Toward a Neurological Understanding of Metacognition

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Toward a Neurological Understanding of Metacognition

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Lesley University
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Abstract

Metacognitive interventions have been shown to be tremendously important to general education and supporting individuals with neurological disabilities (Brown, 1978; Webb, 1989; Dunlosky & Metcalfe, 2009; Dweck, 2017). This paper details the many facets and relationships between neurology and metacognition. The investigation draws from a wide diversity of neuro-investigational techniques and findings related to metacognition, executive function, self-reflection, self-evaluation, self-development and self-directed learning. It ends with a discussion of common threads and themes drawn from the research, and how methodological definitions for metacognitive knowledge and metacognitive regulation can be combined with physiologically-focused neurobiological approaches and consciousness-focused psychological approaches to broaden understanding and further investigation into this field of inquiry.
Toward a Neurological Understanding of Metacognition

The Need for a Neurological Understanding of Metacognition

Metacognition is a distinguishing component of human cognition (Dunlosky & Metcalfe, 2009). Rudimentary examples of metacognition have been seen in other species (Hampton, 2009) ranging from rats (Foote & Crystal, 2007) to dolphins (Smith, Shields & Washburn, 1998), with chimpanzees demonstrating the strongest sense of metacognition (Beran et al., 2015). However, even rudimentary metacognitive behavior is a rare adaption and has failed to be conclusively demonstrated in other species, such as the pigeon (Sutton & Shettleworth, 2008), and other primates, like the Capuchin Monkey (Basile et al. 2009). Moreover, while there is no evidence that any animal is capable of the systematic metacognitive reasoning seen in humans (Kornell, 2014), evolutionary evidence for the advanced development of metacognitive ability seen in humans is beginning to be uncovered.

The modern conception of metacognition was originally defined by John Flavell in 1979, as “learning about learning” (p.906). However, even if not yet named, it was certainly considered before by John Dewey (1997, 2007), the great American teacher and philosopher, who placed self-reflection as the most crucial component of both learning and a healthy democracy. So, while metacognition research is a fairly recent development, the idea that understanding one’s own cognitive faculties can have a tremendously beneficial impact on one’s learning and development is not. For example, in ancient times, Socrates, known as the first great European philosopher and teacher, lamented, “know thyself and thou shalt know the universe and God-” (Vyshedskiy, 2014). Literary and metaphorical evidence of metacognitive thinking is ubiquitously demonstrated across ancient societies (Vyshedskiy, 2014). However, the earliest
expressions of this idea of an interaction between a subjective/experiential self and an objective/contemplative self that can regulate achievement of higher and more developed behavior (Nelson & Narens, 1994; Nelson, 1996) is expressed in a metaphor from the Hindu Rigvadaś parable of the Body and Soul, "Two birds with fair wings, inseparable companions; Have found refuge in the same sheltering tree. One incessantly eats from the fig tree; the other, not eating, just looks on" (De Nicolás, 2003, p.66), and dates to earlier than 2000 BC. It is believed that the mental synthesis involved in metacognitive awareness is among the cognitive skills that separated humans from their ancestral primate relatives (Vyshedskiy, 2014).

The study of the influence of conscious, self reflective, metacognitive thinking on behavior was overshadowed for much of the 20th century by the dominance of Skinner’s (2011) behaviorist conception of the mind as a black box. This form of radical behaviorism saw consciousness as epiphenomenal and believed it to have minimal to no impact on real human action, and that all behaviors were the result of conditioning. However, by the time Flavell (1979) wrote his seminal work on metacognition, behaviorism’s dominance was beginning to wane as its adherents failed to demonstrate their claims conclusively (Harzem, 2004). This set the stage for deeper neurocognitive investigations into human learning and development using paradigms that more fully appreciate the role of conscious thought processes and choice.

Gradually, researchers began to show that rather than being too ephemeral and epiphenomenal to study, certain activities of consciousness could be studied scientifically using the conceptual framework of metacognition research laid out by Flavell (1979). However, Hart (1965) is generally considered the first researcher to probe a metacognitive skill, identified as the feeling of knowing (FOK) if a given answer was correct. Later, Whyte (1978) discovered that
task performance improved the more people believed that it was within their control to affect the course of events to influence outcomes. Today, thanks to modern investigational technologies such as functional magnetic resonance imaging (fMRI), positron-emission tomography (PET), and single-photon emission computerized tomography (SPECT) we have created complex representations of the different brain regions involved in cognitive interactions (Gerhard et al. 2011). Metacognition’s unique relationship to consciousness make it an important methodological and investigational concept in this domain. It provides an experimental framework capable of probing the neurological relationship of not just cognition, but also of conscious behavior, and its relationship to discrete tasks of memory and performance. Due to this, most research into metacognition and executive function have proceeded on separate tracks, (Mazzoni & Nelson, 1998; Nelson, Metcalfe & Shimamura, 1994) with neuroscientists focusing on the relationship between executive control, brain regions and behavior using adults in laboratory settings, and traditional metacognitive researchers focusing on the learning of children in naturalistic settings.

Beyond this, metacognition has been shown to be a defining feature of successful education programs (Hattie, 2012), and many researchers (Weinert, 1987; Mancini, et al. 1991; Pace, 1991; Price, 1991) have identified the various ways metacognitive processes affects learning. Since Brown, in 1987, much focus has been paid to the metacognitive ability of humans to adjust and fine-tune processes of learning through self-regulation. Other researchers have studied metacognition’s role in planning, directing, monitoring and evaluating one’s behaviors (Weinert, 1987), regulating cognitive behavior (Mancini et al., 1991), and in one’s capacity to consider and modify one's own thinking (Pace, 1991) in order to self-regulate, or control ideas
and approaches to solving problems (Price, 1991). What has been found is that metacognitive knowledge and regulation are strongly related to academic success (Dweck, 2013), and, of primary importance to educators, research also indicates that such metacognitive skills need to be taught for students to fully understand and utilize them (Pintrich, 2002; Tanner, 2012, Vanderberg Personal Communication). So, far from being epiphenomenal, metacognition appears to be a learned skill that can be developed much like reading or writing.

Due to the surprisingly robust role metacognition plays in learning and education, it makes sense to more deeply investigate how the physical organ of the brain is able to achieve such a feat. Such knowledge could have a profound impact on pedagogical and clinical practice. Several metacognitive educational approaches have achieved success integrating neurological research into their programs (Medina, 2011; Dweck, 2008, Webb, 1989), but a neurological explanation of the phenomena of metacognition itself has been elusive. The fields of both neurology and psychology are uniquely metacognitive, and in many ways are formalizations of this basic human cognitive ability. Essentially, any advancement made in these fields is and advancement in our broad metacognitive knowledge as a species. Developing a deeper, more nuanced neurological conception of metacognition holds the hope of producing new interventions that could improve human learning, development, productivity, and mental health more generally.

**Neuroimaging**

One cannot overstate the impact of magnetic resonance imaging (MRI) on the forward movement of the field of neurology. Through the use of strong magnetic fields, electric field
gradients, and radio waves, MRI generates images of the brain without exposure to harmful X-rays or ionizing radiation. With the invention of functional magnetic resonance imaging (fMRI) researchers have gained the ability to perform the same kinds of active investigation of nutrient use and blood flow that were once performed by positron-emission tomography (PET) using radioactive isotopes. fMRI enables the detection of increases or decreases in blood flow to different regions of the brain as test subjects engage in differing tasks. Through these investigations it is possible to identify which regions of the brain are most and least heavily utilized during cognitive tasks.

The kinds of tasks one can do in an fMRI are limited, as subjects must be literally strapped to a table inside a magnetic resonance tube. However, this has not deterred researchers from developing novel experiments to identify brain activations associated with specific cognitive functions. Thanks to the accumulating evidence gained from MRI, PET, fMRI and other brain imaging techniques, large scale atlases of the brain and its areas of functions have been produced. These atlases provide researchers with sophisticated renderings of brain regions that can be rapidly analyzed using machine learning technologies to provide deeper insight into the function of these regions (Iqbal, Khan & Karayannis, 2018; Domingos, 2015; Zeng, Tan, Li, & Huang, 2016). These discoveries have in turn projected future fMRI studies into ever more nuanced investigations of the relationships between brain form and function (Milberg, personal communication, March 2018). Possibly the most ambitious initiative is sponsored by the National Institutes of Health called the Human Connectome Project whose goal is to build a network map of the brain's physical connections (Gerhard, et al. 2011). This map of the
anatomical and functional connectivity of a healthy human brain could lead to important research breakthroughs in the future.

Due to its relative safety and increasing availability, fMRI has become the favored neuroimaging tool for collecting data. It is able to provide spatial resolution between 1-2 mm and temporal resolutions between 20-50 ms with a high degree of contrast (Lin & Alessio, 2009). Most importantly, fMRI are able to identify patterns of brain activation correlated with certain cognitive function. The standard methodological approach is to have a subject perform a cognitive or behavioral task while being scanned to detect increases or decreases in blood flow to specific brain regions. Shimamura (2000) has aptly pointed out that neuroimaging, “techniques are helpful only to the extent that careful behavioral methodology is implemented.” (p.320). Because of its unique connection between consciousness, metacognition, executive function and self control many fMRI-based experiments can, and have been, designed to investigate metacognitive abilities (Fleming & Dolan, 2012).

Frontal Lobe

No one area of the brain has been localized as the center of metacognitive activity. However, in many studies (Fernandez-Duque, Baird & Posner, 2000), the frontal cortex has been found to play a major role. Before the wide use of fMRI this area of the brain was implicated through impairments of executive function caused by damage to the frontal cortex called dysexecutive syndrome (Baddeley & Wilson, 1988). fMRI investigations further have been able to provide very detailed and nuanced investigations of the various areas involved in several metacognitive skills. For example, utilizing a similar methodological structure to Heart’s 1965
experiment, feeling-of-knowing (FOK) judgments, have been correlated with frontal areas using fMRI (Fernandez-Duque, Baird & Posner, 2000).

*Figure 1.*

Frontal lobe

The brain seems to function back to front (Medina, 2011; Swanson, 2003). Sensory input pours into the hindbrain through the spinal cord and then into midbrain structures of the Limbic System that are largely responsible for pairing sensory input with an emotional level of arousal. Even the sensory data from the eyes, in the front of our head, is first processed in the occipital lobe in the back. The processing of sensory experience is moved forward through higher and more frontal brain regions like the parietal lobe and somatosensory areas. The frontal lobes are the last areas of the brain to process. It is believed that as the neurological traces of thought move
from hindbrain to forebrain the complexity of those thought traces increase, as ever more refined
details are added from localized brain regions specializing in specific forms of processing.

What emerges from the frontal lobes is a unified conscious thought, which is able to
metacognitively apprehend itself. For example, not just an awareness that you are capable of
learning, but an awareness of the awareness that makes learning possible, which allows planning
and behavioral modulation based on abstract meta-features not directly apparent in the
experience. This causes the frontal lobe to use tremendous amounts of energy, and activate high
numbers of genes related to metabolic energy consumption (Sapolsky, 2017).

The morphology, function, and connectivity of frontal areas of the brain have been
related to self-reflective metacognitive thinking in both qualitative (Macmillan & Lena, 2010,
Baddeley & Wilson, 1988) and quantitative studies (Allen et al., 2017; Fleming and Dolan,
2012). However, closer examination reveals that PFC is a very diverse area and not uniform in
its function. Primate studies confirm the PFCs involvement in social behavior by showing that
the greater the species sociability the larger PFC gray matter (Sapolsky, 2017). Moreover, it
cannot be said that metacognitive function is exclusively correlated with the frontal lobe.
Midbrain and parietal areas have also been shown to play a strong role in metacognitive
processing. In many ways as neurological investigation has intensified it has revealed that rather
than a localized brain region being responsible for metacognition, there are, in fact, many areas
involved across various brain regions.
Hind and Midbrain Structures

Since hind and midbrain structures are among the first areas of the brain to process incoming sensory information it may be assumed that what goes on in these regions should have very little to do with metacognition. However, much of what the midbrain engages in lays the groundwork for later, more advanced cognitive tasks, and it is not clear if these aspects should be considered neurologically separate from the act of metacognition. Some researchers have questioned if some aspects of metacognition are subconscious (Stajkovic, Locke & Blair, 2006; Brown, 1980), meaning that some of metacognitions constituent parts operate outside of conscious control. As discussed, several aspects of executive function, seem to be performed by the brain before conscious awareness is brought to bear. If there are subconscious aspects of metacognition it is likely that they will be related to midbrain and intra-brain structures since these structures are most associated with arousal, attention and emotional function (Goleman, 2006).

Figure 2.

Midbrain/ hindbrain

Location of the hind and midbrain with a detail of the structure.
The hindbrain is located at the base of the spine. Because of its location it is sometimes called the brainstem. It is responsible for the regulation of subconscious autonomic bodily functions like digestion, heart rate and breathing (Swanson, 2003). Though the hindbrain is not considered related to metacognitive function, because its functions generally occur outside of conscious regulation, some degree of conscious regulation can be brought to bear on these autonomic functions.

On top of the hindbrain sits the midbrain. The midbrain is primarily responsible for processing emotional information (Swanson, 2003). All sensory input into the brain passes through this area, where it is emotionally processed. This processing takes place in two dimensions. The first dimension is whether the input is a positive or negative experience. The second dimension processed is the experiences emotional intensity. These emotional aspects drive the attentional processes of the brain by both directing attention and determining the level of emotional arousal behind behavioral responses (Tyng, et al. 2017; Goleman, 2006; Foa & Kozak, 1986; Kleinginna & Kleinginna, 1981).

As information enters the brain it is given an emotional variance, either positive or negative, and an emotional intensity (Kleinginna & Kleinginna, 1981). Emotional intensity in this respect can be best imagined as an energy level that ranges from 1, being very slight, to 10, being unignorably intense (Goleman, 2006). Attention is generally driven toward information of higher emotional intensity (Foa & Kozak, 1986; Kleinginna & Kleinginna, 1981). Though ostensibly a subconscious process, it is one of the first points in processing where the brain makes an abstract judgment about a sensory input. This judgment of emotional variances will
dictate the level and manner of the neurological processing that follows (Tyng, et al. 2017). For example, in a classroom lecture, the professor will likely garner most of your attention both because of the emotional value placed on her role in the classroom, and the information she is imparting. However, if you have a sick parent or child at home, you will find your attention moving to thoughts of them, because they command a higher emotional value than the professor, even though they may not be there in the classroom at that moment.

Moreover, if there were an explosion outside of the classroom, your attention would be immediately drawn to this potential threat and you would experience a corresponding emotional surge of energy, preparing you for action. This is called an acute-stress response or the fight or flight response, first described by William James and Carl Lang in the 1880s. During these events a midbrain structure, called the amygdala, compels action that is driven by the desire for self-preservation. A cascade of neurotransmitters, such as norepinephrine and epinephrine, increase heart rate, dilate pupils, constrict blood vessels in the outer extremities, all to prepare the individual for the physical demands of a life threatening event (Goleman, 2006; Foa & Kozak, 1986; Kleinginna & Kleinginna, 1981). This response is only limited by the more metacognitively regulating frontal areas of the brain, exerting control and regulation. However, this regulation occurs only after this stress response action has been triggered. This level of emotional control and regulation seem to be strongly developmental, and can have a powerfully negative impact on behavior if regulated poorly (Tyng, et al. 2017). It also demonstrates a relationship between conscious and autonomic control, affecting how an individual responds to their own interoceptive feelings and experiences of information, which can impact further neurological response (Sapolsky, 2017).
Part of the reason for this is that the midbrain is really only capable of associative thinking (Tyng, et.al, 2017; Goleman, 2006), Deeper discrimination is a property of higher areas of the brain that are not activated until after they are processed by the emotional midbrain. For example, my wife is ophidiophobic, deathly afraid of snakes, and will have a bit of an emotional stress response when viewing a snake on an advertisement or TV show. So one time we were walking through the woods, and someone had thrown about 20 feet of rope into the bushes off the side of the path. My first thought was disgust that someone litter in the woods like this, but my wife immediately began screaming and running in the other direction. Why? Because the information never made it to her frontal lobes where higher levels of discrimination could have been made. The information got as far as her midbrain, which detected the qualities long, skinny and in a bush, and she immediately associated it with a snake. This left her running in the opposite direction, before a more detail discrimination could be made. This reaction is sometimes called an emotional hijacking (Goleman, 2006), because it results in the midbrain highjacking control away from the frontal lobes. This can result in a host of emotional behavior, where the individual could end up saying and doing things without really thinking through their actions, essentially because the area of the brain that is responsible for thinking has been bypassed by the midbrain, which is not designed to think through actions it is only designed to fight or flee.

It has been found that emotional regulation can powerfully affect learning (Tyng, et al. 2017), and mental health (Aldao & Schweizer, 2010). Even the simple positive negative emotional variance initiated by the midbrain can have strong downstream effects on learning. Studies of this variance have been central to the studies of mindset. For example Carol Dweck
(Dweck, 2017, 2008) found that students who view their ability to learn positively performed better than students who viewed their ability to learn negatively. This simple variance in the confidence one places on their own learning has been shown to be more predictive of a student’s school performance than grades (Dweck, 2017).

Regulating emotional intensity during learning plays an even bigger role in the learning process (Tyng, et.al. 2017). It has been shown that as the emotional intensity of a situation increases, the ability to command control over one's attention also decreases, while neurological access to working memory and other higher-level thinking processes become impaired (Gabel & McAuley, 2018). Increasingly it is being shown that optimal learning occurs in a balanced emotional state. One that is not too overly aroused and emotionally reactive, but not too under aroused, bored or disinterested. Students who can best manage this emotional regulation tend to perform better than students who do not. In fact, increasing evidence is identifying difficulties regulating the stress and anxiety associated with learning that is supremely important in the developing symptomatology of learning disabilities (Gabel & McAuley, 2018, Thakkar et al. 2016; Tobia, et al. 2016). It is well known that there is neurochemical interaction that occurs between emotion and memory (Phelps, 2004). When students make mistakes it produces an emotional response, which in turn provokes the release of neurotrophic compounds that support memory, which in turn primes the brain to better remember events that subsequently follow the mistake (Roediger & Finn, 2009). It has been hypothesized that, in students with learning disabilities, this natural learning process associated with making mistakes is distorted by an education system that provides more shame than support, leading to a feedback cycle that only
reinforces emotional memories of failure rather than useful memories that would aide problem solving (Gabel & McAuley, 2018).

**Caudate Nucleus**

One area of the midbrain that has been implicated in subconscious metacognitive processing is the Caudate Nuclei. This area of the brain is thought to regulate attentional arousal in much the same way a water faucet regulates the flow of water through a garden hose (Hallowell & Ratey, 2011). fMRI and SPECT studies have demonstrated that blood flow to the Caudate increases as the intellectual demands of a task increase, and inversely, decreases as demands decrease. Similar to other autonomic functions in the brain, these changes are generally not initiated consciously, but rather in correspondence to stimuli. So, when we are confronted by a challenge or problem that requires focused attention blood flows into the Caudate increasing the flow of thought, and when we need to relax or get some rest, blood flow decreases to the Caudate slowing the flow of thoughts. The Caudate is one of the areas implicated in Attention Deficit Hyperactivity Disorder (ADHD) because it is the target of attentional medications. Neuroimaging has shown that individuals with ADHD demonstrate lower blood flow to this region than normal subjects when given an attention focusing task (Amen & Carmichael, 1997).

While midbrain structures like the Caudate seem to perform their function, outside of consciousness, it has been demonstrated that conscious awareness can still be brought to bear in their regulation. For example, it has been demonstrated that individuals can use metacognitive executive function to project and maintain their attention to varying degrees (Astle & Scerif, 2011) in a process called endogenous attention. It has also been shown that individuals can
utilize environmental modifications to regulate attention control, such as playing certain kinds of music (Jeffries, et al. 2008). By becoming consciously aware of how certain experiences and environments can enhance or impact attention individuals can purposely choose to develop behaviors or place themselves in situations that improve this innate and subconscious capacity for attention.

Figure 3.
Caudate Nuclei

Location of the midbrain structures of the Caudate Nuclei, Putaman and Amygdala.

Many of the brain’s autonomic functions have also been shown to fall under some influence of conscious control, even the highly autonomic processes of the hindbrain (Swanson, 2003). The simplest demonstration of this would be breathing, which is generally controlled unconsciously by the brain stem. However, at any moment we can move our conscious awareness to our breath to regulate its flow; we can even stop our breathing when needed in situations like swimming. Interestingly, full conscious control of this vital neuro-biological cognitive function is never fully granted. If one attempts to hold their breath, past a certain point,
the hindbrain compels its resumption through a building perceptual pressure, or in extreme cases, literally shutting down consciousness altogether. This leads the individual to pass out, so that normal breathing can resume undeterred by conscious interference. Moreover, it seems that this kind of hindbrain control is not driven by a strictly nonconscious monitoring of oxygen levels, as would be suspected (Stratton, et al. 2001).

The hind brain and frontal lobes are not the only brain regions capable of overriding normal control of breathing protocols. Midbrain structures have the ability to also seize control of breathing functions in instances of high emotional intensity (Deakin, 1991; Stratton et al., 2001). In situations the midbrain deems too dangerous to suspend conscious behavior, it will override the hindbrain response, even when oxygen levels are dangerously low. This has led to many tragic deaths from a condition called Positional Asphyxia. Positional Asphyxia generally occurs in institutional mental health settings when a patient or client falls into a state of acute stress response and must be restrained in order to maintain safety. Often, because of mental health issues, they perceive the intervention as a threat to their life. This leads to the classic fight or flight escalation. These are often terrifyingly physical events. Rather than passing out, these individuals will continue to fight, scream and threaten. Despite the fact that their blood oxygen has dropped to dangerously low levels, these individuals will fight on. When these individuals are maintained in restraint positions that restrict their ability to take full breaths, such as during prone floor restraints, deaths from suffocation can occur, even before the usual warning signs of suffocation, because the midbrains stress response has bypassed them. (Deakin, 1991; Chan, et al. 1997).
While conscious modulation of the autonomic functions of the mid- and hindbrain, like breathing, may seem to have little to do with metacognition, at its heart metacognition is related because it is about an awareness of how to best manage and modulate other neurological functions to maximize the ability to learn. As we learn more about learning we find that to maximize our learning potential we must manage and modulate both the external and internal learning environment. Internal somatic states such as levels of sleep, emotion and fatigue can powerfully impact learning (Palmer, 2013). Our ability to modulate these states is an imperative component of maximizing our capacity to learn. Plus, such conscious modulations of autonomic functions may be demonstrations of a more elementary component of the broader phenomena. It may be that mid and hindbrain areas are more involved in specific kinds of metacognition than presently appreciated, albeit in a less conscious way.

**Hippocampus**

Improvements in resolution capabilities and techniques, such as parallel magnetic resonance imaging (pMRI), have increased the ability of MRI and fMRI to produce highly detailed investigations into the deep structures of the brain. Investigations using this kind of multi-parameter mapping has revealed that there is a strong relationship between memory, hippocampal microstructure and perceptual metacognition (Allen et al. 2017). Historically memory has been considered to be the source of how the known self comes to be known (James, 2013). By ‘known’ I mean: a stable mentally manipulatable memory of an idea that can be recalled and used to demonstrate understanding. Memory allows individuals to not only look back and evaluate experience, but also remember goals and objectives for the future.
Midbrain structures like the hippocampus have repeatedly been found to be related to memory function. Most recently, morphological differences in hippocampal size have been identified in London taxi cab drivers. These drivers must memorize London's entire street layout to secure their license. This daunting cognitive task leaves these cabbies with a larger than average hippocampus (Maguire et al. 2000). Similar results were found to occur in language acquisition (Sluming, et al. 2002) and learning to play an instrument (Gaser & Schlaug, 2003). What has been underappreciated in these studies is the role of metacognitive knowledge and

*Figure 4.*

**Hippocampus**

![Location of the midbrain structures of the Hippocampus in relation to the Caudate Nuclei, and Putamen.](image_url)
regulation have played in this process fostering this unique relationship between the understanding and directing of one's learning and the physical and structural makeup of one’s brain, itself.

More recent investigations of the microstructure of the hippocampus (Allen et al. 2017) have found important relationships between this brain region and metacognitive ability. These results suggest that hippocampal, memory-related, systems may be very important to perceptual metacognition. A broader question to raise would be, are these processes part of the conscious metacognitive memory regulation, or part of an underlying, subconscious memory network that supports metacognitive function.

**Figure 5.**

**Hippocampus and Seahorse**

The name for the Hippocampus was derived from the Greek word for sea horse by Julius Aranzi who first described it in the 1500.
Metamemory

To distinguish aspects of subconscious memory processes from the conscious memory processes most associated with high level metacognition researchers have introduced the concept of metamemory (Flavell & Wellman, 1975). Metamemory is the ability to monitor and predict memory capacity. By definition metamemory involves conscious awareness of a felt capacity. Neurological imaging studies further validate this conception by showing strong neurological conductivity between memory related hippocampal structures and the executive areas that organize and regulate behavior in the frontal and prefrontal cortex (Allen, et.al. 2017).

Metamemory has been studied through simple predictions of memory performance (Yussen & Levy, 1975). For example, Hart (1965) was the first to investigate what has become known as the feeling-of-knowing (FOK) by having subjects assess feelings of confidence that they do, in fact, have something stored in memory, but cannot accurately recall it at the time of questioning. This was achieved by asking subjects how sure they felt they could identify the answer to a question they could not earlier answer if now presented with a short list of possible answers. MRI (Kikyo, Ohki, & Miyashita, 2002; Craig, 2009) and lesion studies (Schnyer et al. 2004) of FOK have identified deep prefrontal regions of the brain being involved in such tasks.

Methodological elaborations of the metamemory conceptualization have been quite fruitful and have led to several experimental designs that have yielded valuable insights into the structural and behavioral qualities of the brain. For example, fundamental methodological investigations of judgments of learning (JOL) (Nelson & Narens, 1990), time allotment and selection of mnemonic study strategies (Brown & Smiley, 1978), ease-of-learning (EOL) (Nelson & Narens, 1990), time spent in memory search (Lachman & Lachman, 1980) and
go-no go studies have provided investigational models that transfer well into neuroimaging studies (Cabeza & Nyberg, 2000, Craig, 2009). The success of the metamemory conceptualization has also produced a unique problem, as the variety of research methods used to measure the various manifestations of metamemory have produced a diversity of definitions for common phenomenon. This inability to settle upon a common language for certain phenomena related to metamemory has contributed to confusion and inconsistent results across the literature (Fernandez-Duque, Baird & Posner, 2000).

**Corpus Callosum**

As one moves up and forward from midbrain structures in the brain one comes to a thick band of neural-connections that enable communication between the two hemispheres of the neocortex and frontal lobes called the corpus callosum. The corpus callosum plays a wide role facilitating the neuronal communication across the brain and has been shown to play a large role in our capacity for both verbal memory and encoding abstract, semantic meanings (Kozlovskiy, et al. 2012). This is particularly important to the study of metacognition as it has been shown that we have considerably better memory for things we have associated the meaning to, and stored using semantic encoding, rather than repetitive rote memorization (Foer, 2012), and we can choose to employ memory strategies, like memory palace, that exploit this neurological predisposition.

Neuroimaging studies have identified morphological size differences in the corpus callosum that can be correlated to individual differences in cognitive function. Differences in the size and shape of the corpus callosum have been found in dyslexics, particularly in the posterior
midbody of the corpus callosum (von Plessen et al. 2002). In fact, malformations of the corpus callosum is among the most common congenital brain malformation observed in human beings (Dobyns, 1996).

Figure 6.

Corpus Callosum

![Diagram of the Corpus Callosum, Caudate Nuclei, and the input area of the Hippocampus called the Fornix.]

Location of the Corpus Callosum in relation to the Caudate Nuclei, and the input area of the Hippocampus called the Fornix.

Interestingly, such morphological differences in the corpus callosum may also be the result of how individuals process information, and their tendency to utilize certain kinds of thinking over others. Much of the brains thinking is lateralized to one hemisphere over the other. For example, most language skills are lateralized in the left hemisphere, and most video-spatial processing skills are processed on the right (Sperry, 1968). There is evidence that some
neurological disabilities are the result of poor interhemispheric integration. Damage to this left-brain right-brain communication network produces striking neurological conditions that will be delved into more deeply later.

The corpus callosum is also one of several areas of the brain that are impacted by habits of learning. It has been shown that behaviors that induce inter-hemispheric communication promote significant morphological differences in the size and shape of the corpus callosum. Such morphological differences have been detected in musicians (Gaser & Schlaug, 2003, Levitin, 2006) and individuals that are ambidextrous or left-handed (Witelson, 1985). Though probably less involved in the conscious regulation of thought processes involved in metacognition, the corpus callosum is certainly significantly involved in the vast neuronal communication networks involved in higher order thinking.

**Anterior Cingulate**

One of the internal structures of the frontal lobe, that resides just outside the midbrain, that has been shown to have definitive involvement in metacognition is an area of brain surrounding the frontal part of the corpus callosum called the anterior cingulate (AC). Initial studies by Bench et al. in 1993 using PET scans identified this area of the frontal lobe’s involvement in attentional control during a Stroop task. Use of this task, which utilizes a field of words denoting different colors, has subjects identify the color of a written word, rather than reading the word naming the color. This task can provoke a measurable state of cognitive interference when the relationship in meaning between ink color and written word are incongruous. Such incongruities between perceptions and meanings produce a measurable delay
in response time, called semantic interference. Further fMRI investigations by Peterson et al. (1999) using this construct identified that the anterior cingulate activates a distributed attention network that is arranged spatially, depending on the specific attentional demands of the task.

Studies have shown a close relationship between the size and activation of regions in the AC with metacognitive ability (Fleming, et al. 2014; McCurdy et al. 2013; Allen, et al. 2017). The work of Peterson et.al. (1999) and others like Carter et al. (1998) who used a letter pattern detection model, have demonstrated that the AC activates most strongly when the test subject is confronted with competing stimulus that require a shift in attentional demands. It has been suggested (Carter et al. 1998) that the AC is involved in error monitoring and detection.

*Figure 7.*

**Anterior Cingulate**

Location of the Anterior Cingulate in relation to the Corpus Callosum and Hippocampus
However, our understanding of the relationship between the AC and error monitoring and detection is not settled. It has been observed by Carter, et al. (1998) that the activity in these brain regions seems to increase as a result of the kind of response competition seen in the Stroop task, and occurs during both correct and incorrect response conditions. This suggests that rather than errors themselves, the AC activates when it detects conditions where errors are likely to occur (Allen et al. 2017). Plus, the AC is not the only region of the brain associated with activation during these kinds of semantic interference tasks (Fleming et al. 2014; McCurdy et al. 2013; Allen et al. 2017), certain areas of the parietal lobes called the precuneus show significant activation. This area, like the AC, is internally located between midbrain structures and the outer layers of the cerebral cortex. Connections between parietal and prefrontal areas show considerable involvement in episodic memory and reflective self-awareness.

**Parietal lobes**

Outside of the frontal lobes, parietal areas are perhaps the most associated with metacognitive and self-regulatory function. According to the parieto-frontal integration theory of intelligence (P-FIT), it is the neural connections between these two regions that provide the best explanation of where intelligence resides in the brain (Haieret, et al.2009). The parietal area has been implicated in specific learning disabilities, such as dyslexia (Eckert, 2004; Catani & Jones, 2005), dysgraphia (Catani & Jones, 2005), and dyscalculia (Von Aster & Shalev, 2007). Damage to areas within this region can produce impairments ranging from the ability to perform specific complex movements, called Apraxia, to impairments in the ability to recognize or discriminate qualities in the sensory field, called Agnosia. Often, localized damage to the parietal can produce
fascinatingly specific kinds of deficits. Perhaps most relevant to the study of metacognition is the condition of Anosognosia, or what is sometimes called hemispheric neglect, a condition in which a person suffers from paralysis due to their injury but seems to be unaware of the disabilities existence.

Figure 8.

Parietal Lobe

Location of the Parietal Lobe in relation to the Frontal lobe.

One reason researchers have been able to identify many parietal functions is that it is a part of the brain that is easily accessible compared to internal areas like the midbrain. This has
enabled researchers to apply electrical stimulation to specific parietal brain regions, which frequently produce noticeable changes in cognitive and perceptual experience (Calvin, & Ojemann, 2010). During brain surgery for severe epilepsy, for example, the patient is awake, while the surgeon applies localized electric current to the physical surfaces of the brain and asks/observes changes correlating with that area of the brain. This is to ensure that the surgeon does not damage regions of the brain involved in important functions of daily living. Through this process researchers have thoroughly mapped the motor area, by stimulating the brain and identifying corresponding body movements (Penfield & Boldrey, 1937), and the sensory areas, by stimulating the brain and identifying corresponding sensations reported by the patient. (Woolsey, Erickson, & Gilson, 1979).

Figure 9.
Motor areas

Location of the Primary Motor and Somatic Areas of the Parietal lobe.
Many of the brain’s most impressive feats of abstract thinking are involved in the parietal. It has been implicated in the understanding of metaphors (Ramachandran & Hubbard, 2003), directing spatio-visual attention toward salient features in the environment (Seghier, 2012), visuospatial working memory (Todd & Marois, 2004), arithmetic fact retrieval (Dehaene, et al. 1999), and symbolic numerical information processing (Cantlon, et al. 2006). The parietal is also strongly associated with various types of social skills. An area called the inferior parietal lobule was found to be involved in the perception of emotions in facial stimuli (Radua et al. 2010). This is consistent with earlier work identifying a parietal roll in interpreting the intent of others (Grafton, 2006).

However, the ability of these techniques to fully localize these functions are not clear cut. For example, while early investigation seemed to identify the angular gyrus as responsible for creating metaphors (Ramachandran & Hubbard, 2003), later investigations found the angular gyrus was actually less involved in creating metaphors, and it was that conceptual metaphors were activating the somatosensory cortex in the parietal operculum (Simon, Stilla & Sathian, 2011). A similar shift has occurred in our understanding of the relationship between formation of, and the access/response to, semantic linguistic expression seen in Wernicke’s area (Milberg & Blumstein, 1981).
Generally speaking, the parietal role seems to be in distinguishing specific contextual details (Wagner et al. 2005). The subjective recollection hypothesis (Yazar, Bergstrom & Simons, 2012) explains the parietal’s role as one of retrieving contextual details and organizing multisensory information stored throughout the brain and likely also support feelings of confidence in judgments about the accuracy of a memory. Further evidence for this pathway is found in the cingulum, which is a collection of white matter fibers that allow for communication between components of the limbic system, parietal, primary sensory and prefrontal cortex (Mountcastle, 1984; Pandya & Barnes, 1987).
Along with intraoperative brain mapping and fMRI blood flow data, anatomical data has also been used to connect the parietal to the performance or mastery of a specific task (Sluming et al. 2002). Size differences in specific areas of the parietal have been correlated with improved performance of different skills and abilities. Perhaps the most famous example of this was discovered in Albert Einstein's brain. Einstein was missing much of a pronounced fold of tissue called the Sylvian fissure. So rather than the usual folds and sulci found in this region, Einstein had a surprisingly plump and smooth parietal operculum region, which is thought to be related to his tremendous spatial abilities (Witelson, Kigar & Harvey, 1999).

*Figure 11.*

**Sylvian Fissure**

![Location of the Sylvian Fissure.](image)
Presently, neuroimaging data investigating intelligence indicates that the parietal subareas of the extrastriate cortex and fusiform gyrus contribute to the recognition of categories of things that are emotionally salient, imagery and elaboration of visual input, in much the same way Wernicke’s area organizes syntactic auditory input in a meaningful way (Deary, Penke & Johnson, 2010). It is thought that information is then moved through the supramarginal, superior parietal, and angular gyri where information is processed for structural symbolism, abstraction and elaboration. Then these parietal regions interact with parts of the frontal lobe as a working memory network capable of holding different pieces of information in memory, so it can be compared to different possible task responses. (Deary, et al. 2010). It may be that conscious metacognitive monitoring occurs between the frontal and parietal cortex, as they exchange information to coordinate their activities. It has been found that this decision circuit between frontal and parietal cortex is most active during free choice decision making tasks (Pesaran, Nelson & Andersen, 2008) that most require a high level of conscious metacognitive thinking.

Prefrontal cortex, working memory and inhibition

As stated earlier the frontal regions of the cerebral cortex seem to play the largest role in metacognition. Of the numerous regions of the frontal lobe, imaging studies have identified the prefrontal cortex (PFC) as having specific involvement in self-regulation, judgment, planning and conscious behavior. This conception is evidenced by data collected from behavioral, electrophysiologial and blood flow techniques. (Allen, et al. 2017; Badre, et.al, 2010, Fleming, Huijgen & Dolan, 2012; D'esposito, et al. 1995) The general consensus view is that PFC is crucial for integrating thought and behavior.
A fundamental component of cognitive neuro-processing is the ability to hold an idea, object or experience in one's mind and shift one's cognitive perspective. This ability to hold ideas in our mind, while we solve problems is called working memory. It has been shown that efficient working memory depends on regions in the prefrontal cortex (Petrides, et al. 1993; Jonides, et al. 1993).

Figure 12.
Prefrontal Cortex

PFC shows increased activation during mental tasks that make greater demands on attention (Shimamura, 2000). For example, one fMRI study that asked subjects to perform a judgment task (e.g., monitor each time a type of vegetable is presented) and a
visuospatial task (e.g., mental rotation) found significant prefrontal activation when both tasks were performed simultaneously rather than separately (D'esposito, et al. 1995). Presently, there are two competing conceptualizations for what is occurring in the frontal lobes during these kinds of experiments. One group of conceptualizations center around the idea that the brain is involved in making ever more accurate associations related to contextual features (Cohen & Servan-Schreiber, 1992; Kimberg & Farah, 1993). The other sees the brain as inhibiting the expression of superfluous or irrelevant information processing (Knight, et al. 1999, Fernandez-Duque, Baird & Posner, 2000, Shimamura, 2000).

One computational model (Grossberg, 1999) proposes that executive control is maintained by exercising both selective and inhibitory control. In this model task-relevant information is enhanced in working memory by a top-down neural mechanism that also inhibits reaction to similar but irrelevant information. Research (Aron, Robbins & Poldrack, 2014) has revealed the existence of both inhibitory and excitatory prefrontal control of distributed neural activity in posterior brain regions. It seems that the cognitive capacities of the prefrontal cortex are bi-directional and exert regulatory influence on numerous cortical, limbic, and subcortical regions (Friedman & Goldman-Rakic, 1994).

Neurophysiological insult to the PFC generally produces problems with inhibitory control (Knight, et al. 1989; Yamaguchi & Knight, 1990, 1991), particularly in relation to sensory information processing. PFC damage has been correlated to difficulty in both sustained attention and selectively focusing (Woods & Knight, 1986), as well as the impaired detection of novel events (Knight, 1984, 1997). In fact, the study of brain lesions offers yet another lens through which to approach and expand our understanding of metacognition and neurology.
Implications of Brain Lesions

Specific functions of brain regions can be inferred through changes in behavior produced by damage or purposely lesioning the brain through surgical procedures. The loss or damage of specific areas of the brain has been strongly implicated in very specific disturbances of metacognitive function. For example, Phineas Gage, one of the first well recorded cases of brain lesion, and possibly the first documented case of dysexecutive syndrome, suffered an accident that destroyed his left frontal lobe, definitively changing his personality and impairing his ability to self-regulate (Macmillan & Lena, 2010). Losses of self-regulation and self-awareness are common features of many brain lesion studies. It has been found that patients with frontal lobe damage generally perseverate on previously rewarded tasks and fail to recognize the full implications of shifts when the relevant dimension of a task changes, as in the Wisconsin Card Sorting Test (Owen et al. 1993), which tests a subject's ability to shift from one cognitive strategy to another. This is achieved by having participants match cards without being told what qualities constitute a match but telling them whether a particular match is right or wrong. Studies using this kind of test suggest another role of the frontal cortex is the ability to shift mental sets from a previously successful or dominant set to a new set (Shamura, 2000).

Wernicke's aphasia generally occurs as the result of an occlusion in the left middle cerebral artery producing a lesion in the posterior superior temporal gyrus (Brookshire, 2007). Damage to this area of the brain leaves subjects unable to produce intelligible speech despite an intact ability to form words and syntactic structure. These individuals seem to lack the ability to perceive the intelligibility of their own language, or self-reflect on their understanding of what has been asked of them. So, while their ability to construct words and sentences remains intact
they do not seem to be aware of the distortions in meaning presented in their manner of speech, and are remarkable because of their ability to engage in conversations with others without acknowledging deeper semantic connections to their language. This stands in stark contrast to Broca's aphasics, who can no longer correctly form the words necessary for fluent speech and are deeply aware of their expressive shortcomings. For this reason, Wernicke’s and Broca’s aphasia seem to implicate separate and specific localized language functions, related to the ability to produce language, and the metacognitive awareness of the meanings their language produces.

*Figure 13.*

**Language areas**
Lesion studies of the brain often demonstrate impairments of metacognitive awareness similar to what is seen in Wernicke's patients. In these cases, the lesion produces more than just a simple inability to perform a given task, but rather obliterates the individual's ability to perceive or be consciously aware that there is a problem. As described earlier, damage to the right parietal lobe can produce a syndrome called Anosognosia, or hemispheric neglect, where an individual fails to attend to, or even notice, that their injury has caused the left side of their body to become paralyzed (Mesulam, 1981; Kertesz & Dobrolowski, 1981; Hier, Mondlock & Caplan, 1983; Stein & Volpe, 1983). Interestingly, this lack of self-awareness extends through the individuals whole perceptual field. In a famous study, V.S. Ramachandran (1997) used a mirror angled to reflect what was occurring on a patient’s neglected left field of vision. After informing and confirming that the subject understood that they were looking into a mirrored reflection, the subject was asked to grab a pen situated next to them on the left, and reflected in the mirror. Remarkably, rather than turning to the left and grabbing the pen, subjects would attempt to reach for the reflection. When asked to explain why they were unable to grab the pen the subjects would reply, “The real pen is inside the mirror,” or, on another occasion:”The pen is behind the darn mirror,”(Ramachandran, 2004, p.35).

Interestingly, other kinds of lesions to the parietal lobe produce visual deficits, but not a loss in the individual's awareness of the deficit. For example, damage to the medial temporal area impacts an individual's ability to perceive the speed and direction of something moving, but not their awareness of their perceptual loss (Ramachandran, 2004). These individuals are frightfully aware of their deficit, despite possessing vision that is functionally normal in all other ways. It seems that only certain kinds of brain damage come with a corresponding damage to
self-perceptual awareness, as seen in these neglect or Wernicke's patients, that leave individuals unknown of their deficits. However, while it is clear that damage to some brain regions impacts the performance of a neurocognitive skill, and others the perception of that skills performance, the cognitive interactions that produce these differences should be a focus of future neuro-metacognitive investigation.

Memory is another cognitive skill,\(^1\) that engenders this elusive quality of performance perception. Memory is a cognitive skill that has long been studied because of its ability to offer a window into the workings of the mind. Hart (1965) demonstrated that despite being unable to clearly remember if an answer to a question was right or wrong most people are able to fairly accurately determine if an answer is right or wrong by accessing a metacognitive feeling about what they know. Another example of this ability to monitor our memory quality is the fact that nearly 1 in 8 Americans over the age of 60 report that they have noticed a decline in their memory (Alzheimer's Association, 2016). Under normal circumstances most people possess a metacognitive awareness described as metamemory (Pannu & Kaszniak, 2005), that allows them to assess the qualities of their own memories. However, brain lesion patients like Henry Gustav Molaison (HM), who had most of his hippocampus removed during a bilateral medial temporal lobectomy to control his seizure activity, demonstrated an inability to form new long term memories, but maintained a relatively intact short term and working memory (Baddeley, Eysenck & Anderson, 2009, Corkin, 2002). HM was able to remember information over short

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\(^1\) I have spent considerable time going back and forth as to what to call memory here. Is memory a feature or attribute of cognition, or is it more of a developable skill of cognition? I have decided to come down on the side of calling memory a skill because it is inherently developable, and when memory is described as an attribute it infers that it there is less room for modification and improvement, which is clearly not the case (see Foer, 2012).
intervals of time, but he would subsequently forget whatever had just happened when his attention was drawn to a new situation, or there was a shift that refocused his working memory. Interestingly, though HM was consciously unable to form new memories he was able to demonstrate motoric, muscle memory and spatial learning through repetitively playing a new piece on the piano (Corkin, 2002). Essentially, HM could be taught to play new music, despite never remembering that he had been taught.

Damage to other Limbic structures can have a dramatic impact on social behavior, like what is seen in Kluver-Bucy syndrome, which produces a range of aggressive and sexual behaviors. Damage limbic structures like the Amygdala can lead to a decline in such aggressive behaviors. Inversely, repeated exposure to fear or traumatic stimuli can lead to an enlargement of the Amygdala seen in patients with PTSD, producing hypersensitivity and increased aggression (Gilboa, et al. 2004. Functional conductivity of the prefrontal cortex and amygdala in PTSD), seeming to indicate that this regions connection to violence are the result of learning (Sapolsky, 2017). The connections between limbic brain and frontal lobes are involved deeply with our emotional responses to others. For some, damage to this pathway produces an inability to change strategies in an economic game when it becomes clear the other player is taking advantage of you, called “pathological altruism”(Oakley et al. 2011, pathological altruism), in others it is an inability to detect angry facial expression like the behaviors seen in Urbach-Wiethe disease.

Brain damage is rarely clean or exact. Often brain damage leads to skill deficits that are only partially obscured to awareness. For example, Young et al. (1990) identified a woman who suffered a right middle cerebral artery subarachnoid hemorrhage leaving her unaware of her deficit in face recognition. However, she was quite aware that she had other deficits in other
domains, such as memory, motor function, and vision. It has been a general assumption of neurologists that if damage were more exact, specific areas of localized brain function would appear. However, while it may be tempting to attribute haphazard destruction of brain matter caused by stroke or injury, to nonuniform presentation and symptomatology of brain lesions, surgical ablation studies, where lesion damage can be very tightly controlled, seem to add more questions than they answer.

**Surgical Ablation**

For ethical reasons ablation studies are generally carried out in animals. Analysis must be inferential when considering metacognition in these studies, since not all species demonstrate metacognitive aptitude (Sutton & Shettleworth, 2008) and no species is able to demonstrate human levels of metacognitive sophistication (Kornell, 2014). However, such studies can be highly selective and specific about the brain regions being studied (Teuber, 1955) and have served to identify the role of specific brain areas, like motor areas or the prefrontal cortex (Jacobsen, 1935). What is interesting is that even with the ability to make exactingly specific brain lesions, there is little evidence of this specificity producing a correspondingly pure expression of a lost skill (Lashley, 1950). In fact, it has been demonstrated that control of complex motor patterns can find a way through lesioned connections between neurons (Lashley, 1950), indicating that there is some kind of neural executive function mechanism regulating this phenomena.

Ablation studies have found behavioral habit formation among the brain’s most highly conserved abilities. Lashley indicated that “Even combined destruction of the prefrontal, parietal,
occipital and temporal areas, exclusive of the primary sensory cortex, does not prevent habit formation, although preexisting habits are lost and their reformation is greatly retarded” (Lashley, 1950 pp.12-13). Observed behavior related to habit formation could be a highly ingrained stimulus response mechanism, or it could represent a primitive manifestation of self-regulation. How one answers this question has tremendous functional and philosophical implications that are outside of the purview of this paper.

Not only do specific brain lesions fail to produce cases of pure localization of function, it is equally difficult to identify if observed effects represent a genuine total loss of a neurocognitive skill or a disruption of the brain’s organization (Lashley, 1950). In other words, it is nearly impossible to rule out that a given presentation is the result of a loss of a functional unit in the brain or the disruption of a more peripheral yet fundamental process in the network. For example, further studies of Wernicke’s aphasics have shown they are unable to group words in relation to shared categories or features (Zurif, et al. 1974) and tie words to affective and situational data (Zurif, et al. 1974). So, rather than a loss of semantic expression, Wernicke’s aphasics may lack the ability to access semantic information for linguistic use or interpretation (Milberg & Blumstein, 1981), perhaps they are more suffering a disruption in brain organization rather than an actual loss of a skill.

**Split Brain and Alien Hand Syndrome**

Of the few surgical ablation related studies performed on humans, most are performed on epileptics to remove the source of their seizures. Only those epileptics with the most dire symptomatology ever received a complete callosotomy, or severing of the corpus callosum, to
prevent their seizure activity from crossing between hemispheres and engulfing the whole brain. These split-brain findings cast considerable confusion into debates about localization of brain function as they seem to demonstrate separate consciousnesses in the opposing hemispheres of the brain. These patients demonstrate an acute inability to monitor inter-hemispheric behavior, manifesting in a condition called alien hand syndrome (AHS) (Gazzaniga, 2005; Joseph, 2011; Sperry, 1968). Patients with AHS, quite literally, have to physically fight for control over the behavior of their alien hand (Joseph, 2011) because its actions fall exclusively under the control of the non-linguistic right hemisphere. Interestingly, this hand behaves in ways the linguistically capable left hemisphere cannot explain, and this behavior seems to be generated from a conscious locus of control that functions outside of their left hemispheres perception (Joseph, 2011; Sperry, 1968).

Sperry received a nobel prize in 1981 for his discoveries into the fundamental processing differences between the two hemispheres, utilizing split brain patients. However, his suggestion (Sperry, 1968) that there are non-linguistic, yet conscious, mechanisms of behavioral control located in the right hemisphere, has inspired considerable research into split brain phenomenon and a lively debate into the differing functions of the two brain hemispheres (Gazzaniga, 2005). For example, while it has been found that linguistic processing is a weakness of the right hemisphere, which extends even to visual tasks like reading (Zaidel & Peters, 1981), the right hemisphere can be thought of as the brain’s ‘interpreter’ of fundamentally ambiguous information (Corballis, 2003; Ramachandran, Blakeslee & Shah, 1998). This is because the right hemisphere engages in problem solving novel solutions, while the left hemisphere puts those solutions into words. It is believed that what is occurring in hemispheric neglect patients is that
stroke damage to the right hemisphere has impaired the patient's ability to interpret novel situations, so they can no longer adequately process the reality of their own paralysis. Instead their linguistically intact left hemisphere creates excuses for a situation it cannot comprehend. Interestingly, it has been demonstrated by Ramachandran et.al (1998) that these excuses follow the familiar Freudian patterns of the psychological defense mechanisms (1992).

*Figure 14.*

**Hemispheres**

*Three views of the two hemispheres of the brain.*

Interestingly, this lack of perceptive self-insight cannot be said to be localized to the right hemisphere. AHS has been found to affect the right hand of individuals with left medial frontal lobe damage also (McNabb, Carroll & Mastaglia, 1988). Similarly, the insight issues of Wernicke's patients discussed earlier are the result of left hemispheric damage, and belye this hypothesis. However, these regions of the brain do play some role in the perceived ability to choose.
I used the wording, “perceived ability to choose,” above carefully. There is considerable debate in the neurological community as to the level of freedom available in human choice. Benjamin Libet (2004) performed experiments that showed that the human mind was already contemplating and organizing the muscular response to an, as yet unmade choice, milliseconds before the conscious mind made the choice (for a brief video of the experiment https://www.youtube.com/watch?v=OjCt-L0Ph5o). Dan Dennet (2017), explained that this novel result suggests that rather than consciously experiencing the moment a choice is made, what is consciously experienced is confabulated by a brain that has already made a choice. This suggests that what has been historically considered free choice is constrained by deterministic, non-conscious mechanisms. However, others like Adina Roskies (2010) have argued that the neuroscientific evidence cannot prove, one way or the other, freewill’s existence.

Whether free will exists, and to what degree, is beyond the purview of this paper, but what split brain patients seem to identify is that the actions of the brain related to choosing seems to reside in the frontal and parietal lobes (Joseph, 2011a; Roskies, 2011). It is also clear that both hemispheres seem to engage in distinctly separate forms of processing when approaching choice, with the left hemisphere employing language and logical reasoning and the right employing more social and spatial reasoning (Joseph, 2011a, b; Ramachandran et.al, 1998; Sperry, 1968). Damage to either the right or left frontal medial motor areas can impact conscious perceptions of choice, and if this damage is accompanied by anterior damage to the corpus callosum than the condition of AHS will arise (Joseph, 2011a). A clean severing of the neural pathways linking the two hemispheres’ supplementary motor areas can lead to two independently focusing attentions (Luck, et al. 1989), and two seemingly conscious entities residing inside the same skull,
exercising a freedom to choose behaviors outside the others conscious perception (Joseph, 2011a,b; Sperry, 1968).

From a metacognitive perspective, patients with brain lesions also demonstrate that a powerful level of metacognitive awareness can be brought to bear, even in the face of such debilitating injury. This is the ability to produce adaptive behavior even in the face of an extreme neurological loss. Ultimately, the brain shows a remarkable degree of plasticity and an ability to heal itself (Bethune & Doidge, 2015). Phineas Gage, mentioned earlier, for example, was able to demonstrate a remarkable level of recovery from his injuries through learning and development over his lifespan, going on to become a stagecoach driver in Chile where his livelihood depended on the use of many of the skills initially damaged by his injury (Macmillan & Lena, 2010). It has been shown that Anosognosia/neglect patients can regain a level of self-awareness of their deficits over time (Bethune & Doidge, 2015). Even when a condition persists due to a neurological insult, like in the case of HM, a remaining level of metacognitive self-awareness can be utilized to compensate for the condition (Corkin, 2002).

**Synesthesia and Acquired Savant Syndrome**

In fact, brain injury does not only result in the loss or impairment of cognitive ability, but some brain injuries can cause the appearance of extreme skills in mathematics, geometry, music and artistic expression. Anecdotal historical evidence of savants is common. Stories of individuals like ‘Blind’ Tom Wiggens who despite being blind and possibly autistic became the first African-American to give a command performance at the White House for president James Buchanan. Plus, popular portrayals like Dustin Hoffman’s character in the movie “Rainman”
have served to romanticize the idea in the mind of the public. Often these savants are born with otherwise debilitating neurological disorders, and yet still possess extreme mental powers. However, building evidence is beginning to demonstrate that such conditions are more than just an accident of birth, they are in fact the result of specific brain injury (Piore, 2013; Snyder, et al. 2003). There are presently at least 50 identified cases of individuals developing extreme cognitive abilities after receiving a head injury resulting in a condition described as Acquired Savant Syndrome (Hughes, 2010).

One of the most surprising cases is the story of Daniel Tammet, who became a synathsted, able to perceive numbers as shapes and colors, following a fit of epileptic seizures at age three (Tjentz, 2012). For most synathsteds their condition causes numbers to slightly glow a distinct color, however Tammet’s condition came with a corresponding vision of a shape. Tammet credits his synaesthesia with his ability to make incredibly complex calculations at lightning speeds (Treskate, 2012). For many with synthesis there is an interaction between abstract cognitive symbols and perceived sensory experiences, which allows for deeper processing of certain kinds of information, like the extreme mathematical skills demonstrated by Tammet. Interestingly, most people who have the condition do not realize they have it, and finding out if one has the condition requires a degree of metacognitive realization. In fact, diagnosing synesthesia was not possible until fairly recently. There are several synthesis tests that, while not standardized, identify the condition by how quickly test subjects identify the frequency of the number 2 in a field of 5s (Eagleman, et al. 2007). Because synathsteds perceive a uniform color corresponding to a given digit, they are able to identify numbers from a field of differing numbers quicker and with fewer mistakes than non-synathsteds.
In a sense, unlike the earlier discussed Wernicke's or neglect patients, that have lost the ability to consciously perceive a dimension of the cognitive world that undamaged individuals take for granted, these individuals suddenly become aware of perceptual dimensions that were previously repressed in their undamaged brain. This perhaps suggests that there are, potentially, neurological governors that restrict our conscious access to certain categories of perception (Snyder et.al 2003) and thereby restrict our ability to metacognitively process information. This line of research also invites the question of whether metacognition, or other processes, could unlock these perceptual restrictions. For example, Snyder et.al (2003; also see Snyder, et al. 2006) demonstrated that transcranial magnetic pulses can be applied to the left-frontal temporal lobes of functionally normal individuals to produce states of improved mathematical and creative performance seen in savants.

*Figure 15.*
Temporal Lobe

*The location of the Temporal Lobe in relation to the Parietal and Frontal.*
Neuroplasticity

Along with the ability to detect and develop our cognitive skills, metacognition also plays a surprising role in neuroplasticity. Neuroplasticity is the brain's ability to reshape and even heal itself. Neuroplastic phenomena were at one time considered to be rare, and even negligible phenomena. However, thanks to the pioneering work of researchers like Norman Doidge (2007, 2016) and the power of advanced neuroimaging capabilities, neuroplasticity has become an area of intense study.

At its simplest level, neuroplasticity works as an extension of the old, “use it or lose it” principle. It has been shown that there are direct morphological effects on brain regions associated with use (Gaser & Schlaug, 2003; Levitin, 2006; Maguire, et.al., 2000; Sluming, et al. 2002). Directed animal studies into memory and learning like those carried out on sea slugs by Eric Kandel (2001), which have demonstrated that learning produces neurostructural changes. As mentioned earlier, the London Cabbie Study by Maguire, et.al. (2000) demonstrated that increased use of visual memory in humans produces noticeable anatomical changes in the size of their hippocampal. While this study is generally cited as evidence for a hippocampus role in memory formation, it is also evidence of a metacognitive impact on brain plasticity.

When it comes to learning humans are doing more than simple operant conditioning. We demonstrate the ability to regulate our behavior towards learning (Dewey, 2007; Flavell, 1979). This feature of metacognitive regulation, that allows for goal directed and executive control, can also produce identifiable morphological changes to the brain, like those seen in the London cabbie study (Maguire et.al., 2000). This effect is not limited to memory. There have been demonstrated impacts on the brain’s linguistic areas in the middle frontal gyrus as well as the
hippocampus during language acquisition (Sluming et al., 2002). Volumetric increases in the size of the hippocampus, increased synaptic density in motor areas, and improved organization of white matter have been found in studies of students learning to play musical instruments (Gaser & Schlaug, 2003; Levitin, 2006).

While the neurological relationship between metacognitive regulation, practice, learning and the brain are recent discoveries a similar metacognitive regulation, practice and learning can be applied to the physical body also. There are presently 131,700,000 (Statistic Brain Research Institute, 2018) people with gym or health club memberships. We can assume that by virtue of their gym membership they intended to directly regulate their behavior to produce changes to their physical being in one way or another. Be it to look more fit, lose weight, improve their cardiovascular health, or any of a myriad of reasons. A form of metacognitive self-regulation is involved in the act of physical fitness. Efforts may wax and wane, just as in studying, but through a cognitive process of metacognitive self-regulation, what is practiced becomes habituated and physically impacts all areas of the body involved in the process in a morphologically similar way. By virtue of this interaction, humans are able to develop their physical brain in much the same way they can develop their physical body, or any practicable skill. Neuroplasticity suggests that humans can even apply this ability to stave off the effects of disability (Doidge, 2007).

There are many examples of individuals using their personal powers of metacognitive regulation to rise above a disability or adversity, but perhaps none is more incredible than the story of John Pepper (Doidge, 2016). In 1968 he was diagnosed with Parkinson's Disease. His response was to learn as much as he could about the illness and develop an exercise routine that
involved daily focused walking to combat the disease’s progression. By the time he reached his 60’s, when most Parkinson’s patients lose the ability to walk and begin to succumb to their disease, Mr. Pepper was coming off his medication, walking 5 miles per day and by most evaluative standards moving quite normally (Doidge, 2016, Doidge, 2007). His story, and others point to the ability of exercise routines, like Pepper’s, to trigger the production of brain-derived neurotrophic factor (BDNF) and other growth factors that stimulate neurogenesis (Cotman & Berchtold, 2002). These neurological compounds have been shown to increase resistance to brain insult, improve learning, boost mental performance, and effect conditions that can lead to both muscle and brain impairment (Adami, et al. 2018).

The knowledge of BDNF and the beneficial effects of movement on the musculoskeletal nervous system has changed the way surgeons and physical therapists interact with patients. After most modern procedures, surgeons rarely require more than 48 hour bed rest, and most are requiring immediate physical therapy. Along with targeted therapeutic exercise, physical therapists are told “effective exercise instruction is based on knowing a patient's learning style” (Kisner, Colby & Borstad, 2017; p.27). Their goal is to expand their patient’s metacognitive knowledge about the brain to positively impact self-regulatory adherence to restorative therapeutic routines. Metacognitive regulation plays an important role in the physical and neurological healing made possible by learning and exercise (Cotman & Berchtold, 2002).
Psycho-cognitive Approaches and Meditation

As neurologists have only recently begun to pin down the biological and chemical neural correlates of metacognition, and its power to induce learning, practice, and habit formation, psychologists have historically worked to utilize these processes more directly. What is new is that now these introspective, cognitive, psychological approaches to the mind can be more frequently investigated utilizing neuroimaging techniques, like fMRI. Neuroimaging studies of psycho-cognitive approaches allow researchers to peer into conscious processes that at one time could only be approached psychometrically. Increasingly there has been a blending of neurophysiological and cognitive modalities of investigation. Today, most psychiatric disorders are treated with a combination of both physiological, often chemical, and psycho-cognitive interventions (Busch & Sandberg, 2012; Picardi & Gaetano, 2014; Vitiello, 2009).

Cognitive-behavioral therapy (CBT) is a psycho-social intervention that focuses on the development of personal-problem solving skills that seek to change patterns of thinking and behavior. It has been shown to be an effective treatment for numerous psychiatric conditions, from depression to psychosis (Hollon & Beck, 1994). CBT has been shown to produce significant metabolic changes in the hippocampus and dorsal cingulate according to PET scans of cerebral glucose metabolism (Goldapple, et al. 2004). Moreover, CBT has demonstrated neurosynaptic neuroplastic effects producing morphological changes that have been demonstrated in the treatment of conditions like phobias (Paquette, et al. 2003), and obsessive-compulsive disorder (Rotge, et al. 2009).

CBT is yet another instance where conscious cognitive action has been shown to lead to neurophysiological changes. There is a clear relationship between CBT, metacognition and
self-regulation. Discoveries, such as these, have served to spark interest into neuro-cognitive research of other purely cognitive and contemplative practices, such as mindfulness and meditation. This, in turn, has led to a wave of neurological findings about the neurotherapeutic effects of meditation that have removed the stigma of scientific investigation into these historically religious practices (Purser & Loy, 2013).

Meditation encompasses a diverse set of ancient introspective practices that seek to develop a unique kind of metacognitive knowledge and regulation. While there are many forms of meditation, all require introspection into the mind’s conscious attention (Cahn & Polich, 2013). Some require the ability to maintain focus on a particular object (Kozasa, et al. 2012) known as concentrative practices (Cahn & Polich, 2013). Other forms, known as mindfulness practices, involve allowing thoughts, feelings, or sensations to arise, while paying close attention (Kabat-Zinn, 2003). Also, different approaches have been correlated with different cognitive impacts. For example, Transcendental Meditation, a concentrative practice, has demonstrated marked improvement in creativity (p< .001), practical intelligence (p<.0003) and fluid intelligence (p<.001) (Hagelin, 2014).

Because of this diversity it can be difficult to determine what aspects of meditative practice are specifically therapeutic, but if earlier studies of learning, practice and habituation are a guide then we will find it is related to metacognitive regulation. Its effect on the morphological structures of the brain are highly correlated to those seen in other metacognitive activities. For example, meditation has been shown to affect the size and conductivity of frontal brain regions (Luders, et al. 2011). However, meditation has also demonstrated a unique impact on the
efficiency of processing (Kozasa, et al. 2012) and even electroencephalographic measures of theta and alpha activation (Cahn & Polich, 2013).

Meditative practices also impart documented therapeutic effects. According to a 2015 meta-analysis of systematic reviews, evidence supports the use of mindfulness programs to alleviate symptoms of a variety of mental and physical disorders (Gotink, Chu, Busschbach, Benson, Fricchione & Hunink, 2015). Mindfulness meditations have shown promising results as a treatment with individuals suffering personality disorders and adolescents with behavior disorders (Swart & Apsche 2014). A study of first through third grade children found that a program of breath awareness and yoga improved the children’s attention and social skills while also decreasing test anxiety when compared to controls (Napoli, Krech, & Holley, 2005). Other investigators (Harrison, Manocha, & Rubia, 2004) found Sahaja Yoga Meditation, an awareness practice related to mindfulness, was an effective intervention for children with ADHD and their families. This intervention demonstrated improved self-esteem, reduced ADHD symptoms, stronger relationships between parent and child (Harrison, Manocha, & Rubia, 2004). The demonstrable neurotherapeutic effects of meditation has led to its inclusion in many newer psycho-cognitive interventions and treatment regiments (Gotink et.al, 2015)

Resting State and the Default Mode

It may also be that the human brain is particularly attuned toward self reflection during times of quiet contemplation. Several studies have found (Buckner & Carroll, 2007; Moran, Kelley, & Heatherton, 2013; Spreng et al. 2009) that people engage in self-referential processing when they are not attending to the outside world. This is because the brain engages in a specific
neuronal activation, which occurs when the brain is at rest, called the default network (Damoiseaux, et al. 2006). The brain's resting state can be thought of as what the brain is doing when it is not doing anything, and this is why the brain's resting state is sometimes called its default mode.

What is interesting about the default mode is that the region of peak activation during rest is in an area of the medial prefrontal cortex (MPFC) called Brodmann’s area 10 (BA 10), which has been found to be engaged in self-referential processing (Denny, Kober, Wager & Ochsner, 2012). The MPFC is the largest of prefrontal regions in the brain (Öngür, Ferry & Price, 2003), and has been found to activate when people reflect on their emotions (Ochsner, et al. 2004), think about their personality (Kelley, et al. 2002), or their past and future (Spreng & Grady, 2010; Spreng, Mar, & Kim, 2009). For this reason the MPFC/BA 10 has important connections to metacognition and self-reflection.

However, along with demonstrating strong reactions during self-reflective tasks, the MPF region, ironically, has also shown activation while processing social information (Moran, Kelley, & Heatherton, 2013). These regions are considered by some researchers to be part of the “social brain” (Heatherton, 2011; Lewis, Rezaie, Brown,
Roberts, & Dunbar, 2011). Research by Meyer and Lieberman (2018) and Spunt, Meyer and Lieberman, (2015) have further localized these to more specific regions, with MPFC/BA 10 being involved with self-reference and dorsal medial prefrontal cortex/ Brodmann's area 9 (DMPFC/BA 9) being more involved with social referencing. This seems to suggest strong neuro physical relationships between introspective self-reflective thought and a natural tendency to connect introspections to social relationships (Meyer & Lieberman, 2018). It may be that during quiet times, when we disengage from directive thinking, the natural tendency of our default mode is to self-reflect on ourselves and our social relationships.

\textit{Figure 17.}  
\textbf{The Neuron}

\textit{Illustration of the structure of the neuron}
The Neuron

The neuron is the most fundamental part of our brain’s architecture. The complexity of the brain is derived from its physical system of fractally branching neurons, spread like a web throughout the body. The brain is made of roughly 100,000,000,000,000 neurons (Swanson, 2003, p.11). Neurons are made up of three basic parts. First, the main cell body, which contains the nucleus, the axon, which transmits messages and the dendrites that receive chemical messages. These chemical messengers, called neurotransmitters, diffuse across a tiny gap between the cells called a synapse. These neurotransmitters connect to receptor sites on the synapse of the receiving dendrite through a lock and key method where the shape of the neurotransmitter fits into a suitably shaped receptor site (Calvin & Ojemann, 1994; Lefkowitz 2004).

*Figure 18.*

The Synapse

![Illustration of neurotransmitter release and absorption in the synaptic cleft](image)
Individual neurons are among the most diverse cell types in the body. They fall into three distinct categories. Sensory neurons that are responsible for carrying information from the sense organs. Motor neurons carry information from the muscles and glands of the body, and often have long axons. The third class of neuron is the interneuron, which lie between connections of sensory and motor neurons and play a role in regulating excitatory and inhibitory patterns in neural networks (Swanson, 2003, pp.37-38). All neurons are thought to work by transmitting information utilizing electrical impulses that travel through the axons and plasma membrane to the synapse where the impulse is converted into a chemical signal (Barnett & Larkman, 2007). When this chemical signal crosses to the other side of the synaptic cleft they are, in turn, converted into electrical impulses that are, in turn, sent down the axon to the synapse between the next neuron. It is thought to be the alternating of electrical and chemical signals between neurons that produces the vast and rich neurological behavior associated with the brain and nervous system (Medina, 2011; Swanson, 2003). This neuronal system of electrical and chemical transmissions of information is common to the nervous systems of all organisms, except single celled protozoa such as paramecium and euglena.

It is presently believed that individual neurons function in the brain much like the individual switches in computer processors. Each neuron is specialized and becomes electrically excited or inhibited in response to specific information (Calvin & Ojemann, 1994). For example, in the case of sight, specialized sensory neurons called rods and cones detect photons entering the eye. These neurons respond only to specific wavelengths of light: red, green or blue. The differing intensities with which these neurons respond to each color, leads to a gradual building of the perception of the other colors we perceive. This information is sent to interneurons that
may, in turn, become excited by qualities of shape, or movement. Chains of interconnected neurons respond in a binary, excitatory or inhibitory fashion as the information moves through a vast neural network to the occipital lobe at the back of the brain. From the occipital lobe a complete visual picture is sent toward the more frontal regions of the brain (Medina, 2011; Swanson, 2003).

As this picture is moved forward through the brain, other neurons are excited or inhibited in more complex and highly specialized ways, adding information to the perception. Much like a computer builds its interface through a computational system of binary bits of information, represented as ones and zeros, the brain builds its perceptual reality through a computational process of excited or inhibited neuron behavior (Medina, 2011). The first computational model of neuron function was a model proposed by Hodgkin and Huxley in 1952.

This model assumes that brains are analogous to the hardware of a computer. It has not been until fairly recently that neurologists have begun to learn enough about computer science, and visa versa, to develop theories about the software that runs on this neuronal hardware that produces cognition. The chief thrust of this research has been driven by computer programmer's trying to program a computer with more human-like cognitive capacities. Presently, computers have been programed to carry out many human activities, from chess to telemarketing phone calls. However, all of these are very narrowly defined, and task focused. Even though the artificial intelligence (AI) of computers is often magnitudes more efficient than a human could ever be at specific programmable tasks, computer scientists have not been able to program a machine with even a rudimentary level of what is known as General Artificial Intelligence (GAI). A machine with GAI would possess the cognitive flexibility and a capacity for problem
solving that is natural for most animals and humans. While many computer scientists would love to produce a working GAI, there are presently no serious laboratories working on the project because there are presently no clear computational solutions to the problem, and the ones that do exist are considered by some to be, "barely coherent" (Pinker, 2018, p. 298).

For this reason, nero-computational theories have focused on modeling specific kinds of brain activity. One computational model of what could be taking place in the frontal lobes is called adaptive resonance theory (Grossberg, 1999). It explains that the brain achieves selective and inhibitory control through a top-down filtering mechanism that enhances task-relevant information and inhibits, similar, but irrelevant information. Along with being among the first neuro-computational cognitive approaches to brain function, the model addressed a problem known as the stability-plasticity dilemma, which is a memory storage dilemma of how one can learn about new objects and events, quickly, without being forced to forget previously learned information. By this neural processing model, center-on, or relevant information, is upregulated, and irrelevant, surround-off activity is inhibited. Through this organizing operation many aspects of neuronal processing are controlled by the prefrontal executive cortex, which uses this dynamic filtering mechanism to globally control task-relevant processing (Shimamura, 2000).

Another computational model is Metcalfe’s, Composite Holographic Associative Recall Model (Metcalfe, 1993). This model is one of the few computational models that specifically addresses metacognition and frontal lobe function. This model proposes that metacognitive evaluations are based on familiarity checks, computed between new and already stored information in memory described as “novelty monitoring.” This monitoring-control
operation determines the degree to which new information is bound into episodic memory. Computational models of this conceptualization have done a notable job at simulating aspects of the monitoring and control functions of the frontal lobe. Computational models have also shown that damage to this executive function program produces behaviors similar to those seen in Korsakoff patients who suffer frontal lobe dysfunction (Metcalf, 1993, Shimamura, 2000).

Another proposed model, which seeks to computationally explain how executive control is imposed, utilizes links that associate information in working memory (Kimberg & Farah, 1993). These links allow for the selection of appropriate items based on contextual factors. Surprisingly, these Connectionist Models do not use an inhibitory control mechanism (Cohen & Servan-Schreiber, 1992). Inhibition turns out to be extremely difficult to program. There are, presently, no computationally easy or reliably accurate variables that can be used to help a machine differentiate between an appropriate response from an inappropriate response. This approach (Cohen & Servan-Schreiber, 1992; Kimberg & Farah, 1993) has tried to show that, perhaps, the use of a common contextual factor could be used to produce similar behavioral outcomes to those produced through inhibition.

**Neurochemical Implications**

While fMRI related imaging technologies and localized brain injury identify areas of high specialization that correlate to specific areas of the brain, this cannot be the whole story. There is a neurochemical level of interaction in the brain that also exerts a powerful effect on thought and the ability to be self reflective. This area neurochemical interaction exists in the tiny spaces between neurons, the synapse, where information is transferred. We know that there are certain
compounds and drugs that can seriously impair judgment and other metacognitive behaviors, and anesthesia can remove consciousness altogether. We also know that a proper balance of neurochemicals in the synapses is necessary for effective functioning, and that certain compounds can even enhance function (Sapolsky, 2017).

One neurochemical that exerts a considerable effect on our metacognitive abilities is dopamine. Dopamine is central to the brain's reward pathway. It is part of that wonderful feeling of accomplishment that our brain naturally rewards us with when we achieve a goal. Nerve cells in the midbrain and frontal lobe form the core of a dopaminergic system, which increases activation while learning and receiving an award. However, closer investigation seems to indicate that dopamine is more about the anticipation of receiving a reward, rather than the actual award, as spikes in dopamine are recorded most prominently when working toward, rather than after receiving a reward (Sapolsky, 2017). By this mechanism dopamine fuels goal directed behavior by calibrating the value of a reward with the work it takes to achieve it.

Dopamine release also decreases over time, relative to a given reward. Over time a reward that was at one time very motivating and enjoyable will gradually fail to produce the same spike in dopamine, making it feel less enjoyable and fulfilling. This property of diminishing dopaminergic returns drives human behavior toward ever expanding goals, but also underlies the human propensity toward addictive behavior (Pessiglione, et al. 2008).

How dopamine does what it does remains somewhat mysterious. Dopamine is known to produce affective states that can help improve focus, which is why ADHD medication like Adderall and Ritalin are prescribed (Cook, et al. 1995), and why many people drink coffee. Paradoxically, dopamine can also impair focus, which is why drugs that work most strongly on
the dopamine system like marijuana and painkillers are prescribed, and also abused. Interestingly, dopamine plays an important role in increasing our control over motor activities, as patients with decreased dopamine production also present with motoric disorders like Parkinson’s (Sapolsky, 2017).

Testosterone is another neurotransmitter that can impact metacognitive thinking. In popular culture, testosterone is linked to aggressive behavior, but closer investigation reveals this link is weak (John Archer, 2006). Testosterone more likely enhances an individual's tendency to fall back on established behavior, making a person who is already prone to aggression more aggressive (Sapolsky, 2017). Testosterone makes individuals more egocentric (Wright, et al. 2012), impulsive and willing to take risks (Bos, et al. 2012), but also increases pro social behavior (Sapolsky, 2017). Testosterone may impact metacognition by decreasing activity in the prefrontal cortex, thereby interfering with the brain's ability to plan and execute. However, testosterone is also a driver of the, “‘winner’ effect in lab animals, where winning a fight increased an animals willingness to participate in, and its success in, another such interaction,”(Sapolsky, 2017, p.102).

Presently, only a relatively small number of neurotransmitters have been well study. The effects of these compounds on human behavior, and the mechanisms of their function requires considerable consideration. While perhaps not directly involved in the brain’s generation of the metacognitive ability it is clear that these chemicals play a powerful role in determining how metacognitive abilities are deployed by the brain.
Single Neurons and Electrical Brain Stimulation

Another tool of neurological investigation that was briefly touched on earlier and enables the close investigation of the behavior of neurons is called electrical brain stimulation (EBS). EBS has been used since the mid 1800’s. The basic procedure of EBS involves applying direct electrical current to specific areas of the brain producing a corresponding neurological experience or behavior. When electrical current is applied to specific areas, a patient may demonstrate unique responses, ranging from changes in blood pressure and breathing to sensory/motor, emotional and cognitive experiences (Calvin & Ojemann, 2010).

Research by Jerry Lettvin (Gross, 2002) suggested that people have neurons that respond, specifically, to photos of their grandmother. These subject-specific neurons have come to be called “grandmother cells”. Later research done by Quiroga (2013) identified neurons that fired steadily each time images of specific celebrities, like Jennifer Aniston, appeared on a screen, but did not fire at all for other photos. The observed effect remained steady for line drawings, profiles, or even if the celebrity was wearing a mask. Interestingly, these activations seemed to be categorical rather than specific, for example a firing, “neuron that responded to Luke Skywalker also fired to Yoda, another Jedi from Star Wars,” (Quiroga, 2013, p.31).

What can be inferred from these studies is the subject of much debate. Equivocally, these findings cannot be evidence of extreme localization, as it would mean that the death of a single neuron would result in the loss of a wide and important concept or memory, such as the memory of one’s grandmother (Quiroga, 2013). Another big problem with these studies was first illustrated by Carl Lashley (1923). After repeated motoric EBS experiments on monkeys, he
found that correlative results changed over time. It seemed, “One day's mapping would no longer be valid on the morrow.” (Quotation Edward G. Boring in Doidge, 2016, p.106)

These findings do suggest two things. First, that the brain structure is more likely composed of networks of neurons that respond to related information rather than interlocking areas of localization. This interrelated neuroanatomy may make the brain far more flexible than previously believed (Doige, 2016). Second, it shows that single neurons are capable of processing information that is far more sophisticated and associative than would be expected from a binary computational system. How the brain makes these sophisticated associations on the neuronal level could have a tremendous impact on our metacognitive understanding and lead to new approaches to learning and self-regulation. This perhaps indicates that there are primitive or perhaps precursive metacognitive actions being performed by the brain at a neuronal level.

**Mirror Neurons and Subcellular Structures**

One particular class of neurons that are especially relevant to the study of metacognition are called mirror neurons. Mirror neurons are neurons that activate when one observes directed action. Interestingly, the neuronal activation mirrors the neuronal activations that would occur if a person was actually engaging in the observed behavior (Keysers, 2009; Keysers & Gazzola, 2006; Rizzolatti & Craighero, 2004). Mirror neurons reside in many of the same areas that have been correlated with metacognitive activity in the prefrontal parietal lobe, such as the premotor areas, and the inferior parietal cortex (Molenberghs, Cunnington & Mattingley, 2009).

Not all researchers are in agreement as to whether mirror neurons are truly a unique class of neuron (Hickok, 2009). Some researchers, like Lingnau, Gesierich, and Caramazza (2009)
dispute their existence altogether. This speculation comes from the fact that much of what has been surmised as the function for mirror neurons has been based on speculative and highly theoretic extrapolation of neuroimaging data (Hickok, 2009).

Chief among the most controversial findings is that mirror neurons seem to only selectively fire when confronted with goal directed behavior, like those done during a teacher’s demonstration in a classroom, as opposed to just the observation of a given movement in general (Fogassi, et al. 2005). The role of the mirror neuron in learning and education has been widely speculated upon since Rizzolatti and Craighero presented their initial findings in 2004. Since this time, there have been continued discoveries of a relationship between these neuron firings in the brains of both teacher and learner in synchrony (Schippers, et al. 2010).

Oberman and Ramachandran (2008) have boldly proposed that mirror neurons are the source of human self-awareness. Ramachandran (2000) has further proposed that it was the evolution of mirror neurons in humans that triggered the noted archeological explosion in human capacity called the ‘Great Leap Forward’ (Diamond & Shermer, 1993, Vyshedsky 2014). This epoch has been called the great leap forward by anthropologists because for much of early hominid history very little innovation in tools and culture can be found. However, suddenly around 60,000 years ago, artifact development became rapidly more advanced, as evidenced by improvements in tools, art and culture. It may be that the biological evolution of mirror neurons ushered in an age of new cognitive capacities in homosapians, explaining this rapid development.

Other researchers like Vyshedskiy (2014) have found evidence in the art, technology and culture of this period of human development that demonstrates these advances in thinking,
imagination and abstract reasoning go beyond the learning and imitation paradigm proposed by Ramachandran (2000). I also believe it is justifiable to suggest another evolutionary candidate for the ‘Great Leap Forward’ in homosapien cognitive development is metacognition. It maybe that mirror neurons are responsible for the ability to shift between the subjective and objective perspectives described by Nelson’s (1996) Metacognitive Model of Consciousness.

Ramachandran’s (2000) theory of mirror neurons has elicited a strong response from some critics. This is because it insinuates that a single neuron is capable of far more complex processing than would be expected from a single neuron. First, because mirror neurons only activate during goal directed behavior, the question of how a single neuron would know that a given action is goal-directed becomes problematic. Kosonogov (2012) has suggested that the mirror neuron cannot possibly be carrying out this function independently and must be being activated only after other brain structures have identified goal directed behavior. To comprehend the intentions of others is highly complex. It generally requires the integration of various kinds of perceptual, historical and inferential information. Though computationally complex, a single neuron would not have the power to process even simple social behavior (Churchland, 2011). Based on our present understanding, even the complexity of simple educationally focused interactions requires the input of large networks of neurons.

Neural Networks and Computation

Presently, there is wide agreement that it is the integration of neural networks, dedicated to specific types of processing that produce the advanced cognitive capabilities of humans (Churchland, 2011; Medina, 2011; Swanson, 2003). This conception best fits with what has been
discovered through the various lines of investigation we have covered so far in this discussion. This approach is further supported by advances that have been made in the field of machine learning. It has been the advent of artificial neural networks that has led to the solutions to several computational problems that were once considered to be intractable, like image identification, speech recognition and other general inflexibilities demonstrated by numerical computation (Zhang, Patuwo, & Hu, 1998; Domingos, 2015). Historically, computational learning models have been limited by the linear nature of computational coding, a technological lack of storage and limited networking capability.

The idea of programing software that utilizes networks of distributed information to solve problems actually can be traced back to the earliest investigations of machine learning (Domingos, 2015). However, this line of inquiry came to be seen as an investigational dead end due to the limits of computation. To make even simple judgments computationally can require access to massive networks of disparate information that seemed to border on the infinite. However, the last 20 years have seen exponential improvements in computational processing hardware and storage capacity. As computer hardware has improved, so has the possibility of programing large expansive neural networks capable of accurate problem solving. Krizhevsky, Sutskever, & Hinton (2012) were among the first researchers to demonstrate the power of computational neural networks by using a graphics processing unit to train a computational neural network with five convolutional layers and 60 million parameters on a set of 1.3 million images. Since this time, the use of what are known as convolutional neural networks (CNN) have become standard in most search operations, particularly in deep learning and data mining.
programs that are capable of detecting subtle patterns in large data sets (McCann, Jin & Unser, 2017), because of their many convolutional layers of processing.

The power of the CNN model is that it requires relatively minimal processing to produce results (Domingos, 2015). Historically, it was believed that for computers to solve even rudimentary problems all aspects of that problem would need to be hand-engineered, meaning that the programmer would need to be able to consider every possible input into a system, and preprogram each of these possibilities into a coded solution. The problem of this computational approach is on display in early, adventure style computer games like Colossal Cave Adventure (https://www.amc.com/shows/halt-and-catch-fire/colossal-cave-adventure/landing) where the player is able to interact with an expansive textual environment. However, gameplay was confounded by the generally non-exact nature of human communication. Humans can express ideas using a seemingly infinite possible collocation of word configurations, whereas computers are limited to only pre-programmed considerations. Due to this computational limitation much of the play in these kinds of early computer games revolved around the player trying to decipher which words or phrases the program could actually understand. This was because each entered response needed to exactly match the programs preprogrammed list of expected responses. If you are unsure of what I am explaining here please go to the above website and spend five to ten minutes playing Colossal Cave Adventure, and I am sure you will quickly realize the limitations of this style of programing for yourself, as you will find yourself spending an inordinate amount of time trying to figure out which text commands the game will actually accept.

Rather than having to program for every possible permutation of an input, CNN allows programs to filter and categorize large sets of data based on similar attributes. It does this in a
neurologically analogous way by passing information through the convolutional layers that, like neurons, process data relevant only to its receptive field. This information is then pooled into more generally related categories and given different weighted values. This process, in conjunction with the ability to self-reflect on the accuracy of earlier responses has allowed algorithmic programs to make increasingly more and more accurate responses, so much so that this computational style is called deep learning. The power of computational neural networks is evidenced by the fact that today the best checkers, chess, go, Atari 2600 video game and even Jeopardy players are all computers running variations of these self-referencing CNN algorithms (Domingos, 2015; Mnih et al. 2015).

The success of machine learning has also highlighted potential shortcomings in trying to understand what the human brain does through the surrogate of computers. The first, and most pronounced shortcoming is the amount of data these systems require to make reasonable answers to the problems they are confronted with. In the case of IBM’s Watson system (Ferrucci et al., 2010) that defeated the world's reigning human Jeopardy champ, Ken Jennings, a vast database of 15-terabytes of general human knowledge was required. This is 16,492,674,416,640 bytes of information! In general humans do not approach problems with such a store of information on hand.

This point is particularly significant when considering the learning and problem-solving abilities of children, who could not possibly have access to the stores of knowledge that computers do to make similar judgments. Essentially this is a variation of Noam Chomsky's (2006) poverty of stimulus argument that was used to disprove early behaviorist conceptions of language development. Behaviorists could never achieve a compelling explanation for how a
child could learn the complexities of a native language as quickly as they did considering the
dearth of proper linguistic examples provided in their environment. Similarly, computational
approaches to learning fail to approximate human learning and understanding (Berwick, et al.
2011; Penrose, 1989) by this same poverty of stimulus reasoning.

The problem is more than simple exposure. Even successful algorithms, like the ones that
learned how to play Atari video games on their own (Mnih et al. 2015) are clearly not
performing a learning function that is akin to what is done by humans. First, the program itself
uses raw pixels as its input data and derives its output from a value function estimate of future
rewards. Humans, inversely, perceive the input of the video game holistically, clusters and
configurations of pixels are viewed as whole objects, like tanks or walls (Goldstein, 2009). These
approaches produce very different learning behaviors. Whereas humans will generally make
large movements that become, through repetition, more inhibited and exact, the computer
program initially makes small moves. Even after 100 trials, it still appears that the computer has
little real understanding of what it is doing. Whereas humans generally apprehend the main
objective of a game like Breakout after only a few trials.

The reason for the program’s different learning behavior is that it is processing,
systematically, through all possible single pixel states. Machine learning, in this sense, is an
extreme extension of the old “not seeing the forest for the trees” metaphor. Except what these
algorithms are doing is literally building a map of the forest tree by tree and storing it in
memory, to get through the forest later. Because machines do not get bored, they can play the
game until they are able to narrow down their movements to a point where it looks like actual
game play. After hundreds of hours of more game play, computers begin to identify the most
optimal way of playing a video game, which they then replicate flawlessly ever after (Mnih et al. 2015). Again, this is very different from what is seen, even in highly skilled human players, who always must remain vigilant not to make a mistake, and are rarely able to replicate game play exactly. It is also important to note that some games, like Video Pinball and Breakout, the computer was able to become extremely good at, while other games like Asteroids and Ms. Pac-Man the program was unable to figure out (Mnih et al. 2015).

It is also important to note that even deep learning programs, like the one described above, require tremendous amounts of continued ‘hand programing’ to help the fledgling algorithm along. Hand programing is not analogous to the help human students receive from teachers, who may help their students along by identifying salient features, or maybe even model the proper learning behavior. When programmers have to hand program a deep learning algorithm it means they are going directly into the code of the program and changing the way it processes and perceives the information. So, while these programs can, in some sense, learn from their past experience, this learning is limited in scope, and they cannot be taught, or learn, in a traditional human sense.

In fact, these programs require humans to watch their development, as they lack the metacognitive ability to self-monitor, and will continue to develop unproductive responses that fall outside of their algorithmic perview. In other words, if a computer algorithm is going to be able to detect a certain class of errors it must be programed to do so. Perhaps the most famous, and humorous, example of this difficulty occurred when Eric Brown tried to prepare IBM’s computer Watson for its television performance on Jeopardy by letting it learn natural human language through studying language on the internet. Ultimately, he had to go back and hand
program the algorithm because the process resulted in Watson peppering its general communications with swear words, and slang taken from a site called The Urban Dictionary (Ferrucci, et al. 2010).

So, while computational neural networks are based on a theory that is analogous to present theories of neuron function, they do not appear to be actually functioning in an analogous way. It is also telling to point out that, despite the complexity and power of the present generation of computational programs and hardware, it presently appears to be impossible to program the human capacity for understanding (Penrose, 1994; Penrose, 1989). Despite the tremendous advances in the field of machine learning, it is unclear if what is being demonstrated can't even be designated as a precursor, or kind of proto-metacognition. Unlike humans, that possess an ever-expanding understanding of the world, punctuated by pronounced developmental leaps in their ability to abstract information from what is known, computers doggedly follow a step by step process. They cannot expand out of their pre-programmed parameters without direct human intervention. Even their capacity for self-reference is algorithmic and restricted to parameters already present in their programing. This is very different from the kind of cognitive flexibility, in the face of ambiguity, that is seen in the cognitive processes of humans, and some animals.

The advanced process of metacognition and understanding do not appear to have a computational solution (Penrose, 1994; Penrose, 1989). Kurt Gödelś (1992) succinct Incompleteness Theorem, which derailed Alfred North Whitehead and Bertrand Russellś work to solidify the logical foundation of mathematics and determinism in 1931, also seems to indicate that computation will never be capable of the kind of self-regulation and self-understanding that
forms the core of human metacognitive capacity. The ability to mathematically represent qualia, such as the experience of the redness of a rose, or a feeling of love or even the basic physical sensation of touching an object all seem to be features of cognition that cannot be represented computationally. This indicates that there are whole classes of cognitive ability that are not well explained by our present theories. This class consists of experiential states, of which understanding (Penrose, 1994; Penrose, 1989) and metacognition are advanced iterations. It has been suggested by Rodger Penrose (1989) that this problem indicates fundamental errors in our present conceptualization of how neurons function and how we understand the basic physics of reality more generally.

Rodger Penrose’s (1989) solution to this problem was to suggest that there were likely subcellular neuronal structures that regulated experiential states and produced understanding by, somehow, interacting with, or exploiting subatomic properties, such as quantum entanglement. Quantum entanglement (QE) is an extremely well verified property of subatomic matter (Horodecki, et al. 2009; Kaiser, 2014). It is particularly relevant because QE has been shown to be related to information transfer between particles (Bennett et al., 1993; Horodecki, et al. 2009). It is also behind a not well understood property of binding discrete parts together to form physically larger single entities. For example, when quarks are subsumed into protons, or protons and electrons from atoms, or atoms form molecules.

The extent to which quantum mechanical properties may be involved in cognition may be under appreciated. It has generally been assumed that quantum mechanical properties of matter are so remotely removed that their effect on everyday physical properties, at our size and scale, is negligible. In as far as these properties could be affecting brain function, Max Tegmark (2000)
proposed that the mathematics of quantum mechanics seemed to indicate that the insides of living cells are too “wet, warm and noisy” (Tegmark, 2000) to produce useful quantum collapses like those proposed by Penrose (1989).

However, since this time there has been building evidence that quantum mechanical properties do indeed exercise important physical effects at everyday scales. Our sun's most important quality to life on this earth, its ability to radiate heat and light, are the result of a macro expression of quantum tunneling phenomena (Siegel, 2015). Presently, the theory that living cells are too wet, warm and noisy for quantum interactions to occur is beginning to fall as more expressions of biological systems exploiting quantum properties are uncovered, such as recent discoveries in plants during photosynthesis (Romero, Novoderezhkin & van Grondelle, 2017) and geese during migration (Hiscock et al., 2016).

Perhaps the easiest demonstration of quantum involvement in a biological system comes from investigations into human smell, and the processing of olfactory stimuli (Palmer, 2013). Turin, (1996), found that humans could smell physically imperceptible differences between hydrogen with one neutron and hydrogen with two neutrons, also called deuterium. Both of these two compounds fit into the same lock and key receptors of the nose, but because of quantum vibrational differences between the two substances, caused by a difference of only one neutron, differences between the two compounds are detectable. How such slight quantum vibrational differences could be detected is still unclear. One possible candidate are intra cellular structures called microtubules, which have been proposed to serve as subcellular regulators of consciousness (Hameroff & Penrose, 2014). The theory portends to hold the answer to several questions confounding neuronal theory, such as why single neurons seem to be capable of so
much more processing power than would be expected, and how single celled organisms hunt for food without neurons. However, the theory is presently lacking a nonmathematical, physical or biological methodology to investigate the validity of its claims.

**Discussion**

The neurological underpinnings of metacognition are complex, multifaceted and presently not well understood. While there are tantalizing areas of localization, clearly dissociable regions of activation for metacognitive functions and behaviors have been rare. Inversely, if metacognition is more the result of large-scale neural networks, distributed across the brain, than why is there as much localization as there is in the parietal-prefrontal pathway? Perhaps both localized and distributed conceptualizations of brain function are the wrong way to describe the relationships between observed neuro-biological activity in these cortices and metacognitive behavior. Or maybe we should be patient and allow the tremendous advances that have brought us to this point to continue to provide deeper levels of investigation and insight into our current explanations. At this stage the hunt for a neurological center of metacognitive activity ends vaguely in the prefrontal cortex, but it traces its way through nearly every level of the brain.

Plus, which types of investigation should we most value? Are blood flow activation studies using PET, SPEC and fMRI truly the most discerning and valuable ways to infer about brain activity? Limiting our investigation to one mode of study or methodology could lead to missing other important avenues of perspective and evidence. However, if we read widely from the cornucopia of experimental literatures and methodological investigations into the brain than
questions of sense-making and organization become daunting. Which experimental models should be given preference, or more or less attention? In this paper I have tried to present a wide sampling of investigational methodologies, such as surgical ablation, electrical brain stimulation, lesion studies, split brain, and primate studies as well as numerous neuroimaging studies. My hope has been that following the themes of metacognition through neurological studies would provide a new depth of understanding for the subject. However, the perennial fear of this approach is have I cast too widely? Is it possible to even maintain a cursory understanding of all these different areas of investigation, and what they mean?

Interestingly, in the course of researching for this paper I have found that metacognition may also have something of true research value to offer the field of neurology. Metacognition can offer a useful taxonomy to the study of the mind that is capable of focusing and guiding future research. Presently the fields of neurology and psychology approach the subject of human cognition from two different loci. Neurology has historically been the investigation of the physical brain, its physical structures and bio-chemical interactions. Psychology has historically been the investigation of the mind, through psychological processes and behaviors.

*Figure 19.*

*The present conceptions of neurology and psychology on a continuum showing how each approach favors investigating physical or conscious phenomena*
In recent years, thanks to the development of advanced neuro imaging technology, neurology has become less about describing the physical features of the brain, and more about describing the physical interactions of the brain during specific kinds of tasks. Similarly, psychology has become less about describing various kinds of thinking and behaviors, and more about interaction and the interplay between thoughts, environment and biology. Historically, research in these fields could be plotted on a continuum from biological to psychological.

Thanks to the amazing insight of John Flavell (1979), the field of metacognition divides cognitive experience into a continuum of metacognitive knowledge, which are ideas about the brain and thinking, and regulation, which are processes and conditions of behavior regulation. In a very real sense this continuum subsumes all fields of investigation into the brain and behavior.

\begin{center}
\textbf{Figure 20.}
\end{center}

The present conceptions of neurology and psychology on a continuum showing how neurology is concerned with the development of knowledge about the brain and psychology is concerned with improving the brain’s regulation.

What is truly interesting, and helpful in terms of research is that both these continuums can be overlaid forming a four-quadrant field. Using an x axis that measures the gradiance from
physicalness to consciousness and a y axis that denotes temporal stability, broader patterns in the data can be identified and visualized, clarifying investigational parameters.

Figure 21.

By combining these two continuums one is better able to visualize the relationships between differing approaches into the study of the workings of the brain.

One of the helpful aspects of this conceptualization is how it highlights both the interrelatedness, and subtle differences of investigation. For example, the more biological nature of
executive function becomes apparent. Research methodologies like fMRI, electrical brain stimulation, cognitive behaviorism and psychology can be represented. Most important, is it helps to identify border concepts that could lie in cross-overable regions in between, facilitating both psychological and neurological investigation about the interface between the biological and mental fields of cognition. It is important to note that this is an organizing conceptualization, and the placement of any one concept is certainly open to reasoned debate, but in that process a deeper level of thought and understanding will occur, facilitating integration of concepts that are key to understanding of brain function.

Executive function is one of those concepts that exists in the border zone between psychological and biological function. Because of this, many of the psychological methodological procedures that were originally developed to investigate it are transferable to methodologies that utilize newer neuro imaging technologies. This is because the methods used in psychological investigations of executive function, such as inhibition and go and no-go activities, transferred well into neuroimaging studies of activations responsible for the behavior.

The model also suggests that another area of potentially fruitful research would be into transitions between division of consciousness, such as those found in subjective and objective regulatory states outlined in Nelsonś (1996) Metacognitive model of Consciousness. By investigating concepts that fall into this central border region it should be possible to find conscious phenomena that are involved in switching from subjective to objective conscious thoughts that could also be imaged using fMRI technology.

Projects like the Human Connectome project will offer unprecedented understanding of the physical conductivity of neurological pathways involved in self-regulation. Imaging
capacities will continue to improve the ability to discern finer grained details of what is occurring when individuals move between differing frames of consciousness. Such research could begin to reveal other mechanisms that exist within consciousness and their connection with the deeper non-conscious biological forces behind successful planning, learning and executive function. Such investigations could help to clarify if the subjective/objective switching of consciousness is an interaction between concrete perceptions and abstract representation, or perhaps an interaction between external and internal experiences by consciousness.

A deeper, neurological, understanding of how conscious shifts between subjective and objective stances could provide a measure of metacognitive capacity. Such a neuro-metacognitive measure of capacity could be applied to developmental and psychiatric conditions to improve treatment and outcomes. The act of learning is generally considered a very psychological activity. However, studies, starting with Eric Kandel’s on the neurosynaptic growth of sea slugs, on through to the famous London Cabbie study, and the discovered links between exercise and the production of brain-derived neurotrophic factor suggests a bidirectional, psychological and biological mechanism, is responsible for learning. This holds tremendous hope that interventions that target one modality, such as a psychological intervention like CBT, could affect biological factors that impact learning and visa versa.

Biological and psychological investigations of individuals like John Popper, who developed an exercise regimen to stave off his Parkinson's disease, as well as studies into the impact of depression and mindset, will yield valuable information about our ability to self-regulate and self-direct learning in neuro-therapeutic ways. This could also explain why combination therapies, like SSR drug and cognitive behavioral therapies have been shown to be
the most effective treatments for certain disorders. It is because such an intervention address both biological and psychological sides of this mechanism. Plus, a better understanding of the underlying processes of cognition will reveal underlying deficits or dimensions to commonly understood disorders that are presently not well understood and remain unexplained. An example of this occurred recently when Stephanie Wong, Bernard Balleine and Fiona Kumford (2018) drew upon the developing body of information on the neurology of executive function and goal setting to propose a behavioral-variant form of frontotemporal dementia that may aid in early detection of dementia patients and new possible treatment options.

The placement of learning on the four quadrant graph denotes its special significance to research. Of all the concepts represented, learning seems to occupy an area in the middle boundary area. This means that its impact can be seen on all four quadrants. This also means that the greatest variety of investigational techniques can be utilized to understand the phenomena. It confirms the central aim of research into the brain is to promote our understanding of the brain's most central function, learning.

Finally, this metacognitive conceptualization of the neurobiological mind is wide enough to suggest areas of investigation that have been historically ignored, requiring greater investigation. It also could suggest the types of investigation that would bring these concepts closer to the border regions where both quantitative and qualitative data on the phenomena could be collected. Highly psychological activities such as meditation and creativity, as well as the biology around electrochemical interaction in the synapse, and the mapping of physical neurological pathways lie in the corners of the model, indicating that these areas may in fact hold new information not yet discovered or integrated with other investigations.
Conclusion

It is hoped that this investigation provides a valuable overview of the many diverse threads of the metacognitive phenomena, and their relationship to an ever-developing body of information about the biological underpinning of our cognition. The explosive growth in our collective neurological understanding as a species has been made possible by our ability to apply powerful new tools of investigation to a long tradition of metacognitive inquiry. I feel there is good reason for this noted crossover. Conceptually, metacognition is our ability to understand the relationships between the mental and physical worlds we inhabit, plus, how that knowledge can be used to affect them. Therefore, I feel that metacognition is a conceptually much wider field of investigation than has been appreciated. Not only does it subsume the concept of executive function, it can accommodate biological insights from neurology and psychological insight about our mental states. Most importantly it seeks to take this information one step further by applying it in ways that improve our overall function as humans.

This is because metacognition represents a conceptual example of what Douglas Hofstader (1980) has called a strange loop. It is a pattern inherent in self-reflection that is able to exist, paradoxically through multiple levels of interpretation. So while each individual, and even some animals can demonstrate metacognitive behaviors, we, in turn, can find regional brain activations that can be thought to regulate these metacognitive demonstrations. Inversely, if we expand our perspective we can also see metacognition exists in a small group or collective like a classroom where interactions between student and teacher make learning explicit. There is even room for the conceptualization of metacognition at the societal level of human interaction, where we can see differences in the ability of some societies to identify problems and regulate
themselves toward a solution, in a process that is analogous to the process of metacognitive integration seen in the brain of the individual person. In fact, it is the general metacognitive ability of the individuals of a society that makes such societal problem solving possible.

Uncovering the neurobiological underpinnings of metacognition, and identifying their connections to deeper psychological processes, will be extremely valuable areas of research. A similar box within a box problem was uncovered through our examinations of what constituted matter. As researchers uncovered deeper conceptual levels of matter we unlocked the power of the atom. This investigation into the relationships and underpinnings of cognition to biology and the physical world could open up our metacognitive understanding and capacity for self regulation in equally startling and powerful ways. Such investigations could provide a scientifically more grounded approach toward education and fundamentally change the way we approach problems of self-development in the future.
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