

A FAIRLY SIMPLE INTRODUCTION TO HOW THE BRAIN WORKS WRITTEN FOR SURVIVORS OF HEAD INJURIES AND THEIR FAMILIES

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A. BACKGROUND

If you are going to take charge of your recovery, you need to know what needs to be fixed. If you need to understand your brain injury, it would help to have a basic understanding of how the brain is supposed to work. This paper is written to give you that understanding. As the director of several brain injury rehabilitation programs, I have taught several courses on how the brain works for therapists and nurses. As an instructor at the University of Central Florida, for several years I taught a course on the brain to psychology students. But this is not intended to be like a professional or college course. The same ideas can be explained in plain English.

The general public has a great deal of information about the brain, from health classes in school, and from the media. Unfortunately, most of it is based on ideas from the brain science of past centuries, and those ideas have fallen far behind what we know now. In fact, most of those ideas are now considered false and misleading. So as you prepare to learn about the brain, be prepared to discard some of your old ideas.

1. Old Ideas About the Brain

In this section, I will discuss how people have tried all through history to figure out how to brain works. The most popular idea has been that the brain is made up of separate parts, and each part performs a different behavior or behavioral ability. One part talks, another part remembers, another part sings, and so on. Although even the brain scientists of the 1800's came to believe in this idea, it turned out to be false and misleading. But the belief that the brain works that way is still with us. We were all taught to think about the brain that way in school, and we still see programs that express the same idea on the media today. It is difficult to stop thinking of the brain that way, but we need to do that if we are going to cope with brain injuries effectively.

Even before civilization, people knew that the brain is necessary to support life, and suspected or believed that the brain held the mind and the soul. People with brain wounds lost their abilities to sense the world around them, to make sense of things, to act, and to react in the way that they always had. So it was known that the self lives in the brain, and that a healthy brain is necessary to keep being yourself.

However, it was not clear how the brain managed to do all of these things. Until the 20th century, most people with brain wounds died either from the injury or the infection that followed it. The church forbade autopsies until after the Renaissance, so the few efforts to dissect the brain took place in secret. Moreover, the brain is a soft, gloppy organ much of which is made of fat. Just trying

to cut into it doesn't show you much about how it is put together. Science would not learn much about how the brain was built until chemicals were found that made the brain hard and traced out the pathways that brain cells take. This work only started to truly pay off in the 20th century. For most of human history, questions about how the brain worked had to be answered by philosophers, and their answers were nothing more than clever guesses.

The very first question that people asked could not be answered, and it hung up the whole business of figuring out how the brain worked. That question was, does the brain work as a whole, or is it like a machine, made up of parts that do different things? In the study of the body, it had been discovered that the intestines, the lungs, the bone marrow, and the skin work as a whole. If one part of those organs gets damaged, it has pretty much the same effect no matter where the damage takes place. What matters is how much of the organ gets damaged. On the other hand, an organ such as the heart or the eye works like a machine. Each part performs a particular function, and if a part gets damaged, the effects depend very much on which part it was. Since the science of anatomy said that body organs work one way or the other, it was assumed that we needed to know which way the brain worked, as a whole (a viewpoint called equipotentiality) or as a unit made up of different parts (called localizationism).

Any effort to closely watch people with brain disorders makes it obvious that some people have problems with particular parts of their body, and some people lose senses from that part of the body while others lose the ability to move it. Others lose a particular mental ability, like the power to speak or to remember. If brain disorders take out certain, specific brain functions, that suggests that the brain is like a machine. We have even found a three thousand year-old document from ancient Egypt that catalogues the different disorders and what part of the brain they come from. However, important philosophers in Greece, Rome, and Renaissance Europe argued for the brain working as a whole, so the whole thing was a huge mess until the 19th century.

By the early 1800's, physicians had begun to specialize, and brain doctors were starting to notice a very precise relationship between the locations of brain wounds or strokes and the symptoms they caused. In 1799, a powerful physician named Gall set forth a whole system that mapped out different functions for different brain areas. Gall believed that the bigger a brain area was, the more of that ability a person had. That idea is not far from the truth we know today, but unfortunately he took it one step further, and argued that the bumps on the skull indicate the brain areas that are biggest. He created the field of phrenology, which "tested" people's abilities by measuring the bumps on their heads. Even in the 1800's, this idea quickly fell out of favor and became ridiculed. Although few people believed in phrenology, it got people thinking about localizationism.

By the 1840's, a French doctor (Bouillaud) had determined that stroke victims who lose the ability to talk have damage found by autopsy in the front half of the brain. Another French doctor (Dax) found that the damage was located in the left half of the brain. By the 1860's, a third French doctor (Broca) found that the damage was located in a particular part of the front of the brain, almost always on the left side. And within a few years, a German doctor (Wernicke) found that most stroke patients who retain the ability to speak but lose the ability to understand language have damage in the back of the brain, on the left side. From this evidence, the medical and scientific communities decided that language was "located" in the left brain, and that more specific functions

of language could be located in different places as well. It was agreed by almost everyone that the localizatonists were correct.

Meanwhile, the brand new field of psychology was trying to figure out how the *mind* worked. The debates of philosophers about how the brain worked also spilled over into two ways of thinking about this problem. Perhaps the mind functions as a whole, or perhaps the mind is made up of many separate abilities. By the year 1800, it had become fashionable in philosophy to develop category systems for all of the abilities that made up the mind. That was how phrenology got started--by linking up parts of the brain with these different so-called abilities. The idea that each person has a set of abilities, each at a particular level, like bank accounts in different banks, and that the level of those abilities determines how well a person functions in life, was new to the world and gaining popularity. This idea was set in stone by Sir Francis Galton, the cousin of Charles Darwin. Galton wrote some very influential books in the mid-1800's that tried to convince people that mental abilities were lifetime assets you inherited from your family. Galton is the one who gave us the notion that there is a thing called general intelligence, a macro-ability of overall smartness by which people could be measured and ranked. Galton's ideas led directly to the development of I.Q. tests, which were first used to determine which French children were going to be ready to learn how to read when they went to school.

The general acceptance of Galton's ideas about mental abilities fused with the general acceptance of Broca's ideas about brain localization, to turn phrenology into the belief system of both mainstream science and the general public. It became obvious to *everyone* that the portfolio of abilities with which you were endowed, each one built into an area of your brain, determined your capabilities and thus your destiny as a human being. If you were intelligent, it was because you had received a good brain and kept it in good shape, and as long as you kept it up, you would always be smart, always better than most others in everything you did. People with these good brains became the leaders of the world, and ran things, while people with okay brains took orders from them, and people with bad brains got put in prisons, asylums, and poorhouses.

Almost from the time that these powerful ideas took root, some scientists began to discover that they were not accurate. Psychology would spend the end of the 19th and most of the 20th centuries trying to overturn these ideas. Yet most of us were brought up to think this way, and most of us think about ourselves and about others on the basis of these ideas of mental abilities that are located in the brain and set in cement.

What does localizationism have to say about people with brain injuries? To put it plainly, it says their life is toast. They have damaged the equipment people need to live. They have lost abilities, or in the term which has become popular in recent years, they have impairments. Impairments are supposed to make people unable to function, unable to meet the requirements and expectations of the jobs and roles of adult life (which is called disability). And since localizationism says that the damaged brain area is where the ability comes from, there is no logical or obvious way to fix it. Die-hard localizationists assume that nothing can be done to fix a damaged brain. If you have the damage, you must be disabled, and you always will. This is how our legal system works, in lawsuits about brain injuries, and in awarding disability benefits. If you have the damage, you have a diminished future, and the story ends there.

Although in polite society we try to avoid saying insulting things about people with impairments and disabilities, another logical consequence of localizationism is that if you damage those parts of the brain that produce intelligence, the brain damage will make you stupid. For example, a hundred years of careful statistical study of intelligence tests finds that they are related to scores on memory tests and attention tests, particularly the abilities to learn new information presented in words (also called recent verbal memory) and to make quick decisions (for example, when the ability being measured is divided attention). Our research provides plenty of evidence that people with head injuries earn lower scores on I.Q. tests, and particularly low scores on certain tests of memory and attention, even many years after the injury. Thus it is sometimes said that head injury reduces intelligence. Psychologists don't come right out and say that head injury makes you stupid, but that's what they mean. And if your "intelligence center" has been partly or completely destroyed by the injury, you are doomed to remain stupid forever, or so this theory says.

2. New Ideas About the Brain and Abilities

Even back in the 19th century, when localizationism came to power, there were some brain experts who did not agree with it. The guy who discovered the so-called center for language comprehension, Carl Wernicke, actually wrote (in German) that the brain must send signals from one part of the brain to another in order to process language--it can't possibly be done in one spot. The father of British neurology, John Hughlings Jackson, also said that thinking required a whole system of brain centers to work together. Jackson also argued that there are many different ways that the brain centers can connect, and that our abilities can result from many different combinations of brain areas. In particular, he complained about the view that there was only one way to be smart. Jackson said that the two halves of the brain each have their own, very different way of being smart, and that the kind of thinking that Galton and most of the neurologists of the day called intelligence probably was the less smart of the two. It took over one hundred years for brain scientists to prove that Jackson was correct--that a kind of intelligence based on seeing pictures in your mind is actually more important for real-life functioning than the intelligence based on language.

Jackson's idea that the brain has more than one way to skin a cat--that more than one arrangement of brain areas can perform a task--would later prove to be by far the best way to get a person to recover functioning after a brain injury. So this dispute about how the brain does things was more than just a pointless argument between scientists--it was an argument about whether brain recovery can really happen, and the Jackson side of the argument actually explained how to make recovery happen!

When psychology became an organized profession, the father of American psychology, William James, took Jackson's side. James pointed out that human abilities and real-life functions must be controlled not by a single brain center but rather by the whole *pathway* that connects many centers with one another. Real-life behaviors are always complicated--they always involve a whole bunch of brain functions. Take something as simple as eating a hot dog. We simply do not have a hot dog center in the brain, or for that matter, an eating center. There is a place in the brain that keeps track of your blood sugar level, and another that keeps track of how expanded or shrunken your stomach is at the moment. When those two centers fire off at the same time, they indicate that you need some food, which is indicated by a signal put out by a center that is connected by a pathway to the blood sugar and stomach-sensing centers. That signal travels down a pathway that

leads to another center where you feel hunger. That signal for hunger travels down a pathway that gets you pumped up with energy to do something about being hungry. The same signal also travels down a pathway that focuses attention on your sense of smell. The center that recognizes the smell of a hot dog sends a signal down a pathway that focuses attention on your sense of vision, and another signal that turns on the function of looking around, until you see a hot dog. Signals will have to get sent down other pathways to decide whether or not you are willing and able to eat a hot dog, whether you have the money to pay for one, whether the person you came with will mind if you get one, and then all of those signals will come together in a network that will make the decision about going for the dog. If you decide to go for it, a whole set of signals will be needed to call up the energy and operate the muscles and balance organs to get you up out of your seat, to walk over to the vendor, to ask for the dog, to pay for it, to put on the condiments, and to take it back to your seat. Eating solid food requires an intricate dance of signals in many centers so that you chew first, then swallow, and don't choke. Signals to a number of centers are needed to make sure you don't spill mustard on your new chinos. And all through this series of actions, your sleep-wake center is busy making sure you don't go to sleep with a hot dog sticking out of your mouth. By now, you have lit up almost every part of your brain, and this is just to eat a hot dog.

James never went into detail about how extensive the pathways for real-life actions are, but Canadian psychologist Donald Hebb and Russian psychologist and neurologist Alexander Luria both talked at length about this in the mid-1950's. Hebb said that our sensations, actions, and memories always involve a "cell assembly"--the pathway that extends from one brain center to another to another. Hebb argued that learning builds those pathways, and then repeated use deepens them, just like the canals down which boats travel. Luria went even further, explaining that every practical activity we perform requires us to use three different *sets* of pathways, or what Luria called functional systems.

The 1980's saw the beginning of an explosion of brain science, and the cutting-edge scientists of that time began to study mainly the pathways, which they began to refer to as "networks." There was a similar explosion of scientific study of thinking in psychology, and it, too, was using the concept of networks. Today, the ideas of localizationism have been set aside by modern neuroscience. We no longer think in terms of specific areas of the brain that perform specific tasks, and it is now generally understood that therapy can teach a brain-injury survivor ways to "wire around" a damaged area by finding or creating other pathways that can get the same behavior done. However, this also means that when you learn about the brain, you have to learn both about what the brain centers do, and about what the main networks are. And that is where we are going in this paper.

There is one more issue that you need to be aware of. In the 20th century, psychology sharply questioned the belief that abilities are unchanging, simple properties that a person takes into every situation and uses the same way every time. Instead, it was argued that when we do something by old habit, we may do it the same way every time. However, we are equipped to stop and think about how we are going to do something, and when the need exists, we can decide to do it many different ways. Some of these ways can make us more effective than we usually are, while others can make us less effective. So it's really too simple to say that a person has a certain *level* of smarts or mechanical ability or musical ability or any other kind of ability. How well a person performs *depends*, and the person has the option to do things much better than they normally do

them if they see the need. Consequently, in some situations, we may be at our best because we are careful to use our best approaches, while in others we may seem dumb and dense and totally lacking in talent--maybe because we don't care, or maybe because we believe we can't win in that situation, or maybe because our priorities are somewhere else. Abilities are not simple things--they vary from situation to situation, and they are *dynamic* (in other words, we can change them at will by making different choices).

The rejection of old school ideas about abilities was loudest when it came to the idea of intelligence. Modern scholars now echo Hughlings Jackson by talking about many different forms of intelligence. Modern research also shows that people look smart in some situations that interest, excite, stimulate, and encourage them, and dumb in others that bore, frighten, or oppress them. Many modern scholars believe that the most useful part of the old concept of intelligence is the ability to adapt. We agree that being able to adapt is important. But I.Q. also involves a number of other mental abilities that are not related to the ability to adapt. For example, one of the single abilities most closely related to the total I.Q. score is the size of a person's vocabulary. Other scores that are related reflect the person's storehouse of knowledge. In traumatic brain injury (TBI), vocabulary is usually unaffected by the injury, as is the storehouse of knowledge. So most survivors have not lost their "intelligence." It would certainly be inaccurate to call them dumb. Dumbness has nothing to do with the effects of a head injury. It is only because we have rethought what intelligence means that we have a basis for realizing these things.

Our new ideas about the brain and about abilities make it clear that the individual person can have a great deal of control over how well they function, even after a head injury. A person can offset the symptoms of the injury by using carefully chosen strategies for performing behaviors. It is also possible to improve the quality of behavior simply by making more effort, and by relying on your strengths while avoiding reliance on your weaknesses. Since most head injuries leave most of the brain intact, it should be possible to do almost anything well if enough effort is put into figuring out the best way to do it.

B. BRAIN CENTERS AND HOW THEY WORK

The evolution of the brain has built new layers on top of older layers, one after another. So as you move up the brain, from the lower end where it connects to the spinal cord, you move from abilities that primitive creatures have to abilities that only the more advanced creatures have.

1, The Brainstem: the Work Stations at the Very Bottom of the Brain

Even the lowest of animals with a brain (worms and fish) have certain brain functions. The brain reacts to the organism's senses, it moves, and it gets more active or less active, depending on the circumstances. Each of these functions can be found in a center at the bottom of the brain. There is a center for controlling and coordinating movement. There is a center for controlling mental energy or arousal. And each sensory mode has a center that processes the incoming information.

The center for controlling arousal has been dubbed the reticular activating system. That is because the control box at the bottom of the brain, in the brain stem, is connected to a network that is shaped like a net (that's what reticulated means) that extends up to all of the higher levels of the

brain. The center at the bottom sends out signals that wake a creature up, that energize a network so that it can be used to do something, and that put the creature to sleep. Along with those signals, the center is connected to chemical factories in the bottom of the brain that pump brain chemicals up to the higher centers. Those are the chemicals the brain uses to talk to itself, to focus attention, and to do things. So the reticular system totally controls everything, in the sense that the energy and the chemicals it provides are necessary for any kind of brain activity. If the reticular system gets damaged, the person goes into a coma.

The reticular system is a two-way network. When thinking goes on, in the top of the brain, the higher centers send signals down to the brainstem calling for more energy. It's just like a conversation between the captain of the ship and the engine room, or between the engineer of a steam train and the guy who stokes the engine with pieces of wood. The more thinking a network does, the more energy it calls down for. And thinking can take place only if that energy is sent back up. The thinking systems of the brain are very touchy and very needy. When they become active, they immediately need extra blood for the oxygen and the nutrients, as well as extra energy from below. Unless they get them within seconds, thinking begins to shut down. So we cannot do anything that takes more than a few seconds unless the reticular system is communicating properly with the higher centers and working well to supply the moment-to-moment needs.

One of the things a head injury does is to break some of the long, slender communication lines from the bottom of the brain to the top and from the top to the bottom. This makes thinking sluggish, dull, and easily overcome by fatigue. It requires the survivor to focus extra hard to get pumped up before doing something, so that there will be enough energy and chemicals to power the action. It requires doing things with extra effort so that the actions don't become too weak. It requires intensely focusing the mind, so that there will be enough energy to allow making decisions during the task. And it requires being careful to take rest breaks and to get enough sleep, and to avoid doing things the hard way, so that the limited energy supplies don't get used up too soon.

The bottom of the brain operates the gateway through which the mind opens up to pay attention to the things that happen. This is an automatic, simple-minded reflex that turns your attention to anything that suddenly appears and is large enough or moving fast enough to warrant notice. When the brainstem is damaged, things that come into view and unexpected sounds may not be noticed.

The bottom of the brain also operates some of the circuits that control the movement of muscles of the head and body, including the muscles used for swallowing, speaking, and breathing. Brainstem injuries are often physically disabling or obvious to others because they can produce a kind of spasticity in these muscles that makes the face look strange, the voice sound strange, or the limbs act strange.

Finally, a work station in the bottom of the brain controls your breathing and other life-support activities. Major damage here is deadly. Minor damage produces a problem called sleep apnea, where you stop breathing in the middle of the night, and then start again so suddenly that it wakes you up. Severe apnea can leave you exhausted after a night of sleep, or even damage the brain further. It is not something to mess with--you need to get checked by a sleep specialist if you think you have it.

2. Separate Half-Brain Systems to Process Input and Output

Throughout the entire nervous system, the front part is dedicated to the control of output, while the rear is dedicated to input. Output includes movement, and also includes preparing to move and deliberately focusing attention. Input refers to taking in sensations and making sense out of them, as well as listening to one's own thoughts and monitoring feelings and other reactions.

Just to make things more confusing, the process of output always involves some input circuits, just as the process of input always involves some output circuits. When we prepare to move, we have to notice what position that part of the body begins in, and we have to read feedback about how it is moving and what it bumps into in order to control it properly. And similarly, when we read input, we do it not only by taking in signals, but by guessing what the input might be (an output operation called feed-forward). So output and input circuits are not completely separated from one another but tend to work together. Nevertheless, output processing mainly involves the front half of the nervous system, while input processing mainly involves the back half.

Just to make sure this is clear, here are some examples. In language, listening and reading are input operations while speaking and writing are output operations. In music, listening is input while playing, humming, singing, and dancing are all output. When you get hungry, the smell of the food is the input, and getting and eating it is the output.

3. The Levels of Perception

When the mind perceives something out in the world, like a hot dog in a bun, it does not actually make contact with the object at all. Instead, the senses produce a stream of information into the brain, and the brain makes a copy of the hot dog inside the mind. So perception, which involves making sense out of input, is a process of building up pictures of the world inside the head. Our mind doesn't actually make contact with the hot dog out in the world; instead, we see the copy that our mind made.

For the last 50 years, most brain scientists have believed that our senses give us streams of tiny details and our minds build those details up into larger patterns. The senses send us data about colors and contours and textures, and we put all of those tiny pieces together into a picture of a hut. The sense send us data about loudness and pitch and timbre, and a different part of the brain puts that together to make the roaring of a lion. Our body senses send us a stream of information about pressure and temperature and pain, and a different part of the brain puts it together to give us the feeling of hot sun on our skin. Then still another part of the brain puts the perceptions from all three of the senses together, and we recognize a scene on the edge of a village in the African jungle. These are networks that relay the input information from one level of perception to another, until the final work station gives us the big picture.

The work stations that process vision are found in the back of the brain. The stations that process sound are found directly beneath the ears, on the sides of the brain. The stations that process body feelings are found on the top of the brain, at the far front end of the back half. Right in the

middle of the three zones is the final work station that puts together the big picture. That analysis accounts for the processing of the top of the input brain.

Directly beneath our fancy input brain, there is a smaller and simpler set of circuits that do the same thing, but they work quickly and they don't tell us much about the world. This second set of circuits can tell the difference between things that look dangerous, things that look interesting, and things that don't appear to be of much use one way or the other. Because it is so simple, this system processes much more quickly than the system above it, so we depend on it to give us an early warning of things that are dangerous. When you first see a snake moving in the bushes, you react right away with a sense of danger and an urge to get away from it. That reaction is processed by the second system. It doesn't tell you what kind of snake it is--just that it looks snakey and maybe you ought to move back until you know exactly what it is.

Head injuries tend to affect certain work stations in the input system. The work stations for processing vision are very well protected, and they rarely get seriously damaged. The systems for body perception are located in an area where damage from car accidents and falls is rare. However, the circuits that process memory are in a place that is very easy to injure. Many survivors have trouble from focal damage to this part of the brain, usually in the form of being oversensitive to noises, but also sometimes in the form of having difficulty understanding what people are saying. Finally, the work station for getting the big picture is big and located in a place that can get injured. If it gets injured, there are many serious problems, an issue we will discuss further later on.

4. A Center for Controlling Learning and Memory

Deep in the temporal lobes, beneath the area for processing sounds, lies a very old part of the brain called the hippocampus. It is shaped kind of like a praying mantis with its legs folded back to form a complete circuit with the body. Whenever there is perception of new information, the hippocampus organizes the deepening of those connections, which is how memories are made. If the perceived information leads to a reward or an emotional reaction, the connection is grooved even deeper, as we tend to remember best those things that have a payoff or a personal meaning.

There is a hippocampus on each side of the head. In most people, the left hippocampus is involved in learning information from reading, spoken instruction, and conversation, and in learning to refine well-established habits. The hippocampus on the right side is involved in learning what things look and feel like and where they are found, in learning about people, and in learning brand new skills and settings.

Each hippocampus is very delicate. They sit inside a boxy part of the skull on the side of the head, which makes them both easy to damage when the head is struck on either side. The communication pathways are relatively long and slender, which makes them susceptible to damage in any kind of accident that involves a lot of force. They are filled with a brain chemical (glutamate) that is very toxic, so that if one brain cell gets torn open it tends to kill those around it. So most head injuries produce problems with learning new memories.

When a hippocampus is damaged by an injury, it usually keeps working, but it can process less information than it could before, and it makes weaker memories that the person is less certain

to remember. The practical effect of damage to these centers is to create special problems when large amounts of material must be learned in one sitting, as when reading, taking classes, or going through job orientation and training. By making weaker and less reliable memories, damage to these centers also leaves a person very vulnerable to head-injured moments that involve forgetting or mis-remembering important information at crucial times.

There is a set of strategies that can pump up hippocampus function, and we teach students in high school, college, or graduate school to use these. First, you learn more if you study smaller amounts of information, so we recommend that students learn to underline their notes and books so that they are only studying the important information. Second, the hippocampus grooves memories deeper if you make the information feel important, so we recommend the strategy of "deep processing" (which means thinking about how new information is important, and thinking about how it relates to things you already know, and *reacting* to it emotionally). Third, you punch memories in by getting rewarded, so we recommend testing yourself on the material through flash cards. Each time you get it right, the pleasure of nailing it stamps that piece of information in deeper. It is a good idea to start studying as soon as you get the information, so you don't have to learn too much in any one day. As exam time draws near, you use your flash cards to focus your studying only on the information you haven't already learned. This method can take a hippocampus that is seriously injured and pump it up enough to get A's in college or grad school. However, it takes hours and hours of homework to use this method, making it necessary for most students to take a small number of classes each term.

Damage to the hippocampi (the term for more than one hippocampus) is unlike damage to most other brain systems. It doesn't have any easy "work around" options. In other words, there is no other network that can commit information to memory. This is why head injury experts advise their patients who are not in school to stop relying on mental memory and instead develop the habit of committing all important information to written notes. A well-developed system of note writing and note-filing can almost completely take the place of the defective memory systems.

There are other memory systems that have nothing to do with the hippocampus. Remembering how to do something (which is called procedural memory) operates through a network deep in the brain which is almost never damaged by TBI. For this reason, even survivors who have a great deal of difficulty remembering new information generally have no problem remembering all of their skills. Accessing stored knowledge also involves a robust network that is rarely destroyed by TBI. For this reason, survivors who cannot remember what they did yesterday have no difficulty remembering what they did on their first date, or their first prom night, or their first job, even if it was many years ago. TBI selectively disrupts new learning.

Keep in mind that memory is not stored *in* the hippocampi. They just keep it organized. The actual memories are stored in networks all through the brain.

5. A Center for Creating, Projecting, and Controlling Emotions

Just down the street from the hippocampi are two other, ancient brain centers called the amygdalas. Shaped like almonds, these little do-dads are extremely powerful broadcasting stations sending out the signals that carry the emotions all over the brain. When you become extremely

emotional, amygdala signals zap your entire brain. That is where one of the main forms of brain overload comes from. Emotions are like Hulk Hogan or The Rock. They make your brain stop what it's doing and *pay attention*. One of the main things that the right amygdala does is to sound the warning for danger. If a lion or a mugger is following you, the hippocampus recognizes that this is has been a danger situation in the past, and it tells the amygdala to zap the rest of the brain and make it get the heck out of there. If you are about to do something stupid, the amygdala blasts you with a warning to stop. If you are about to miss an opportunity to do something good, the left amygdala blasts you and gets you to re-think your priorities. If you need to get pumped up to deal with a big problem or challenge, the amygdala helps with that, too. Finally, if you have what seems like a good idea right now, but it's something that backfired on you some time in the past, your hippocampus reviews your past history and tells your amygdala to stop you from doing it. So when it's working properly, your emotional system helps you to think, forces you to make better decisions, and energizes the actions that need it.

Depending on the kind of brain injury, the emotional system can get messed up in three different ways. First of all, a mini-network covers each amygdala like donut around jelly filling. The purpose of this network is to limit or turn down emotions if they become too intense. These circuits sit up against the skull in a place that is very easily injured to some extent in almost any head trauma, and seriously injured when the head gets hit on either side. So damage here reduces emotional control. Emotions tend to run away with behavior, which can produce all kinds of problems getting along with people and following the rules of social life. This is a very common problem in people with severe head injuries.

Second, severe injury to the side of the head can damage the mini-network enough that emotions become super-intense. Anything that creates emotion is painfully confusing and totally disorienting. It becomes difficult to function at all when emotions are aroused. Only those with temporal lobe contusions (major bruises on the brain) or injuries that penetrate the skull and damage brain tissue directly tend to get these symptoms. However, occasionally, patients with severe damage from a closed head injury in this area develop a special kind of seizures (complex partial seizures) that cause sudden, painfully intense emotional reactions occasionally.

Third, there are certain extreme injuries that dramatically reduce the output of one amygdala in comparison with the other one. This produces an imbalance of emotions. For example, when the left amygdala sustains this damage, the dominant moods are irritable, angry, discouraged, frustrated, and/or sad. When the right amygdala sustains the damage, the dominant moods are enthusiastic, excited, joyful, and/or contented. This probably sounds like an advertisement for damage to the right amygdala, but in fact the injury leaves the person unable to be realistically concerned about problems, dangers, and personal flaws, including the symptoms of the injury. People with damage here tend to have less successful recoveries.

It is important to remember that emotions do not come from the amygdala, nor are they felt in the amygdala. The perceptions that give rise to emotion come from the perceptual network, and from the network in the brainstem that monitors the satisfaction of basic biological needs. The amygdala triggers and broadcasts the emotional signals, and they are then felt in parts of the perceptual system. So any damage along these pathways will produce emotional symptoms.

6. A Center for Organizing Familiar Actions

Recently, many people have bought into the theory that most of the things people do are done by automatic reactions. It really isn't necessary to do much planning in order to do something that is part of our familiar routines, even when it is complicated. Most people who have been working at a job for several years will tell you that they usually do it "on automatic pilot" even if it is brain surgery or rocket science. Our daily chores, our routines of activity in the community, and our ways of handling the common problems of daily life, are all so well learned that they can be done without much heavy thinking. It is generally believed that these automatic actions are sent through a network deep in the brain. The processing stations that determine which actions are to be performed now and which ones later, in what sequence, are called the basal ganglia.

Because they are deep in the brain, they are rarely damaged by head trauma. If they do get damaged, the sequencing of behaviors goes awry. One symptom of this kind of damage is the tendency to keep doing something over and over again for no good reason. Another involves the interruption of purposeful actions by actions that serve absolutely no purpose. For example, patients with Tourette's syndrome interrupt the things they are doing with curses, peculiar sounds, and twitchy movements.

Since this center rarely sustains serious damage, familiar actions can usually be executed with no special difficulty. Since most survivors remember how to perform the familiar sequences and they can perform them correctly, they experience little difficulty in using their established skills. The most common problem in using old skills is slow execution, which is caused by minor damage to the transmission lines that connect the input to the output control centers, and the output control centers to the spinal cord. The amount of minor damage, which affects all of the networks to some extent, is determined by the strength of the forces that were applied to the brain. The amount of force is related to the speeds involved in an auto accident or the height from which a person falls. It is also reflected in the length of coma, which is the most important diagnostic measure in TBI. The second problem in using old skills is that the minor damage weakens the perceptual system just enough so that it can overlook the events and signals that tell us when to start a skill sequence. For example, if a survivor knew how to play outfield in softball, knowing how to do it won't be a problem after the injury. But when someone hits a fly ball in the survivor's direction, he/she may get a late start because of reacting slowly to the hit and taking longer to judge where the ball is going. Slow responding may be a big enough problem to make someone unsafe driving a car. Overlooking signals may cause someone to make enough mistakes that their job knowledge or computer know-how is no longer effective. So these problems, which interfere with the use of familiar skills, become targets in rehabilitation or self-therapy.

7. A Center For Taking Willful Control of Special Situations

As important as familiar, automatically executed habits are in our lifestyle, people are not robots, and they don't just do things on automatic pilot no matter what happens. Sometimes, the automatic response that is based on an old habit turns out to be dangerous, because of some factor we didn't expect. For example, driving down to the local mini-mart becomes an old habit, but if the road you take suddenly develops a pot-hole, you had better shut off your automatic pilot and react fast if you want to avoid blowing out a tire. There is a system set on top of the basal ganglia, the

anterior cingulate cortex, that helps you to recognize these special situations quickly, and allows the will and emotions to take control of thoughts and actions. This part of your brain is extremely important in getting you to notice things and to stop doing things that are going to work out badly.

The work station itself is set in a place that is well protected from injury, so damage here is not a major issue in TBI. However, the anterior cingulate does its work through a network, the executive network, and the whole network is extremely easy to damage in TBI. We will have more to say about that network, and the other major networks, in a later section.

8. A Command Center to Organize, Oversee, and Correct Actions

The largest part of the human brain is the frontal lobes. It contains between one-third and one-half of the brain cells. It has grown bigger during the progression from monkeys to apes to man, and humans have the biggest frontal lobes for body size in the natural kingdom. The frontal lobes do many things. The circuits in the back organize and help to control the movement of muscles. As you move forward, the circuits take a larger role in planning actions, and even in figuring out new ways to do things. The circuits above the eyes play a special role in deciding to make you stop doing something, thinking about something, or feeling something. The frontal lobes are the central communication station for the brain. Almost all of the important networks end up here. Almost anything you do that requires organizing widespread brain activities depends on the supervision provided by the frontal lobes. When you decide to do something not by old habit but through thinking, this is where the decision gets made and where it starts to be put into effect. The frontal lobes play a crucial role in self-control. They play an equally important role in preventing and correcting errors.

Because the huge frontal lobes of a human being are such a new design, the skull has not yet evolved to provide the protection they need. The inside of the skull in front is rough, with ridges of bone jutting back toward the brain. When the head is hit hard, the brain gets speared on these bony points and the brain is damaged in those areas. This not only happens from a blow in front, but even from a blow in the back of the head. More zones of concentrated damage are found here than in any other part of the brain. It is difficult to estimate how many people have long-term problems due to a large contusion of the frontal lobes, but a rough figure of one-third of car accident survivors is probably reasonable. That number is just the people with damage to the work stations of the frontal lobe. If you include people with damage to the main networks that are connected to the frontal lobes, it appears that every coma-producing auto accident and most head injuries of any kind involve frontal lobe symptoms.

The nature of these symptoms depends on the amount of damage. Very large zones of damage toward the sides can leave the survivor disengaged from the world, silent and passive and non-reactive. Very large zones of damage above the eyes can result in a complete loss of self-control, a tendency to react to everything in a crude and impulsive way. Most head injuries do less damage, and their effects tend to be seen only in the situations in which old habits don't work and the brain is supposed to hatch a new plan. The frontal networks either fail to take charge, or they do so without thinking through the actions they plan out. The result is a head-injured moment--a sudden breakdown in behavior that results in a missed opportunity, an error, an action with unfortunate side-effects that were not considered, or an action that is not executed carefully enough

to meet the standards of the situation. This is the most common and most important symptom of TBI, and I will have more to say about it below.

9. An Output Control Station to Smooth Out Movements and Maintain Balance

Once the decision is made to make a skilled movement, the various muscles and sensory organs need an almost unimaginable amount of coordination for every step. The cerebellum, a work station that sticks out of the back of the brain, performs a number of functions that help with this coordination. Most obviously, the cerebellum is the organ of balance. Your body needs to be steadily anchored in place if your movements are going to be properly forceful and accurate. The cerebellum also appears to contain the programs that spell out how specific movements are made, because it smoothes out the shifts from one muscle contraction to another. In a more general sense, it seems to help organize actions.

The cerebellum is protected from impact injuries, but not from high-speed collisions. A high-speed collision sends a wave of force moving through the brain like a tsunami or a tidal wave moves through the ocean. As this wave of force goes through the gloppy, gelatin-like substance of the brain, it pulls apart the brain tissue that is found in chunks, like the hippocampus. The cerebellum is made up of two huge chunks, with a slender body connecting them, very much like a butterfly has two huge wings attached to a tiny body. The waves of force tend to tear the chunks apart where they join the body (called the vermis). These tears interrupt the network inside the cerebellum that coordinates the left side of the body with the right side. As a result, it becomes very difficult for survivors of high-impact injuries to keep their balance. They tend to tip over to the side, or to fall when they move their weight forward onto one foot while walking. Over months of recovery, they learn to make an adjustment, compensating by using their eyes to tell them when they are leaning off-center. This adjustment tends to be okay for walking on even surfaces, but it is still difficult to walk on a pitching boat or a moving bus, or to walk on uneven surfaces. The easiest way to see how badly the cerebellum was hurt is to test walking in the dark. People with a factory-fresh cerebellum may walk into things, but they don't lose their balance and fall over on the open floor. People with cerebellar damage do lose their balance in the dark.. (Warning--don't try this by yourself. One injury is enough.)

B. BRAIN NETWORKS

1. The Emergency Network

The brain is equipped with a special-purpose network that handles emergencies. It connects the perceptual system of the right half to the energy system in the bottom of the brain and the emotion broadcaster. When you are about to step off a cliff, or pick up a poisonous spider, or turn a corner to find an angry husband training a shotgun on you, this system sets off an alarm that pulls your attention away from whatever you are doing. The emergency network triggers the simplest response that gets you out of danger, and it is acted on, even before you have time to think about what you are doing. This system only works with things that are well known to be dangerous, but it is capable of learning. We are born to alert the emergency system in response to deep drop-offs in the ground and certain animals. We learn that certain people, or classes of people, and certain places and things are dangerous to us during the course of life. These things we experience as dangerous

can trigger the emergency system. They are highly individualized. Something that sets off my emergency system may not set yours off.

This system is usually intact after a head injury. It may be sluggish when you don't pay attention to something dangerous, but as soon as you do notice it, the system will work as it is supposed to function. The main exception is when there is a focal, right parietal injury. These injuries, if they are large enough, can still the emergency network entirely, and leave people without an early warning system when they face dangers. Injuries of this kind often produce disability because they not only affect emergency reactions, but safety judgment generally. These survivors may need to be distantly supervised in order to remain safe. But most survivors still have a fully operative emergency network.

2. The Automatic Pilot

As we have already discussed, automatic behaviors are controlled by a network that extends from the perceptual system's central work station (which is found where the parietal, occipital, and temporal lobes join one another on the side of the head behind and below the ear) to the basal ganglia toward the front of the head. This system is very robust and rarely stops working after a head injury. It is deep in the brain, and there is a system on both sides, so even an injury with focal damage rarely disables this system. This system's resistance to injury explains why old skills and habits are retained after an injury.

3. The Language Information Processing System

As Wernicke pointed out, functional language requires the output circuits that support speech and writing to interact with the input circuits that support understanding speech and reading. The key circuits for these systems are usually found in the left brain. Through this network, we can think about our ideas, study on what we are going to say before we say it, take new ideas and put them into our own words, and perform other essential tasks that help us to make sense. The interconnections between the work stations are heavy, short cables that are not easily damaged. The work stations themselves are close enough to the surface of the brain that they can get damaged if there is a focal injury. Thus patients with injuries to the temporal and parietal lobes often have trouble understanding speech, while those with injuries to the frontal and temporal lobes often have trouble putting their ideas into words and/or getting the words into the proper sequence. Fortunately, these systems are large and seem to have some duplicated circuits, so in most cases of TBI in which there are language problems, those problems tend to recovery fairly well over time. However, damage to the language system can produce disability for students and for adults who work in jobs that require strong language skills.

4. The Nonverbal Information Processing System or Systems

The right brain has a similar set of circuits, but it has taken years to figure out what these circuits do, and there is still some disagreement about it. Current brain scientists believe that the right brain has special circuits for processing emotional language (as expressed by tone of voice, facial expression, gestures, and body language) and other kinds of emotional ideas. This system seems to be responsible for our self-concept. That makes a lot of sense, since the self-concept is the

set of ideas distinguished by how subjective and emotionally loaded it is. So this is the system through which we see ourselves, change our views of ourselves as we change in our actual capabilities and behavior, and through which we express our individuality and our most cherished beliefs. Some scientists also think that this system handles information about people, while others believe that our people-processing circuits run next to this system in a network all to themselves. In any event, this network is massively important to adaptation, managing our people skills, our common sense, our recognition of our capabilities and limitations, and our capacity to be true to ourselves.

Like the language system, this system only tends to get damaged if there is focal damage to the right temporal/parietal area or frontal/temporal area. However, when it does get damaged, it serves as a "recovery killer." People who have damage to this system become totally locked in to seeing themselves as they were before the injury. More than the typical survivor, they can see no point in trying to make any effort to recover. They tend to completely trust their damaged adaptive systems, and that trust is not altered by thousands of head-injured moments and extremely serious damage to their lifestyle. While people with this injury have not proven to be hopeless in rehabilitation, there are very few good recoveries, and those who are able to achieve them must be unusually dedicated to working on themselves.

5. The Emotional and Memory Influence Networks

The command and control station is connected to the memory organizer and the emotion broadcaster by a single set of cables. It is possible for this interconnecting pathway to get damaged by the forces of an unusually powerful head injury. If that happens, planning actions in a critical situation ceases to be influenced by emotions or by the lessons of the past. This gives behavior a kind of impulsive and automatic quality. That quality is celebrated in the old joke about the seafood diet: "I'm on a seafood diet. Anything I see I eat." Behavior is particularly likely to get "captured" by things that go on in the outside world. If something is desirable, the person goes for it, regardless of the consequences. This can produce all sorts of embarrassing moments, and can be annoying or infuriating or even frightening to other people. For example, survivors with this kind of injury can be highly inappropriate sexually, hitting on people who are clearly not interested in situations in which sexual come-on behavior is out of the question. It is as if the person inside has lost control, and the world outside has taken control.

Because there are two emotional systems, one specialized for positive emotions and the other for negative emotions, damage to one of the networks produces very different (and often opposite) effects than damage to the other one. For example, when the right amygdala is damaged by a massive focal temporal lobe injury, fear loses its anticipatory and protective functions. The survivor rushes into situations of danger feeling no hesitation. When the left amygdala is damaged, optimism loses its energizing function. The survivor feels like giving up or avoiding challenging situations with minimal provocation. However, this is not quite so cut-and-dried. When the right brain has a moderate focal injury, the amygdala may remain intact, but the circuits that control it and turn it down may be incapacitated. That means that fear and anger may erupt and seize control of behavior out of proportion to any real need. When the left brain has a moderate focal injury, enthusiasm may become overwhelming or give rise to easy irritability. In all four instances, the net

result is that a certain emotion tends to run away with behavior, pulling the person toward actions that are not appropriate or advantageous.

Damage to these networks also makes the search for a memory more difficult, and easier to abandon before the memory has been found. People who have this injury often profit from taking extra time to search for memories, as the circuits are often partially intact and can eventually get the job done if the person remains patient.

6. The Control Network

There are five work stations that help to control thoughts and actions, the basal ganglia for automatic actions, the anterior cingulate for willful switching, the dorsolateral prefrontal area (on the sides) for planning, the orbitofrontal area (over the eyes) for stopping thoughts and actions and for processing internal needs, and an area we have not discussed called the supplementary motor area, behind the dorsolateral prefrontal area. These five work stations are all linked, and they form a network that gives people the power to make themselves do anything they decide to do. Everyone has seen how this network works--when a policeman or firefighter rushes into a collapsing building, when a parent takes deadly risks to save the life of his/her child, when a hero ignores wounds and ridiculous odds of survival to perform acts of valor, and when contestants on a popular game show eat tanks full of worms or spiders for huge cash prizes and national bragging rights. No other creature on earth has a control network anything like as powerful as this one, and no other creature is capable of forcing itself to do so many things that work against survival.

The control network is usually damaged by TBI. Consequently, enforcing decisions and carrying out plans takes extra mental effort. Occasionally, frontal focal injuries are large enough to ruin this network, and the resulting behavior is totally uncontrolled. But such an injury is very rare.

The control network plays an essential function in recovery. As patients with head injury get better, they teach themselves to amp up this network, so that it puts out enough control to pilot the damaged central nervous system. Almost any symptom requires extra control to be overcome. However, patients who have relatively poor recoveries pump up this network less than those who have good recoveries. My patients who have had exceptional recoveries tell me that they must crank up their mental effort all the way to the maximum setting in order to perform complicated tasks without having head-injured moments. So it appears that this network is the key to good recovery. While we all know how to give maximum mental effort when we are full of emotion and feeling extremely aroused, it seems to take a lot of practice to learn how to turn on this network by simply deciding that it is needed. That is some of the most important work of self-therapy.

7. The Problem-Solving Network

This network connects the planning center of the frontal lobes with the perception center of the back of the brain. This is the system that works plans out. It is the system that takes your behavior off of automatic pilot, works out what to do, and then makes sure you do it properly. This is the system that anticipates how your actions are going to work out. This is also the system that notices when things don't work out the way they are supposed to, and realizes that you can't do all

of the things you thought you could do. This is the system that keeps your self-concept realistic. In many ways, this is the most important network in the brain.

Here is an example of how this network cycles through a possible plan of action, adjusting it based on how it is expected to work. Imagine that you are a teenager who has an argument with your parents about buying a one thousand dollar leather jacket. Your parents put their feet down and forbid you from buying it. You are enraged and want to get away from them. The planning center in the front of your brain comes up with the idea of running away from home. It relays that goal and that plan to the perception center, where your mind imagines how that plan would work. You picture yourself walking down the street in the rain, and realize that you have no car. The perception work station rejects that plan based on the outcome, and asks for a new one. The planning work station comes up with the idea of stealing your father's car. This gets sent back to the perception center for review. The perception center shows you a picture of you being arrested by a police cruiser, followed by a picture of you sitting in jail. The perception center rejects this plan and sends back for another one. This time, your planning center comes up with the idea of hitch-hiking. But your perception center shows you being molested by a pervert. The planning center suggests the plan of calling your girlfriend, but the picture you get is of you trying to sit on the handlebars of her bike as she pedals toward her home. None of these plans is acceptable, so the front of your brain changes the goal to getting back at your parents. You imagine calling them "old farts" and then stamping off to your room and slamming the door. Your perceptual center pictures your parents letting you get away with that, and your dad getting irritated when he hears the door slam. That is acceptable, so your perceptual center tells your command network to go ahead and execute that plan, and you do it. This planning process cycles at a rate of ten plans proposed and checked out per second. So the whole thought process described in this paragraph could be completed in less than a second.

Unfortunately, this network is damaged very easily by head trauma. The work stations are far apart, and the lines that connect them are long and thick. As such, they get torn apart more easily by waves of force than any other brain cells. And this network is very touchy about the accuracy of the information. Any time it gets too much garbage in the lines, it shuts down. After a head injury, the signals all have too much garbage in them, and this network just stops doing its job. Worse than that, whenever it shuts down due to garbage in the lines, it sends out the "all clear" signal that means everything is going perfectly. This is why survivors feel so sure that they are not making mistakes, so sure that they are making good decisions, so sure that they are thinking well, and so disinterested in doing things to repair their deteriorating lifestyles.

When the problem-solving network goes offline, every action is run on automatic pilot, which means that acts that require extra effort, extra caution, or extra fine-tuning don't get them. Whenever a situation calls for a carefully planned rather than an automatic action, a head-injured moment happens. This is what makes behavior so impulsive, so inflexible, and so inconsistent. The loss of this network is the main problem in TBI.

Fortunately, we know that the control network, when it is cranked up all the way to maximum, makes the mind obey instructions one at a time. And since a survivor has not forgotten how to solve problems, the control network can, if turned up high enough, take the place of the problem-solving network. For example, if you happen to get caught in the swamp in a downpour

while wearing your best dress shoes, your control network will talk you through each footstep one at a time. It is only by taking each step with extreme care that you can keep the mud from sucking the shoe off your foot. You use the same control to remove a splinter from the face of your child. But this method of total control works only as long as the person makes this maximum mental effort. As soon as the person relaxes, the control network goes back to its normal level of operation, and behavior becomes impulsive and inadequately controlled again. Recovery requires a lifetime commitment to learn when the control network needs to be turned on, and to keep it on as long as it is needed. Words cannot express how difficult this is to learn to do properly. It takes a lifetime of self-training.

There are other networks which I did not discuss because they are not important to head injury and recovery. You should also know that more networks are being discovered every year as brain scientists continue to investigate network theory.

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