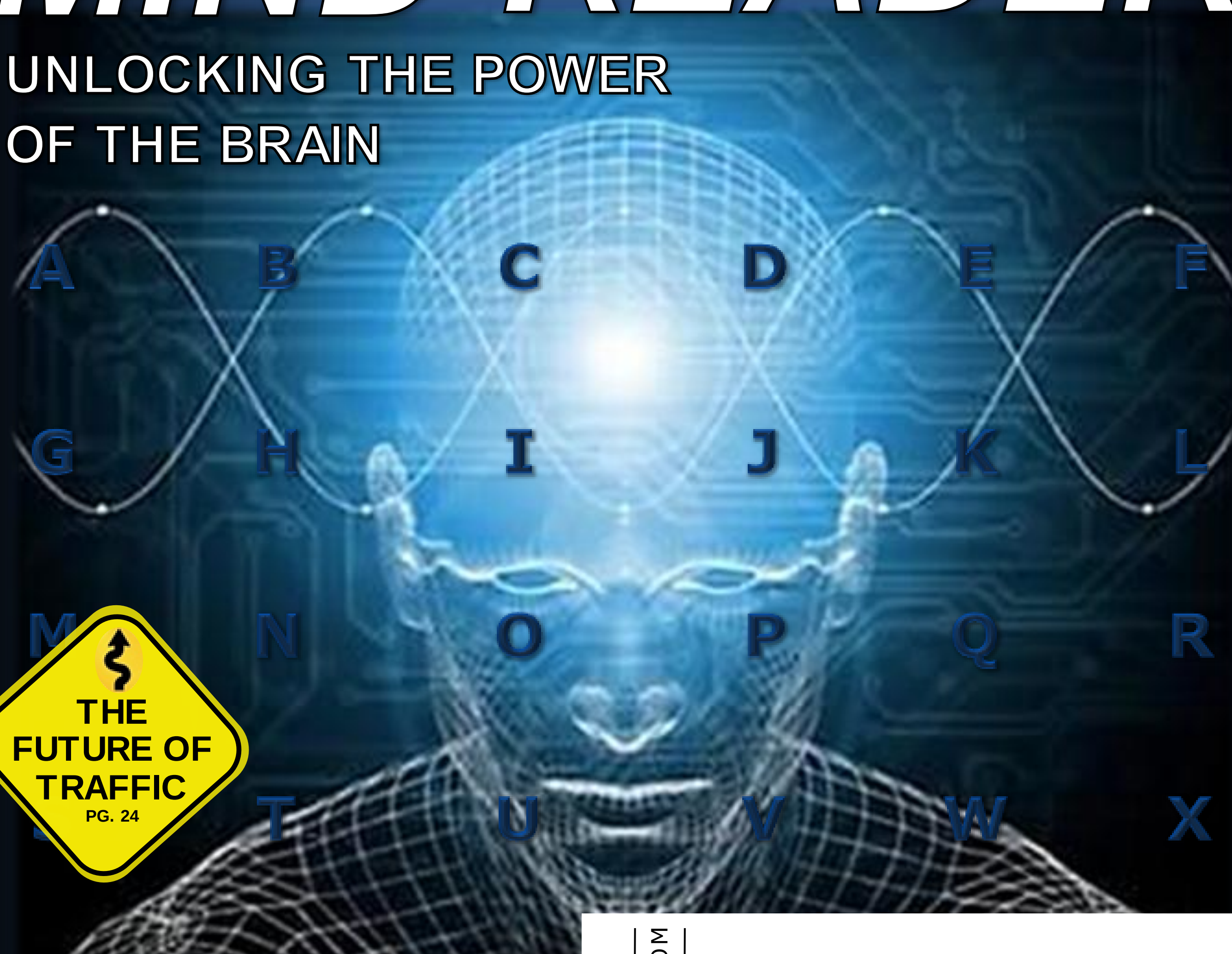
MIND READER

UNLOCKING THE POWER
OF THE BRAIN



THE FUTURE OF TRAFFIC
PG. 24

ALGAE BIOFUELS PG. 36
A SPECIAL INVESTIGATION

JANUARY 2013
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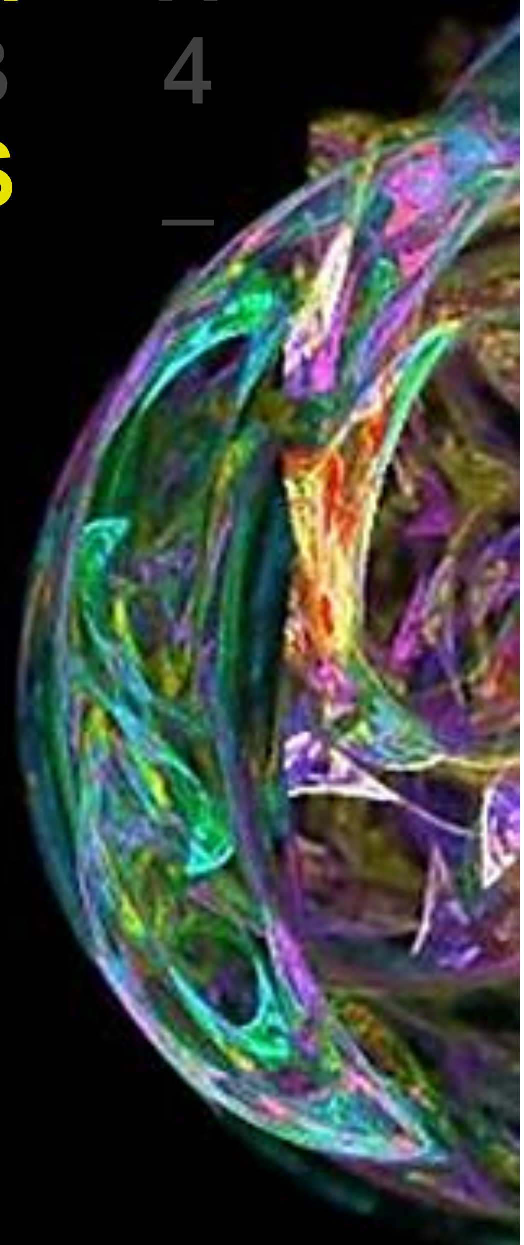
By Steven Peterson



Twenty-four years ago, two scientists achieved something only thought possible in science fiction: being able to type on a computer simply by thinking about it. However, problems with speed and accuracy forced their speller to undergo decades of further research. Today, an Austrian company called Guger Technologies has created a commercially available speller, while taking the idea to a level never before dreamed of.

In 2009, Richard Marsh had a massive stroke. He regained consciousness unable to move or even to speak. Richard could only lie helplessly and listen as doctors talked with his wife about whether or not they should turn off his life support.

Richard had a rare condition known as locked-in syndrome. This occurs after a massive stroke and usually leaves all muscles paralyzed except for the eyes. However, the brain is usually fine. In 2007, a movie called *The Diving Bell and the Butterfly* gained much international acclaim for discussing the hardships that locked-in syndrome patients faced every day. The movie was based on a book that was completely transcribed from Jean-Dominique Bauby, who had locked-in syndrome and could only communicate by blinking his left eye. One of the major problems with locked-in syndrome is that there is no cure for it, with many of its victims dying within four months. Richard Marsh was given only a 2% chance of survival. Miraculously, Richard was able to overcome his paralysis and is currently 95% recovered (Hill 2012).

Stroke has been the 4th leading cause of death in the United States over the past year. Many serious strokes can result in either permanent or temporary paralysis. But what makes a stroke so terrifying is that it can occur in anyone, at any time (Stroke 2012). The risk factors of high blood pressure and high cholesterol are both quite common and are not always given the serious attention they deserve. About 1 in every 3 U.S. adults has high blood pressure, and high cholesterol is just as common (Centers 2012). As a large portion of the U.S. population gets older, there is a huge need to find ways to combat the effects of stroke, especially locked-in syndrome.

Enter in Dr. Christoph Guger, founder and CEO of Guger Technologies. Guger Technologies, or G-Tec, is an Austrian company that is currently pioneering the use of brain-computer interfaces to allow a subject to control a computer. They have been remarkably successful, introducing the first commercially available brain-computer interface (BCI) that allowed a user to type on a computer using only the user's mind in 2009. Christoph has been motivated in the work of his company because victims of locked-in syndrome lack the ability to perform the most basic tasks that are taken for granted by most of us. "The first thing that paralyzed patients want to do is to play with their children," he says (G.tec 2012).

So why use BCI technology to overcome the effects of locked-in syndrome? Christoph explains, "Locked-in patients are totally paralyzed and cannot move, cannot speak. The only thing that's usually working is the brain" (G.tec 2012). And this is where the BCI comes in. Brain-computer interfaces take brain waves from a patient, interpret these brain waves, and use these interpretations to control some external device. This is an attractive solution for patients suffering from locked-in syndrome in that it makes use of the patient's still functional brain. "If such patients got back body control," says Guger, "that would be fantastic. This would also change the lives of other paralyzed patients and stroke patients. It would help millions of people worldwide" (G.tec 2012).

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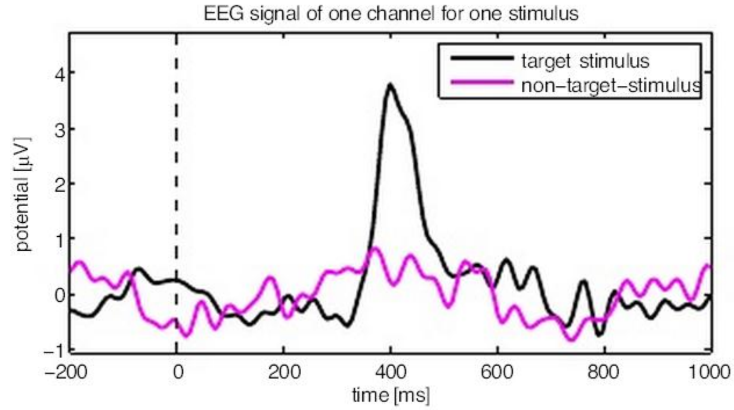
Many people think of a magical mind-reading device when a BCI is discussed. But what actually is a BCI? A brain-computer interface involves measuring a subject's brain waves and then manipulating the extracted data in such a way to determine what the subject is thinking. The goal of this is to allow a patient to control an external device simply with the brain. There are three main parts of a BCI system: a recording device, a computer to translate the recordings into a command, and an external device that will perform the function desired.

One of the most popular ways to record brain waves for a BCI system is to use electroencephalography (or EEG for short). This involves placing recording electrodes on the subject's head. These electrodes measure the waves emitted by the brain, and using many of them can help determine where the signal is coming from and what it looks like. While the electrodes cannot record the signal from a single neuron, they can detect an average of large groups of neurons that fire nearby the recording electrode. While there are other brain recording techniques such as electrocorticography (ECoG) that result in

WIRED UP

A typical EEG involves many passive electrodes attached to a person's head.



STAYING POSITIVE

An event-related potential (ERP) follows from an external stimulus (shown by a dashed line). The large positive peak of the ERP (shown in black) is a P300 wave.

better signal quality, most of these techniques are impractical and not as easy to use as an EEG. ECoG is not used outside of a research setting because it involves putting electrodes directly on the surface of the brain, which is highly invasive. Since EEG is noninvasive, people can conveniently use it.

However, there are some trade-offs that come with being non-invasive. The major issues for the EEG are twofold. First, there is the thick skull around the brain. While it is needed to protect the brain, it makes recording brain signals extremely difficult. The skull diffuses a significant amount of the signal, resulting in much worse signal resolution for the EEG than other recording methods. It is similar to having a friend talk to you on the other side of a wall. The wall diffuses your friend's voice, making it harder to hear what he or she is saying. The loss in resolution for the EEG severely limits what it can record from the brain.

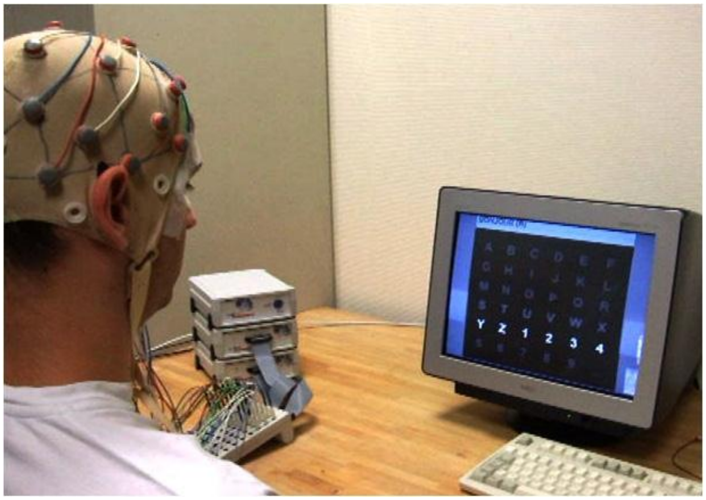
People debilitated from stroke, like Richard Marsh, could communicate with other people, using nothing other than their mind.

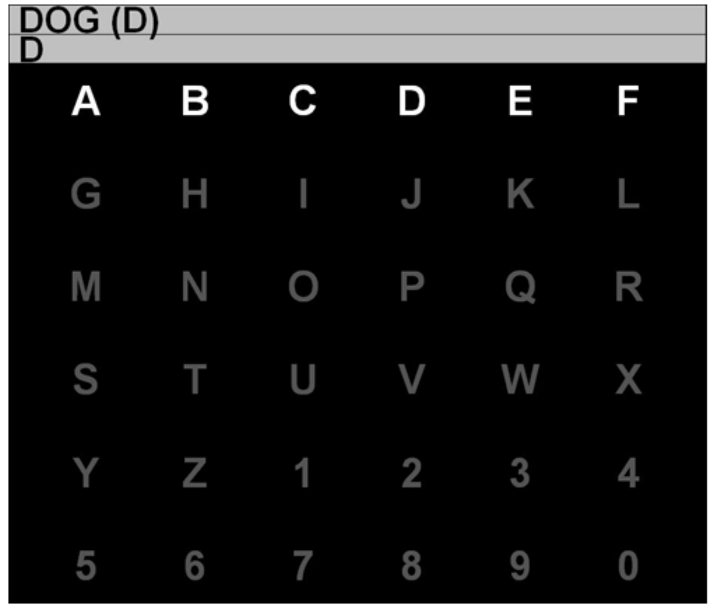
The other issue with EEG is that there are many other signals in the head interfering with the EEG signal. This can make it hard to tell what the desired signal is and what is simply noise. Some of these other signals occur during blinking, head movements, and eye movements. Since these are common movements, EEG recordings require ideal conditions for best results.

So, what exactly are these brain waves that the EEG is detecting? The brain is made up of many neurons, which communicate with each other by voltage changes. This is similar to how many electronics work, and it allows the brain to process a large amount of information in a short amount of time. Neurons emit spikes of positive voltage, known as action potentials, in order to communicate with each other. These spikes occur at regular intervals, so they have a distinct frequency and can be classified as waves (Silva 1991). While there have been many different types of brain waves classified over the past few decades, Christoph and his team focus their attention on a certain type of wave, called an event-related potential (ERP).

ERP's are brain waves that change over time in response to a stimulus. They are composed of certain positive and negative voltage peaks, with the positive portions corresponding to peaks. The two important characteristics of any component of an ERP are its polarity and its latency. Polarity refers to whether the component is positive or negative in voltage. Latency refers to how long the peak occurs after the stimulus that caused the ERP. Since most ERP's occur very quickly, their latencies are usually expressed in milliseconds, which are one thousandth of a second (Fernando 1991).

G-Tec looks at one of the most distinguishable components of an ERP called the P300 potential. The P300 wave corresponds to a positive peak with a 300 ms latency. The most common way to elicit this wave is using a technique known as the oddball paradigm. So what exactly is the oddball paradigm? When I was in grade school, our teachers always had ways to get the class's attention if we started talking and stopped paying attention. One of the most effective techniques involved the teacher turning the lights off and on. While it only lasted a second, it was





HANDSFREE SPELLING

The P300 speller involves flashing characters in a 6x6 matrix one row or column at a time. The picture on the right shows a close-up of this matrix interface.

enough to cause everyone in the room to stop what they were doing. In this case, turning off the lights was an unusual stimulus that was introduced amid the normal stimulus of having the lights on. This difference caused all of us to stop what we were doing because we recognized a difference in our surroundings. This is what the oddball paradigm is all about. When people recognize something distinctly different in their surroundings, their brains emit P300 waves (Picton 1992). These are the brain waves that allow people like Christoph Guger to work their magic.

In 1988, two scientists at the University of Illinois developed a system by which a patient could type words onto a screen using nothing but the patient's own mind. This device, known as the P300 Speller, used the P300 component of the ERP to figure out what letter or number the person was thinking about. Suddenly, a virtual keyboard had become a reality. People debilitated from a stroke, like Richard Marsh, could use this device to communicate with other people, using nothing other than their mind. This fantastic breakthrough remains one of the most popular BCI systems today.

One of the most remarkable things about the P300 Speller was its elegantly simple design. The two scientists placed a matrix of 6 rows and 6 columns on the computer screen in front of the subject. The subject looked at the letter or number on the screen that he or she wished to type. In order to elicit the P300 wave, the scientists used an oddball paradigm similar to the one I explained previously from my grade school. Each character on the computer screen was a nondescript gray color against a black background. The speller had a character flash white on the screen for a short period of time, creating the unusual stimulus. This was done randomly in whole rows or columns so that the subject was never expecting it. The idea was that when the character that the subject was focusing on lit up, the P300 would be elicited and detected by the computer. Since whole columns and rows were lit up, the P300 should be elicited for one of the lit up rows and one of the lit up columns. The intersection of the row and column would be where the desired character was located. During the original experiment, the subject could originally communicate at a rate of roughly 2.3 characters per minute. This is slow but quite novel because it only comes from the subject looking at what character he or she wants to type. It utilized how the oddball paradigm elicits a P300 and used this to create a simple mental prosthesis (Farwell 1988). This was the first major breakthrough in P300 BCI systems.

Evoking the P300 potential is relatively easy in this case. However, detecting it has proved to be much harder. One of the major issues with EEG recordings is getting rid of the excess noise around the desired signal. A common way to do this is by using a technique known as signal averaging. This technique can be illustrated using a simple example. Suppose you have 20 coins. You know that some of them are weighted, but you do not know which. If you flip each coin once, you will still have no idea which coins are weighted and which ones aren't. The easiest way to figure this out is too flip each coin many times and to see how many times each coin comes up heads and how many times it comes up tails. The normal coins will have a fairly equal number of heads and tails, while the weighted coins will have some bias for either heads or tails.

In the same way, signal averaging uses many trials to determine which parts of the measurement are biased and which parts are unbiased. The noise in the recordings should be unbiased, because it is random noise from other parts of the head. However, the signal desired should occur every time in the same spot with a similar magnitude because it is biased to the trial being run. For the P300 Speller, the desired signal was the P300. When the oddball paradigm was used, the P300 should have been seen every time, while the random noise was independent of the oddball paradigm. Averaging involves overlaying each trial's recorded response on top of each other and then averaging the measured signals. The random noise should average out because the recorded noise is just as likely to be above baseline as below it.

However, the P300 should have occurred in each trial, so the average of the P300 should have been noticeable compared to the average of the noise. Averaging allows the computer to use other various algorithms to determine whether or not the P300 was elicited by a certain row or column (Laguna 1992). The only problem with averaging is it requires a large amount of trials to work effectively. The original P300 speller used more than 40 trials before spelling a particular character. This is likely why the speller had such a slow spelling rate (Farwell 1988). Various other algorithms are used to determine if the averaged signal shows high enough P300 amplitude for it to be considered a response to the blinking light.

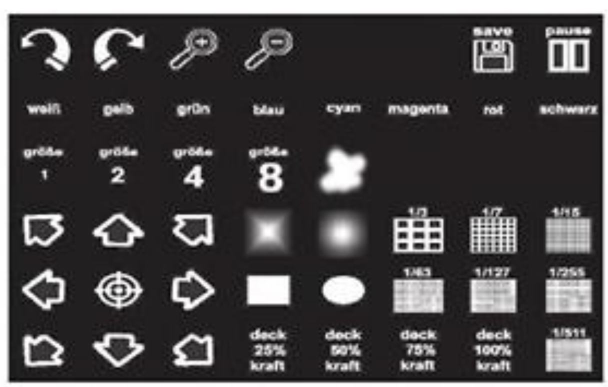
However there were considerable shortcomings in the P300 speller when it first came out. It required 50 to 200 trials per letter to achieve 95% accuracy. This meant that it took roughly 26 seconds for the speller to decide which letter was correct. It was too slow and expensive to be used by handicapped patients at that point.

Decades after the creation of the P300 speller and numerous improvements to increase its speed and accuracy, Guger Technologies released the first commercially available laptop speller, known as Intendix. While it is quite expensive at $12,000, Intendix represents a huge step for P300 BCI's. Intendix brings the magic of BCI's that much closer to real world use, allowing Christoph to move closer towards his ultimate goal of helping victims of locked-in syndrome and stroke (Intendix 2012). However, Christoph and his team didn't simply stop at being able to spell words on a screen. They took the idea behind the speller and applied it in ways that are truly incredible.

Christoph and his team took the idea behind the speller and applied it in ways that are truly incredible.

While spelling with your mind is exciting, it can seem boring and tedious after a while, especially given how long it takes. To help engage patients more, scientists in Germany partnered with an artist to create a P300 speller that could draw pictures instead of type words. The matrix of letters and numbers was replaced with symbols for shapes, colors, and other drawing functions. This allowed patients to produce paintings, while actively engaging them for hours. This helped improve the accuracy of the P300 BCI system because the brain adapts to perform better over time. This was a problem with the speller because patients lost interest in typing after a while. When the patient loses interest and stops focusing on the character they are looking at, the P300 is not as distinct, leading to greater inaccuracy with the P300 speller.

However, many people enjoy painting pictures for an hour or two. It is actively engaging and allows them to be creative. It was shown that allowing patients to work with brain painting made them more accurate with the P300 speller. The only initial concern with brain painting was

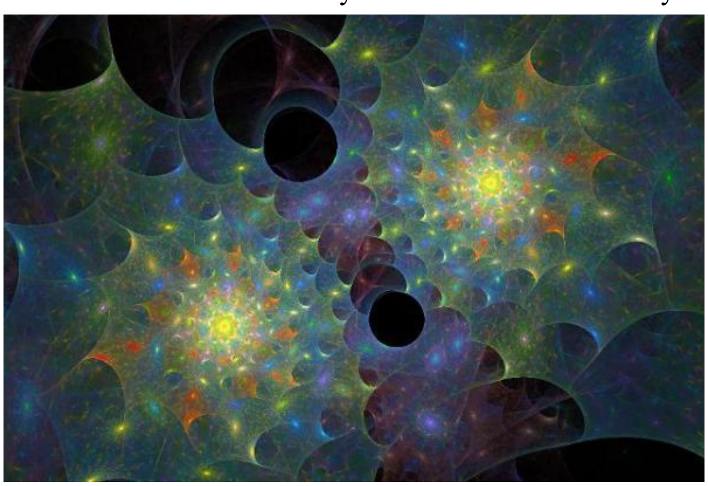


A PICTURE SAYS A THOUSAND WORDS

The inventors of brain painting took the matrix interface from the P300 speller and included painting tools. There are icons for colors, shapes, and sizes.

that it was much less accurate than the P300 speller. A comparison between the two systems revealed that brain painting was significantly less accurate. P300 speller accuracy was found to be 92%, while the brain painting application had an accuracy of only 81% (Garwicz 2011). This has been thought to be due to the rigidity of spelling as opposed to the more flexibility in painting. Namely, the user definitively knows which letter he or she wants to type next to spell a certain word. There is no flexibility, so the patient will not consider focusing on any of the other letters. However, painting is much more open, allowing the user to decide what to do next. The user may not always be entirely sure what to use next, and this uncertainty could affect the accuracy of the brain painting program.

Christoph and his team at G-Tec saw brain painting as another great way for paralyzed patients to be able to express themselves. Brain painting was limited only by the creativity of the user. Also, paintings, unlike words, can be understood in any language, allowing greater access to anyone. G-Tec was able to increase the speed and accuracy of the brain painting BCI system so that their version, known as Intendix Painting, required only a few quick minutes of training and allowed the user to make 5 to 10 painting actions each minute. One of the most ingenious features of this new device is that it detects how focused the user is to avoid selection mistakes while painting. This is great because most people need some time to think about what they want to do next while they're painting. By detecting the user's attention level, the Intendix Painting application greatly increased the accuracy of Brain Painting.



AN ARTIST'S TOUCH

Brain painting allows users to create artwork comparable to any drawing done by hand, and yet completely different.

Adi Hoesle, one of the German scientists that first developed brain painting, said this about G-Tec's Intendix Painting: "As a co-developer and experienced user of brain painting software, I would state that Intendix from G-Tec has set a milestone in BCI application, especially for handicapped people" (Intendix 2012). Guger Technologies clearly has had an impact in making BCI technologies a realistic option for handicapped people.

However, Christoph and his team were once again not content to stop with brain painting. They tried to apply the work they had done so far to something quite futuristic: allowing users to interact in a virtual environment, using only their minds. Christoph explains, "Our goal of this project is to give patients a sense of embodiment. They should feel that they have a type of extension of their own body. This gives them back some of their own motion. And even more important is that the patients appear on social networks – these handicapped patients – but just like anybody else" (G.tec 2012).

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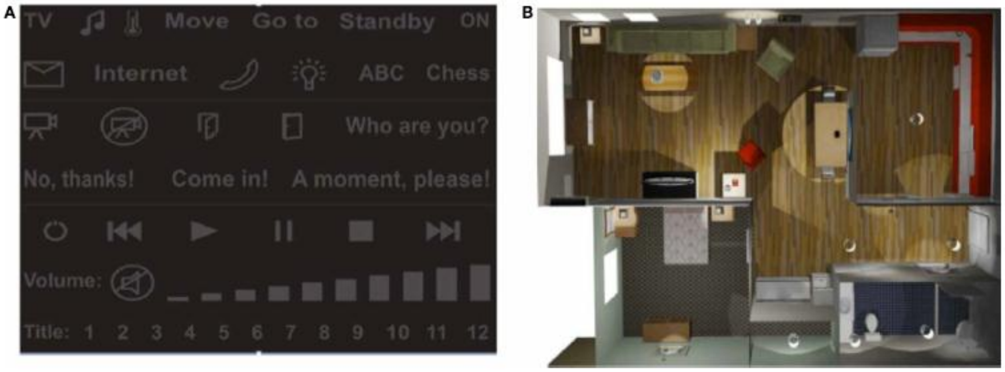
First, G-Tec tried having a user to interact with a smart home interface. Users could control the smart home environment with accuracy between 83 to 100%. This variation in accuracy depended on how many different commands were available for each new setting. When more options were available, it was easier to determine which option the subject was looking at because the likelihood of it being another character dropped. However, this greatly increased the time it took to determine the subject's choice **(**Edlinger 2009). This was a novel way to help improve the quality of life for a victim of a stroke who may not be able to interact or even communicate with the outside world. The P300 BCI system allows a patient the ability to perform normal tasks and move about a virtual environment simply by using his or her mind.



HOME SWEET HOME

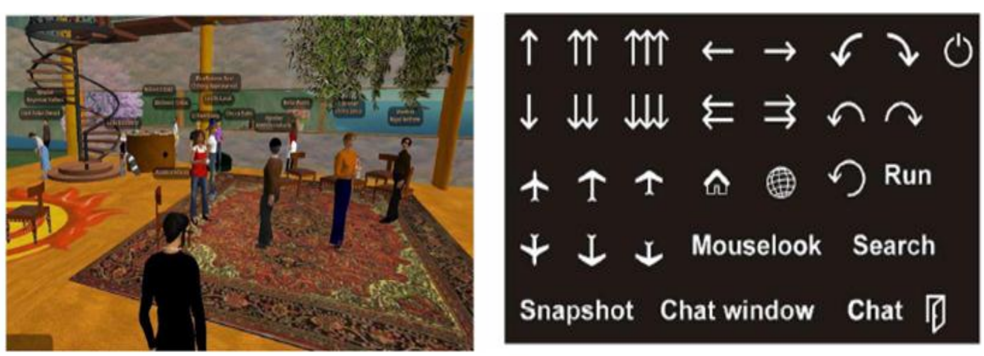
G-Tec adapted the interface of the P300 speller to allow a user to control various aspects of a smart home, shown on the right. The user could move to any part of the house simply by looking at a spot on the map of the house.

Guger Technologies used the developments it made with the smart home to launch a new Intendix application that was released this past year. This was called the Intendix SOCI, which stands for screen overlay control interface. The Intendix SOCI takes the ideas from virtual reality and expands them to a more familiar subject: videogames. Online activities such as posting tweets on Twitter and playing *Second Life* were experimented with using this P300 BCI. A similar approach was used as for the virtual reality interface, with a matrix of commands in used to control the character or type a tweet (Fazel-Rezai 2012). This would allow handicapped patients to interact with other people as they normally would, except in a virtual environment.

Twitter was one of the first applications looked at. Twitter involves sending messages that are limited to 140 characters and can be sent from any device with internet. Twitter allows for a means of communication to large numbers of people, so it can also be instrumental in improving the quality of life for handicapped people. Sending tweets with a P300 BCI uses essentially the same configuration as the P300 speller, with a few extra rows. However, only a single interface is needed to control all of the normal functions of Twitter, making it quite easy to tweet from a modified Intendix Speller. Using Twitter could allow handicapped patients to easily communicate with their family and friends.

Applying the Intendix to Twitter was a huge step towards increasing a handicapped patient's quality of life. However, Christoph and his team still wanted to be able to give handicapped patients back some of the motion they had lost too. Their idea was to apply the Intendix SOCI to videogames. The initial videogame that they focused on was *Second Life*, which involves controlling an avatar that can move around and interact with other users. Having a user control an avatar in *Second Life* is much more complicated than sending tweets. Because of this, Christoph and his team drew off of the smart home interface they had previously developed. They created a similar interface that included various movement commands so that the user could easily control the avatar. They also created a chat option so that the user could type whatever they wished to another character in the game.

Before releasing SOCI, G-Tec released a video showing how a user could control a character in *World of Warcraft*, a popular computer game. This used a few arrows and commands outside the playing screen that the subject could look at to control the character. The computer recognizes what the user wants the character to do in a matter of seconds. G-Tec has made SOCI much more accurate than its predecessors as well, with accuracy in correct detection up to 98%. This is quite an exciting development in P300 BCI systems and will likely influence where they go from here (Edlinger 2011).



GIVING HANDICAPPED PATIENTS A SECOND LIFE

Using a similar idea as the smart home, Christoph and his team adapted a P300 configuration for the online videogame *Second Life*. Icons in this matrix allowed the avatar to move around and talk with other people, enabling handicapped people to interact normally with other people.

P300 BCI systems have had many new exciting developments in recent years thanks to G-Tec. They provide a viable alternative to increasing the quality of life for handicapped patients suffering from a stroke, as well as assisting them in communicating. Had the Intendix been used at the hospital Richard Marsh was at after his massive stroke, the doctors could have quickly discovered that his brain was still fully functional.

"In the future, we will push this technology to be faster, more accurate, and easily available to get."

The Intendix is appealing because it requires a very short training time and seems to be the capstone for much of the previous research done with P300 BCI's. However, G-Tec continues to perform research in this area. Says Christoph, "In the future, we will push this technology to be faster, more accurate, and easily available to get" (G.tec 2012). With all of the strides G-Tec has made in recent years, it is hard to doubt him. It will be exciting to see what new developments G-Tec comes out with over the next few years. Perhaps in ten or twenty years, I won't have to move my fingers to type this article, but simply look at a screen.

FROM RESEARCH TO REALITY

The Intendix laptop was the first commercially available P300 speller. Newer versions can also run brain painting and SOCI applications.

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