UTILIZING BIOMETRIC MOUTHGUARDS TO DETECT MILD TRAUMATIC BRAIN INJURIES IN AMERICAN FOOTBALL: INVESTIGATING THE CORRELATION BETWEEN BRAIN STRAIN AND COGNITIVE FUNCTION TO ENHANCE PLAYER SAFETY

A thesis presented to the faculty of the Graduate School of Western Carolina University in partial fulfillment of the requirements for the degree of Master of Science in Technology

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ABSTRACT

Utilizing Biometric Mouthguards to Detect Mild Traumatic Brain Injuries in American Football: Investigating the Correlation Between Brain Strain and Cognitive Function to Enhance Player Safety

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Traumatic Brain Injuries (TBIs) are a persistent concern in American football, posing significant risks to players' long-term health and cognitive function. This thesis explores the intricate dynamics of TBIs in football, with a focus on leveraging instrumented mouthguards (iMGs) and brain strain modeling to enhance player safety. The study builds upon the evolving literature by integrating wearable sensors to gather data on head impacts, facilitating the modeling of brain kinematics and assessment of injury potential. Through the utilization of iMGs and cognitive function tests, the research aims to provide a holistic framework for evaluating and mitigating TBIs. Data collected from the 2023 Western Carolina University Football season revealed the effectiveness of iMG brain modeling in forecasting associated cognitive impairments, particularly when axonal damage is focused in the ventricles and cerebellum. Strain in these regions were found to have roughly a 52% to 57% greater prediction percentage than the other regions. Additionally, the study identified a linear acceleration value of 30Gs as indicative of mild TBIs, even in the absence of noticeable symptoms. The findings underscore the capability of iMGs to detect and quantify axonal damage from TBIs, offering valuable insights for coaches, trainers, and medical professionals to mitigate these injuries in American football. While the study marks significant progress in linking iMG data to cognitive function across various brain regions, further research is warranted to expand participant quantity and refine cognitive testing methodologies. Nevertheless, this thesis contributes to advancing instrumented mouthguard technology, cognitive function testing, and brain modeling, paving the way for continued exploration and advancements in TBI detection and prevention strategies

CHAPTER 1: INTRODUCTION

Traumatic Brain Injuries (TBIs) are a pressing concern in American football, where players face constant physical strain and the ever-present risk of head impacts. Despite strides made in protective equipment and rule adjustments, TBIs remain prevalent, necessitating innovative approaches for understanding and addressing this critical issue. TBI based research has gained significant head way in recent years due to now widespread knowledge of possible neurocognitive diseases, such as Chronic Traumatic Encephalopathy, that are associated with longevity of a football career [1].

Efforts to address TBIs in football have been hindered by significant gaps in knowledge, particularly concerning the underreporting phenomenon and the silent impact of mild TBIs (mTBIs). Undetected mTBIs can drastically increase the accumulation of neurological damage creating possible long-term damage [3]. These knowledge gaps are compounded by the understanding that high-impact sports significantly elevate the risk of developing severe neurodegenerative conditions such as Alzheimer's disease, Parkinson's disease, and Chronic Traumatic Encephalopathy (CTE) [1].

Over the past two decades, the literature on TBIs in football has evolved significantly, witnessing a shift towards integrating wearable sensors like iMGs. Equipped with accelerometers and gyroscopes, these devices offer a novel means of gathering data on head impacts, facilitating the modeling of brain kinematics and assessment of injury potential. The primary injury mode is axonal damage caused by linear and angular accelerations. The collection and post-processing of this data can play a pivotal role in detecting and modeling possible TBIs [2]. When coupled with cognitive function tests such as ImPACT, these technologies provide a holistic framework for evaluating and mitigating TBIs.

The significance of this research lies in its potential to redefine our understanding of TBIs and provide actionable insights for improving player safety. By leveraging iMGs and brain strain modeling, this study aims to find the correlation between brain strain and cognitive function in various brain regions, thereby paving the way for more effective player safety initiatives.

This research ventures to explore the intricate dynamics of TBIs in American football, with a particular emphasis on leveraging instrumented mouthguards (iMGs) and brain strain modeling to enhance player safety. Fitting collegiate football players on the Western Carolina University football team with custom iMGs, we aim to draw correlations between brain areas, brain strain, and cognitive function. With these findings we could enhance our knowledge of mTBI/TBIs and impact players safety for the next generation. The structured progression of this thesis will encompass a thorough exploration of the background, literature review, methodologies employed, results obtained, and conclusion with implications and recommendations for future research.

CHAPTER 2: LITERAUTRE REVIEW

2.1. Traumatic Brian Injuries in Sports (vs TBI)

Traumatic Brain Injury (TBI) can be defined as neurological dysfunction after a head trauma, usually presented along with acute symptoms of cognitive impairment [1]. The term TBI has taken the place of the term concussion as a proper diagnosis of neurological dysfunction following head trauma, according to the CDC and WHO [1]. Many instances of TBIs are obvious following contact with the head, with athletes experiencing loss of consciousness (LOC) and muscle convulsion. Football is one of the most TBI-prone sports that a human can participate in; recent studies have found that in the NFL, there is an average of 0.41 TBIs per game [2]. Assuming nearly 50% of TBIs go unreported, we can estimate approximately 1.00 TBIs per game [2]. Since 1982, there have been 133 catastrophic brain injuries from football; 90% are from high school and 9% from college [3]. Most TBIs occur from rapid acceleration and deceleration [3], [4]. When forces acting on the brain exceed the tolerance of brain tissue, injury occurs [4]. When a TBI occurs, symptoms typically resolve in 7-10 days, but functional disturbance can take 30-45 days to return to baseline [3]. When symptoms do not resolve after three months, this is known as post-concussion syndrome (PCS).

In a recent study, of the individuals who have received a TBI, 40-80% have gotten PCS, and 10-15% have symptoms that last longer than a year [3]. Most collisions in impact sports are not TBIs; instead, a minor impact that does not show immediate cognitive and or physical impairment is known as a sub-concussion, also known as a mild traumatic brain injury(mTBI). The relative lightness of symptoms in an mTBI vs. a TBI causes players to not report the mild symptoms that occur as well as the players' desire to better themselves and be a region of the team often supersedes their health. Unreported mTBIs/TBIs lead to Second Impact Syndrome (SIS). SIS occurs when an athlete receives a mTBI/TBI before previous symptoms have fully cleared. Over time, mTBIs, SIS, and TBIs can lead to neurodegenerative diseases such as Alzheimer's, Chronic Traumatic Encephalopathy (CTE), and Lew Body disease [5]. Of the 103 confirmed cases of CTE in 2014, 12% had Lew Body disease, 13% had motor neuron degenerative disease, 15% had Alzheimer's disease, and 6% had frontotemporal lobar degeneration [2]. Football players who play for more than five seasons have a four times greater mortality rate from ALS than the average [3].

2.2. Diffuse Axonal Injury and Brain Strain

Frequent occurrences of traumatic brain injury (TBI) often stem from the intricate pathology of diffuse axonal injury (DAI), a condition characterized by widespread damage to the neural network, particularly the axonal connections, contributing to the complex spectrum of neurological impairments observed in affected individuals. DAIs predominantly occur when the brain experiences both linear and rotational head accelerations due to head impacts, shearing forces cause mechanical axonal damage [4], [5]. These injuries are often linked to the disruption of brain centers responsible for essential functions like breathing, heart rate, and consciousness. However, more commonly, they result in various symptoms such as memory loss, cognitive deficits, balance issues, and a variety of physical complaints. It's important to note that the severity of these symptoms can vary, and not all cases lead to severe disruptions [6]. Brain strain encompasses the intricate process of diffuse axonal injury (DAI), characterized by the tearing and shearing of nerve fibers within the brain. When assessing brain strain, the paramount concern revolves around quantifying the degree of damage sustained by these delicate nerve fibers [7]. DAIs and brain strain can be fatal over time because brain fibers do not regenerate. Keeping track of the amount of brain strain a player receives throughout their career can help athletic trainers and doctors determine whether a player is safe to continue playing.

2.3. Instrumented mouthguards

Instrumented mouth guards are equipped with accelerometers, gyroscopes, and data transmitters to relay data from impacts that happen on the field of play. Most iMGs have flexible circuit boards placed between the exterior shell of the mouthguard and the interior of the mouthguard that comes into contact with the teeth. Impact metrics collected include linear acceleration, linear velocities, angular accelerations, and linear velocities on the X, Y, and Z plane (6-DOF). IMGs can be custom fit or fitted using the boil bite method; custom fit mouthguards are often used to eliminate any non-impact (NIT) recordings. From this data variables such as MPS, MPS95, CSDM, and CSDM-10 can be calculated to determine how the impact effected brain tissue. Many iMGs must use algorithms with filters with discrete Fourier transforms out the NIT recordings.

In the past, researchers and engineers have used head impact devices (HIT) to measure head acceleration and impact data. A possible issue with the HIT system is that the sensors are not fixed to the cranium or body, this leaves room for movement between the sensor and the user that is likely not from the impact. Factors such as sweat, improper helmet fit, unbuckled helmets, and padding compression could lead to a skewed data set. The iMGs are fixed to the maxilla preventing movement upon impact. Custom fitting ensures a snug fit that does not move when pressed onto the teeth.

Figure 1: Instrumented Mouthguard

2.4. Brain Modeling

As the concern of safety in football continues to rise, engineers and doctors seek to find solutions to help the safety and well-being of athletes. Brain modeling has been an active region of research in the last 40 years, with millions of dollars invested by the US government [8]. Given impact variables from IMGs and or sensors, engineers have been able to generate finite element (FE) models of strain on brain tissue. The most common measurement of strain in a FE model is peak maximum principal strain (MPS) [9] which measures the strain on axons in the brain. MPS95 is often seen when analyzing brain strain, MPS95 takes the top 95% of the brain strain values. FE models are useful because it allows for estimating complex brain responses in real-world kinematic events through computer simulations that are otherwise difficult or impossible to measure directly [10]. Similar to mechanical FE models, the brain is separated into thousands of elements using a discretized mesh and simple-shaped elements, material properties of brain matter and boundary conditions are implemented to generate an accurate model of the human brain in response to head trauma [10].

2.5. Immediate Post-Concussion Assessment and Cognitive Testing

ImPACT is a computerized neurocognitive battery that compares baseline testing data to post-impact data to determine whether a possible TBI has occurred. ImPACT uses six different modules to test brain functions such as impulse control, visual memory (VIS), reaction time (RT), visual-motor speed (VMS), and visual memory [11]. VIS can determine whether an athlete has visual-motor deficits post-impact and has also been demonstrated to be the most precise of the ImPACT criterion [12]. Reaction time tests test for visual professing function and visual memory for oculomotor speed. If an athlete's post-impact test shows a deficit in all three (VIS, RT, and VMS), this can indicate possible axonal damage according to ImPACT [12]. The six modules inside ImPACT are word memory, design memory, X's and O's, symbol match, color match, and three letters.

2.5.1. *Word Memory – Module 1*

Word Memory tests the brain's ability to keep attention and verbal memory recognition [13]. The test provides 12 words twice for 750 milliseconds. Following the display of the 12 words, a list of words is displayed one at a time. The participant is then asked if the word on the screen was one of the 12 listed at the beginning, and the participant responds yes or no.

Figure 2: Word Memory Test - Module 1 [13]

2.5.2. *Design Memory – Module 2*

Design memory tests the brain's attention ability and visual recognition memory [13]. Following the same pattern as the word memory exam, 12 abstract shapes are displayed one at a time on the screen every 750 milliseconds. The designs will reappear in all different orientations; the test taker must identify if the shape shown was one of the initial shapes displayed at the beginning of the module, responding yes or no. The shape must be in the same orientation for the design to be correct.

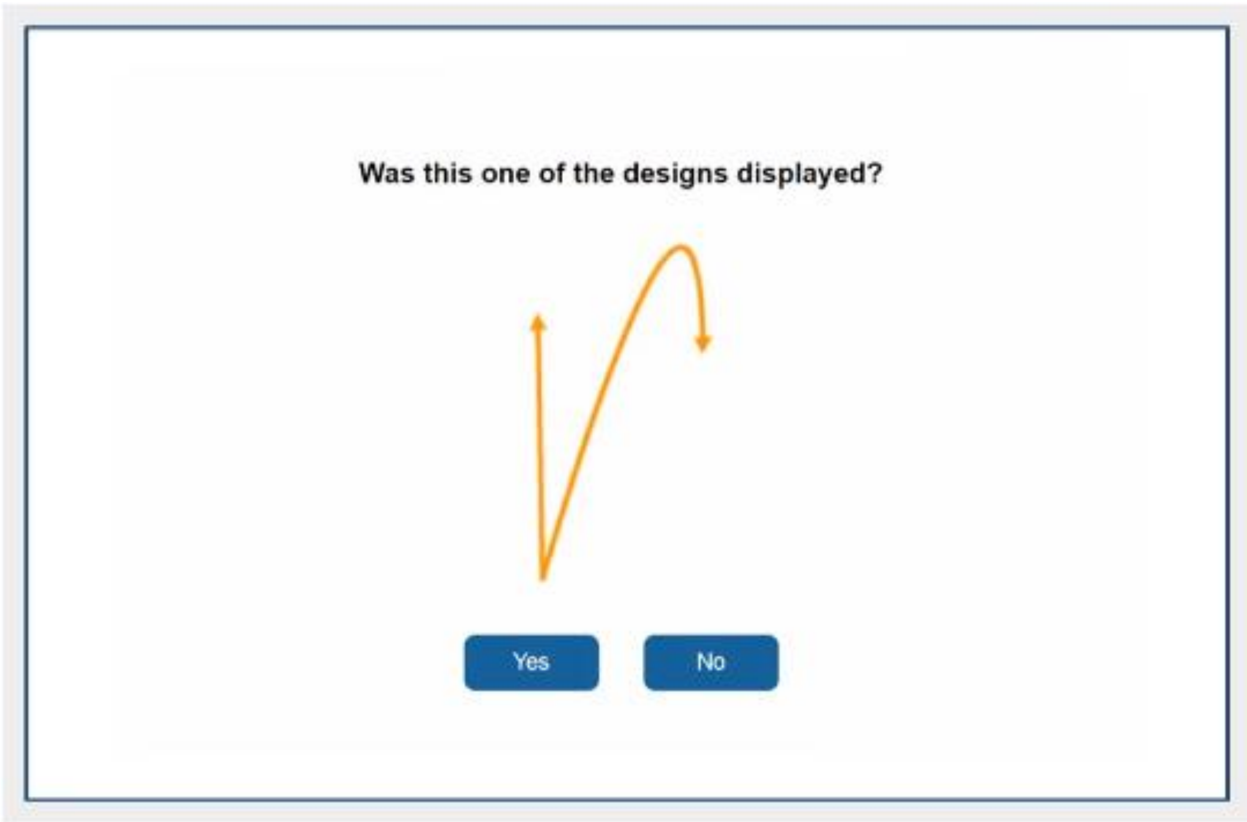


Figure 3: Visual Memory - Module 2 [13]

2.5.3. *X's and O's – Module 3*

The X's and O's exams test the brain's working memory, visual processing, and motor speed [13]. This exam has two features. The first feature serves as a distraction from the actual exam. The focal point of the exam shows first is a random display of X's and O's on the screen; three of the X's and O's will be highlighted yellow while the rest stay black; this is displayed for 1.5 seconds. Following this, the distractor will be displayed; the distraction is a reaction-based test. A blue square or a red circle will appear in the middle of the screen. If the blue square appears, the tester is to click left ("Q - key") as fast as possible; if the red circle appears, the tester is to click right ("P - key") as fast as possible. Following the reaction test, the X's and O's will reappear all black, and the tester must click the X's or O's highlighted yellow. This pattern is repeated three times with all different X and O patterns.

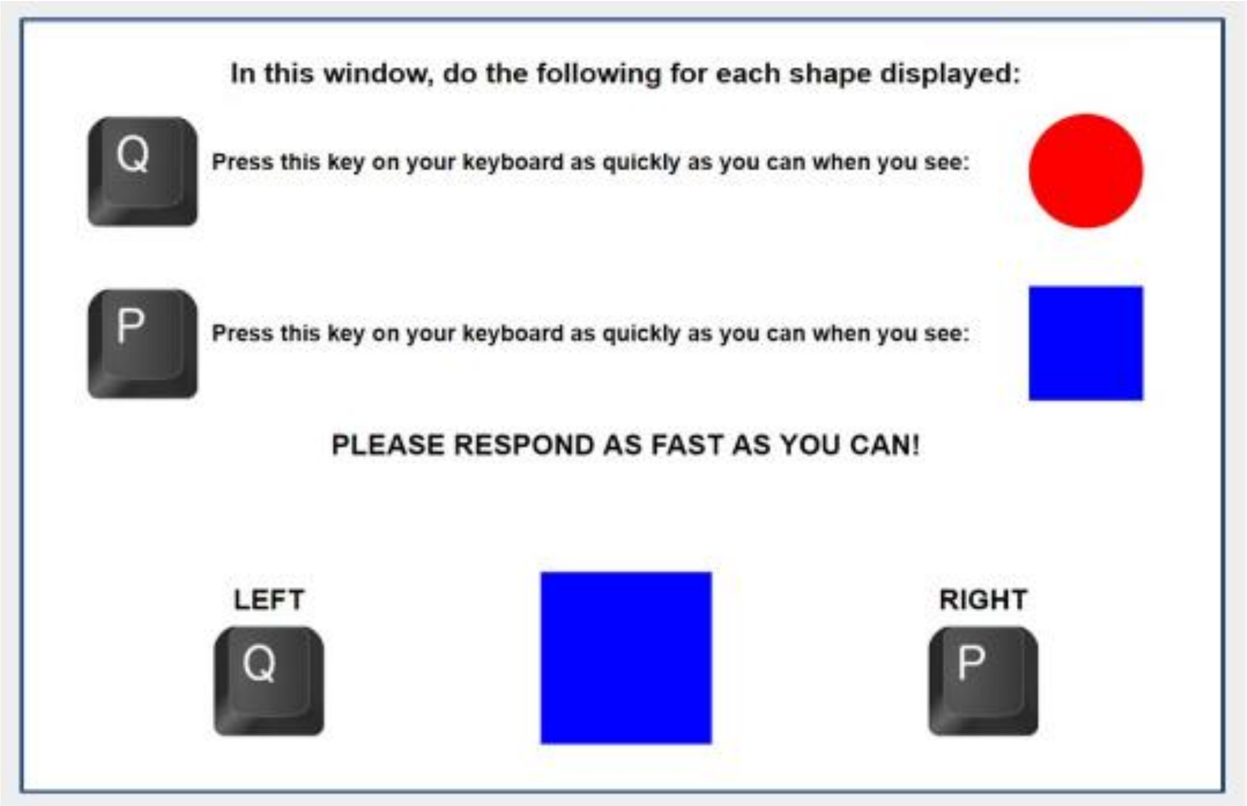


Figure 4: X's and O's – Module 3 [13]

2.5.4. *Symbol Match – Module 4*

Symbol Match tests the brain's visual processing speed, learning, and memory [13]. A 2x10 table is displayed on the screen; the bottom row is numbered 1 – 9, and the top row is nine different shapes. Above the table, one of the symbols appears, and the test taker must select the corresponding number to the shape presented. This is done 27 times; after the 27th time, all symbols disappear, and the participant is instructed to remember which symbol was associated with each number. This process is repeated without the symbols on the top row of the table.

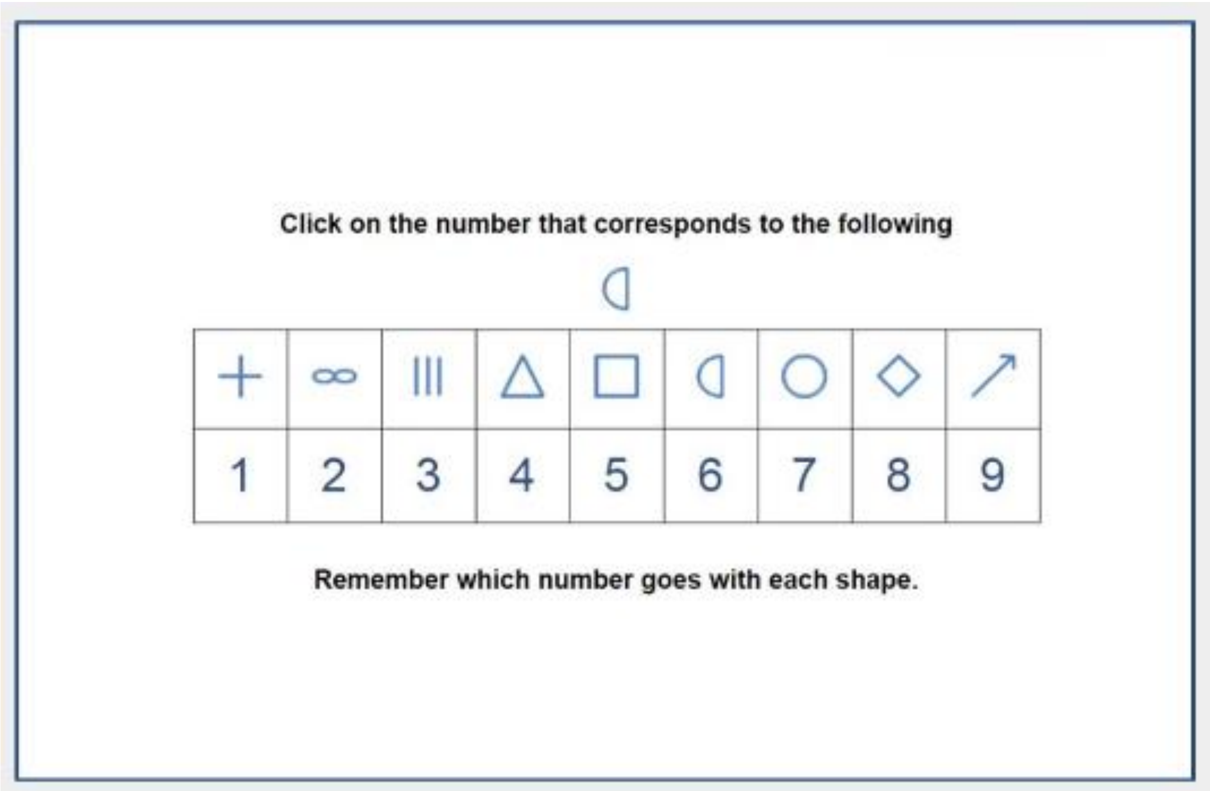


Figure 5: Symbol Match – Module 4 [13]

2.5.5. *Color Match – Module 5*

Color matches test the brain's reaction time, impulse control, and response inhibition [13]. This test displays three words inside a box: red, blue, and green. The participant is instructed to click the screen as quickly as possible when the color of the word/box is correct to the word displayed.

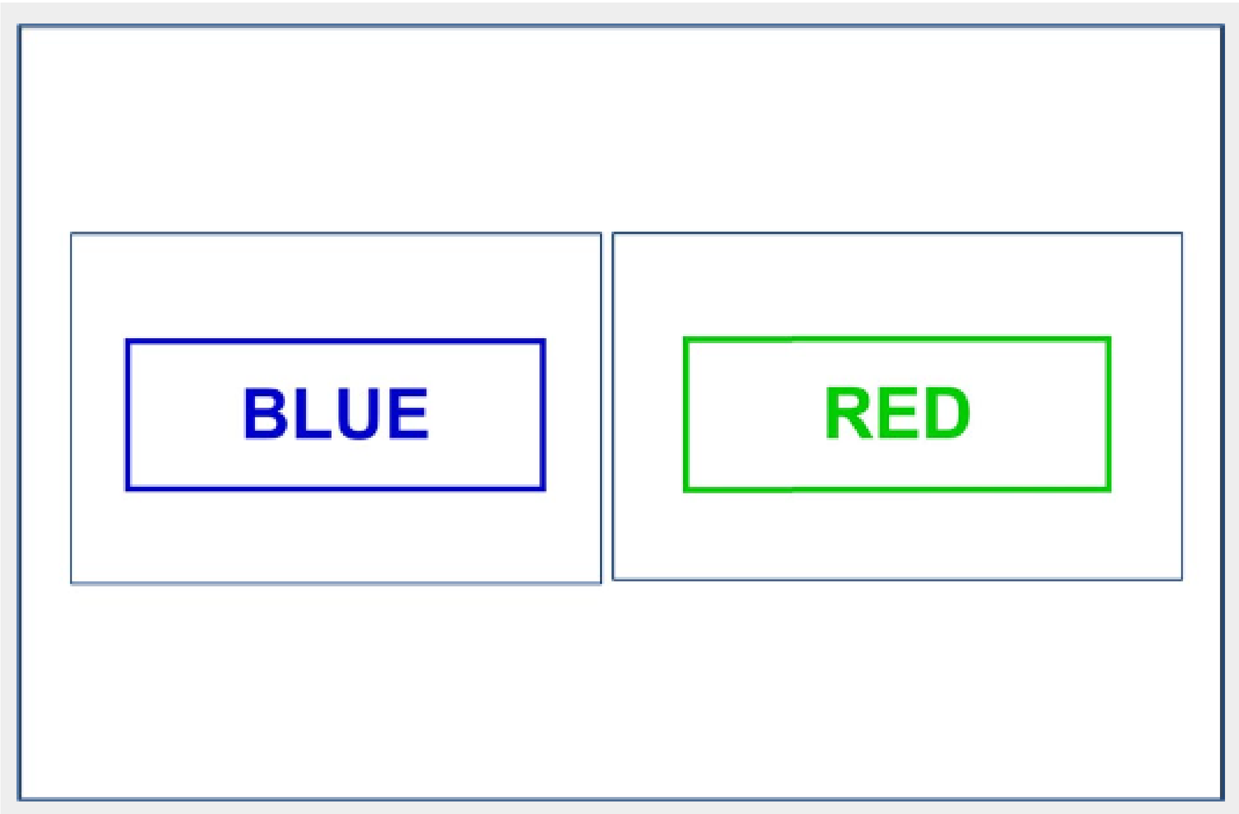


Figure 6: Color Match – Module 5 [13]

2.5.6. *Three Letters – Module 6*

Three letters test the brain's working memory and visual-motor response speed [13]. This test has two regions; first, a 5x5 grid with the numbers 1 – 25 displayed in a randomized order. The participant is instructed to click the numbers as fast as possible, counting down sequentially from 25. After 18 seconds, the grid disappears, and three consonants appear on the screen; then, the grid reappears, and the participant counts down from 25 as quickly as possible for 18 seconds. After the time has elapsed, three blank boxes appear on the screen, and the participant must enter the three consonants.

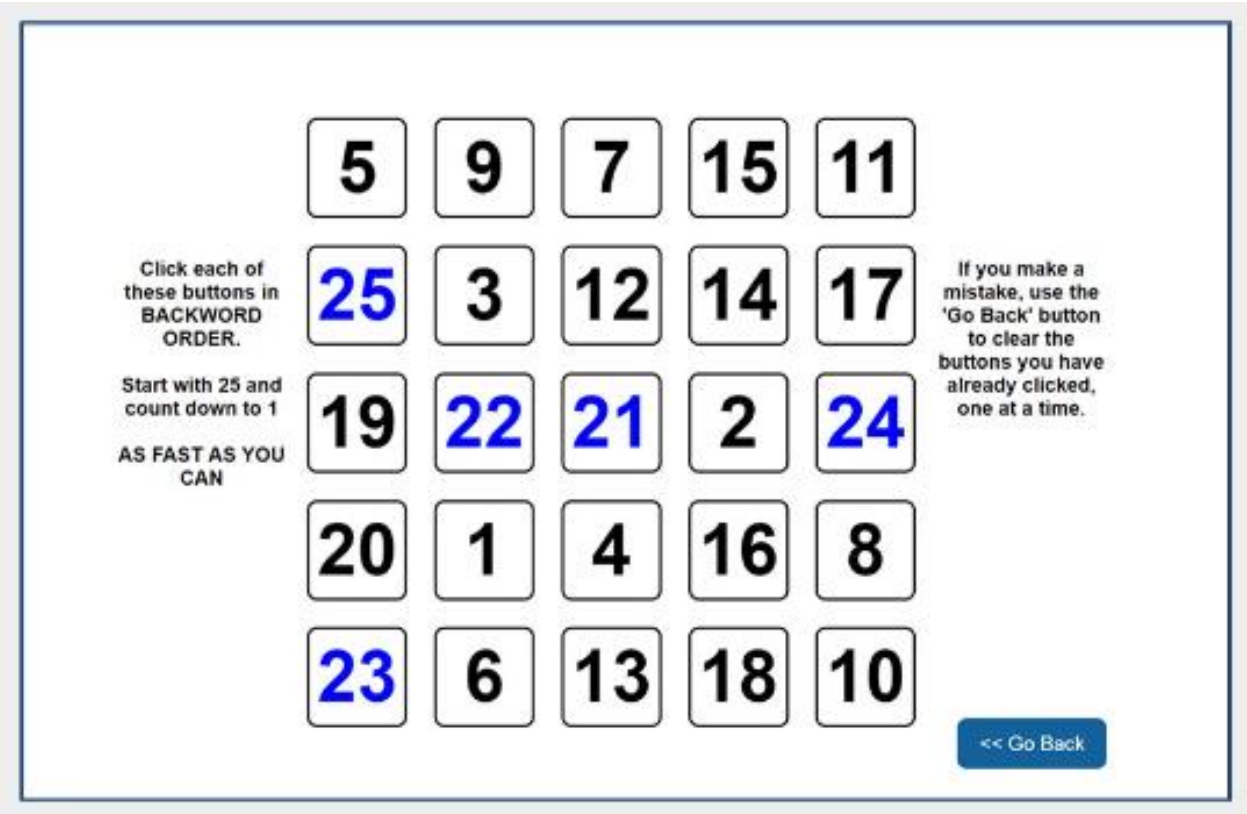


Figure 7: Three Letters – Module 6 [13]

2.6. Brain Regions and Cognitive Function

2.6.1. *Basal Ganglia*

The basal ganglia, a group of structures deep within the brain hemispheres, have been extensively studied in the 20th century [14], leading to significant insights into their functions. These structures play crucial roles in various non-motor behaviors, including emotions, language, decision making, procedural learning, and working memory [15]. Research, particularly with rodents, has highlighted the importance of the striatum, the largest region of the basal ganglia, in tasks involving stimulus-response learning [16]. Damage to the basal ganglia can result in speech and movement ataxia, indicating their importance in coordinating voluntary movements [16]. Additionally, studies suggest that the basal ganglia are involved in probabilistic learning tasks, where subjects must classify objects based on the likelihood of belonging to a certain category rather than explicit rules [16]. It's worth noting that the basal ganglia consist not only of structures within the brain hemispheres, but also related nuclei located in the diencephalon, mesencephalon, and pons, underscoring their complex and widespread involvement in brain function.

2.6.2. *Thalamus*

The thalamus, a paired gray matter structure located centrally in the brain's diencephalon, serves as a vital relay station for sensory signals, facilitating nerve fiber connections to the cerebral cortex [17]. Comprising various nuclei, it filters and prioritizes sensory information before transmitting it to the cortex through thalamocortical neurons. Acting as a critical node in networks supporting cognitive functions, particularly those prone to decline with aging, such as memory and executive functions, the thalamus is intricately involved in information processing and attention [18]. Notably, it is closely linked to memory, as evidenced by its implication in conditions like Korsakoff syndrome, characterized by dense amnesia [19, 20]. Research further highlights specific thalamic regions, including the anterior nucleus, dorsal medial nucleus, and midline and intralaminar structures, in contributing to amnesia [19]. These findings underscore the pivotal role of the thalamus in cognitive function, memory, and attention, shedding light on its significance in understanding neurological disorders and cognitive decline.

2.6.3. *Hippocampus*

The hippocampus, a complex brain structure embedded deep within the temporal lobe, plays a pivotal role in cognitive function, particularly in learning and memory processes [21]. It is identifiable externally by a layer of densely packed neurons that form an S-shaped structure along the edge of the temporal lobe, extending from the cerebral cortex's temporal region [21]. As an integral region of the limbic system, the hippocampus is involved in regulating various aspects of memory, including encoding, consolidation, and spatial navigation [22]. Research spanning from rodents to humans underscores its significance in minute-to-minute cognitive tasks such as spatial information processing, temporal sequencing, and the establishment of relationships between objects in the environment [23]. Furthermore, extensive studies have elucidated the hippocampus's involvement in memory functions, including verbal encoding and retrieval, spatial navigation, and short-term memory. It is also implicated in memory consolidation and decision-making processes [24]. Autopsy and imaging studies have revealed the interconnectedness between the hippocampus, the parahippocampal region of the medial temporal lobe, and the neocortical association in memory processing. Bilateral damage to these regions results in impaired short-term memory and an inability to form new memories, highlighting the hippocampus's indispensable role in cognitive function[24], [25].

2.6.4. *Ventricles*

The cerebral ventricular system encompasses four ventricles: two lateral ventricles located in each cerebral hemisphere, the third ventricle in the diencephalon, and the fourth ventricle in the hindbrain [26]. This system facilitates the circulation of cerebrospinal fluid (CSF), which envelops the brain and spinal cord, shielding them from injury [27]. TBIs can cause disruptions in CSF flow through the ventricular system that can lead to hydrocephalus, characterized by excessive fluid buildup in the brain, contributing to cognitive decline. Hydrocephalus, marked by an abnormal accumulation of fluid within the brain, often accompanies short-term memory loss, especially following head trauma [26]. Executive dysfunction, including difficulties in planning, organizing, multitasking, processing speed, decision-making, and attention tasks, is commonly observed in individuals with hydrocephalus [28]. Understanding the interplay between ventricular system abnormalities and cognitive impairment is crucial for effectively addressing neurological conditions and their impact on cognitive function.

2.6.5. *Corpus Collosum*

The corpus callosum, situated within the brain, serves as a crucial conduit for interhemispheric communication, facilitating the integration and transfer of information between the brain's two hemispheres. Analogous to a bridge connecting separated land masses, the corpus callosum plays a pivotal role in coordinating various cognitive functions essential for mental processing. Its functions encompass a wide array of cognitive processes, including visual-spatial integration, sensory perception, motor control, language processing, problem-solving, balance maintenance, learning, and memory [29]. In a study involving infarctions of the corpus callosum, it was found that subjects performed significantly poorly on the Mini Mental State Examination (MMSE) in regions concerning six factors: orientation, immediate recall, attention, short-term memory, and language[30]. Moreover, such infarctions can lead to a decline in visuospatial abilities, attention, calculating abilities, three-dimensional visual ability, visual reaction time, executive function, and may manifest as speech and movement ataxia, characterized by a lack of coordination in voluntary movements. Understanding the intricate role of the corpus callosum in cognitive processing is paramount for unraveling the complexities of brain function and its implications for various cognitive disorders.

2.6.6. *Brain Stem*

The brainstem serves as the vital connection between the cerebrum and the spinal cord/cerebellum. Comprising the midbrain, pons, and medulla oblongata, it regulates fundamental life functions such as breathing, heart rate, and consciousness [31]. Recent research indicates that the brainstem not only influences basic physiological processes but also plays a crucial role in cognitive functions. Studies suggest that brainstem lesions can result in cognitive deficits, including attentional deficits, executive dysfunction, and impairments in intellectual capacity. Additionally, memory, language, visuospatial skills, and praxis may also be affected by brainstem impairment [32]. The midbrain contributes to muscle movement, particularly eye movement, while the pons acts as a bridge between the cerebellum and spinal cord, influencing balance among other functions. At the base of the brainstem, the medulla governs essential life functions like breathing, heart rate, and swallowing [33]. Understanding the intricate relationship between brainstem function and cognition is crucial for elucidating the mechanisms underlying cognitive impairments associated with brainstem lesions.

2.6.7. *Cerebellum*

The cerebellum, comprising two hemispheres, plays a crucial role in controlling movement and cognitive processes requiring precise timing, along with contributing significantly to Pavlovian learning [34]. While its influence on thinking processes, including language processing and mood regulation, is acknowledged, further research is warranted to fully elucidate these functions. The cerebellum's impact extends to executive functions, attention, memory, visuospatial abilities, language, and emotions [35, 36]. Positioned at the back of the head, just above the spinal cord-brain junction, it is also known as the hindbrain [37]. Notably, studies such as Xie et al. (2007) have highlighted the repercussions of cerebellar injury on orientation efficiency and executive control, underscoring its integral role in cognitive function [36]. This synthesis underscores the multifaceted importance of the cerebellum in cognitive processes, urging continued exploration in the realm of neuroscience.

2.6.8. *Frontal Lobe*

The frontal lobe is integral to a wide array of cognitive functions, including initiation, problem-solving, judgment, planning, anticipation, motor planning, awareness of abilities and limitations, organization, attention, concentration, and mental flexibility [38]. It serves as a cornerstone for initiating and coordinating motor movements, as well as facilitating higher cognitive skills such as problem-solving, planning, and organization [34, 38, 39]. Additionally, observed difficulties in impulse control and coordination following frontal lobe lesions. Notably, frontal lobe involvement extends beyond motor control, encompassing cognition and neuropsychiatric functions [40]. Lesions, particularly in the right hemisphere, are associated with deficits in sustained attention and learning, impacting long-term memory retention. Tasks requiring planning and organizational strategies, such as word-list learning or recall of remote memories, are notably affected by frontal deficits, highlighting the critical role of the frontal lobe in various cognitive processes [40]. Understanding its intricate functions and repercussions of impairment is crucial for comprehending cognitive function and dysfunction.

2.6.9. *Temporal Lobe*

The temporal lobe is essential for various cognitive functions, notably memory and language comprehension. It encompasses receptive language skills, organizing, and sequencing information, particularly in short-term memory processes [38, 41]. Short-term memory, including immediate and operative memory, relies on the temporal lobe's function, enabling us to temporarily store and manipulate information. Challenges in identifying and categorizing objects may arise from temporal lobe dysfunction [42]. Moreover, the ventral temporal lobe is implicated in semantic memory, crucial for word and concept recall necessary for language understanding and use. Subdivided into the superior, middle, and inferior temporal lobes, this region houses critical structures like the hippocampus and amygdala, integral for memory processing and emotional regulation [43]. Understanding the cognitive functions associated with the temporal lobe elucidates its role in memory, language, and perceptual processes, contributing significantly to our comprehension of brain function and dysfunction.

2.6.10. *Parietal Lobe*

The parietal lobe, positioned towards the front underneath the crown of your skull, plays a fundamental role in various cognitive functions, including differentiation of size, shape, and color, spatial perception, and visual processing essential for academic skills such as reading [38, 41]. In addition, the posterior parietal lobe plays a particularly vital role in working memory retrieval [44]. It serves as a hub for integrating visual and auditory stimuli, facilitating coherent perception of the environment. Studies pinpoint the left inferior parietal lobule's activity during calculation tasks, emphasizing its involvement in numerical processing [45]. Damage to the parietal lobe can lead to difficulties in distinguishing left from right [46]. Understanding the cognitive functions associated with the parietal lobe contributes significantly to our comprehension of sensory perception, spatial cognition, and numerical processing, shedding light on brain function and dysfunction.

2.6.11. *Occipital Lobe*

The occipital lobe, located at the back of the head underneath the occipital bone, serves as the brain's visual processing region, crucial for various cognitive functions related to vision. It enables vision, including the perception and recognition of printed words, facilitating reading comprehension [38, 47]. Moreover, the occipital lobe allows for the identification of linguistic images, contributing to language processing [41]. Its functions encompass visuospatial processing, distance and depth perception, color determination, object and face recognition, as well as memory formation [47]. Understanding the cognitive functions associated with the occipital lobe is essential for comprehending visual perception, language processing, and memory formation, providing valuable insights into brain function and dysfunction.

2.6.12. *Motor Sensory Cortex*

The motor sensory cortex is a critical brain region comprised of two components: the sensory cortex and the motor cortex. The motor cortex, situated in the frontal lobe anterior to the central sulcus, primarily generates signals directing body movements [48]. Meanwhile, the primary somatosensory cortex is pivotal in processing incoming somatosensory information and integrating sensory and motor signals essential for skilled movement [49]. Numerous studies have revealed the involvement of the motor cortex in higher cognitive functions like attention, motor learning, movement inhibition, and imagery [50]. Additionally, research indicates that the premotor cortex serves both motor and cognitive functions, transforming object properties into actions and aiding in spatial perception, action understanding, and imitation [51]. Moreover, the motor and sensory cortex contribute significantly to balance, movement, and coordination, particularly in scenarios where visual cues are lacking [52]. Understanding the intricate roles of these cortical regions is paramount in comprehending their implications for cognitive function within the broader context of brain function and dysfunction associated with cortical abnormalities.

2.6.13. *Cerebral Hemispheres*

The Cerebral Hemispheres include the frontal, temporal, parietal, and occipital lobe. The Cognitive function of the Cerebral Hemispheres are the functions of the four lobes of the brain.

2.7. Brain Regions Related to Cognitive Function

Through extensive research of brain regions and what ImPACT tests related to cognitive functions, table (x) was created to show brain region, cognitive impairment, associated modules, and associated composite scores.

Brain Regions	Cognitive Issues Related to Injury	Associated ImPACT Modules	Associated Composite Scores	Citation
Basal Ganglia	Object Classification, working memory, procedural learning, stimulus-response learning	● Symbol Match *(object classification)* ● X's and O's *(Working Memory, stimulus-response learning)* ● Color Match *(Stimulus-Response Learning)* ● Three Letters *(Working Memory)*	Verbal Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[14 , 15, 16]
Thalamus	attention, information processing	● Design Memory *(Attention)* ● Word Memory *(Attention)*	Verbal Memory, Visual Memory	[17, 18 19, 20]
Hippocampus	Orientation recognition, consolation memory, encoding memory, temporal sequencing	● Word Memory *(Encoding Memory)* ● Design Memory *(Orientation,)* ● Three letters ● Symbol Match *(Consolidation Memory)* ● Three Letters *(Temporal Sequencing, Encoding Memory)*	Verbal Memory, Visual Memory, Visual Motor Speed, Reaction Time	[21, 22, 23, 24]
Ventricles	Attention, Executive Dysfunction, processing speed, decision making	● Design Memory *(attention)* ● X's and O's *(Processing Speed)* ● Color Match *(Processing Speed)*	Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[26, 27, 28]
Corpus Collosum	Color recognition, visual-spatial integration, attention, reaction time	● Design Memory *(attention)* ● Word Memory *(attention, visual-spatial)* ● Color Match *(color recognition)* ● X's and O's *(reaction time, color recognition, visual-spatial)* ● Color match *(Color Recognition)* ● Three Letters *(Reaction Time)*	Impulse Control, Reaction Time, Visual Memory, Visual Motor Speed, Reaction Time	[29, 30, 31]
Brian Stem	Attention, executive dysfunction	● Word Memory *(attention)* ● Design Memory *(attention)* ● Color Match *(Executive Dysfunction*	Visual Memory, Reaction Time, Impulse Control	[32, 33, 34]
Cerebellum	Orientation, executive control	● Design Memory *(Orientation)* ● Color Match *(Executive Control)*	Visual Memory, Impulse Control	[35, 36, 37, 38]

Motor & Sensory Cortex	Attention, Motor learning, Space perception, Coordination, Consolidation	● Word Memory *(attention)* ● Symbol Match *(Consolidation)* ● Three Letters *(Coordination)*	Verbal Memory, Visual Motor Speed, Reaction Time,	[49, 50, 51, 52, 53]
Frontal Lobe	Attention, concentration, mental flexibility, impulse control, Word list learning	● Word Memory *(attention, word list learning)* ● Design memory *(attention)* ● X's and O's *(Concentration, Impulse Control)* ● Color Match *(Concentration, Impulse Control)*	Verbal Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[35, 39, 40, 41]
Temporal Lobe	Sequencing information, Operative memory, categorizing objects	● X's and O's *(Operative learning)* ● Symbol Match *(Categorizing objects)* ● Three Letters *(Sequencing)*	Visual Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[39, 42, 43, 44]
Parietal Lobe	differentiation of size, shape, and color, numerical processing, directional confusion, Working Memory	● Design Memory *(Size differentiation)* ● X's and O's *(color differentiation, directional confusion)* ● Symbol Match *(Working Memory)* ● Color Match *(Color Differentiation)* ● Three Letters *(Numerical Processing)*	Visual Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[39, 42, 45, 46, 47]
Occipital Lobe	Linguistic identification, perception, color determination, distance and depth perception,	● X's and O's *(Color, Differentiation)* ● Color Match *(Color, Differentiation)* ● Three Letters (Distance and Depth Perception)	Visual Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control	[39, 42, 48]

Table 1: Brain Regions Associated with Dysfunction, ImPACT Modules, and Composite Scores

To further understand the complex innerworkings of cognitive function in different brain regions, it was imperative to understand what we should expect to see if a particular brain region is damaged. Composite scores are calculated using a combination of various testing modules to give an all-encompassing representation for each composite score. Following Table 1, theoretical cognitive functions related to brain regions are displayed. Composite scores are ranked based on how many associated ImPACT modules (column 3 Table 1) are involved in the calculations of the associated composite scores (column 4 Table 1).

Expected Cognitive Results

Basal Ganglia

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	2 of 3	67%	1	Reaction Time
Visual Memory	1 of 2	50%	2	Visual Motor Speed
Visual Motor Speed	2 of 2	100%	3	Impulse Control
Reaction Time	3 of 3	100%	4	Verbal Memory
Impulse Control	2 of 2	100%	5	Visual Memory

Thalamus

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	1 of 3	33%	1	Verbal Memory
Visual Memory	1 of 3	33%	1	Visual Memory

Brain Stem

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	1 of 3	33%	1	Reaction Time
Reaction Time	1 of 3	33%	1	Visual Motor Speed
Impulse Control	1 of 3	33%	1	Impulse Control

Hippocampus

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	3 of 3	100%	1	Verbal Memory
Visual Memory	1 of 2	50%	1	Visual Motor Speed
Visual Motor Speed	2 of 2	100%	2	Visual Memory
Reaction Time	1 of 3	33%	3	Verbal Reaction Time

Cerebellum

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Visual Memory	1 of 2	50%	1	Verbal Memory
Impulse Control	1 of 2	50%	1	Impulse Control

Frontal Lobe

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	1 of 3	33%	1	Impulse Control
Visual Memory	2 of 2	100%	1	Visual Memory
Visual Motor Speed	1 of 2	50%	2	Reaction Time
Reaction Time	2 of 3	67%	3	Visual Motor Speed
Impulse Control	2 of 2	100%	4	Verbal Memory

Cerebral Hemispheres

Composite Scores	# of Modules Assosiated	Composite Scores Ranked	
Temporal, and Occipital Lobes. Functions are rate accordingly to the top composites in those areas		1	Visual Memory
		1	Visual Motor Speed
		1	Reaction Time

Corpus Collosum

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	2 of 3	67%	1	Visual Memory
Visual Memory	2 of 2	100%	1	Visual Motor Speed
Visual Motor Speed	2 of 2	100%	1	Impulse Control
Reaction Time	2 of 3	67%	2	Verbal Memory
Impulse Control	2 of 2	100%	2	Reaction Time

Temporal Lobe

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	2 of 3	67%	1	Visual Motor Speed
Visual Memory	1 of 2	50%	2	Verbal Memory
Visual Motor Speed	2 of 2	100%	2	Reaction Time
Reaction Time	2 of 3	67%	3	Visual Memory
Impulse Control	1 of 2	50%	3	Impulse Control

Parietal Lobe

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	2 of 3	67%	1	Visual Motor Speed
Visual Memory	2 of 2	100%	1	Impulse Control
Visual Motor Speed	2 of 2	100%	1	Reaction Time
Reaction Time	3 of 3	100%	1	Visual Memory
Impulse Control	2 of 2	100%	2	Verbal Memory

Occipital Lobe

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	1 of 3	33%	1	Visual Memory
Visual Memory	2 of 2	100%	1	Visual Motor Speed
Visual Motor Speed	2 of 2	100%	1	Impulse Control
Reaction Time	2 of 3	67%	2	Reaction Time
Impulse Control	2 of 2	100%	3	Verbal Memory

Ventricles

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Impulse Control	2 of 2	100%	1	Impulse Control
Visual Memory	1 of 2	50%	1	Reaction Time
Visual Motor Speed	1 of 2	50%	2	Visual Memory
Reaction Time	2 of 3	67%	3	Visual Motor Speed

Motor and Sensory Cortex

Composite Scores	# of Modules Assosiated		Composite Scores Ranked	
Verbal Memory	3 of 3	100%	1	Verbal Memory
Reaction Time	1 of 3	33%	1	Reaction Time
Visual Motor Speed	1 of 3	33%	1	Visual Motor Speed

Table 2: Ranking Composite Scores Per Literature Review

2.8. Statistical Analysis

Linear regression models are valuable tools for analyzing the relationship between two variables. Typically represented by the equation Y = mx + b, where Y is the dependent variable, X is the independent variable, m is the slope of the line representing the rate of change of Y with respect to X, and b is the y-intercept, these models help quantify how changes in one variable affect the other [53]. A linear regression line's slope indicates this relationship's direction and strength. A positive slope signifies that as the independent variable increases, the dependent variable also increases, while a negative slope suggests that as the independent variable increases, the dependent variable decreases. The magnitude of the slope reflects the strength of the relationship; a steeper slope indicates a stronger relationship, while a slope closer to zero suggests a weaker connection. Thus, linear regression analysis provides insights into the nature and intensity of the association between variables, aiding in making predictions and informed decisions in various fields. The slope in most statistical models is known as the regression coefficient [53].

CHAPTER 3: METHODS

The premise of this study is to find a correlation between brain strain data generated from instrumented mouthguards (iMGs) and cognitive function generated from a neurocognitive testing battery. In theory, the brain regions with the highest levels of strain should show dysfunction in cognitive testing. The brain strain will be processed using finite element analysis and brain modeling from two programs: Brain Simulation Platform, an FEA and brain modeling program written by Pennsylvania State University, and ParaView 5.11.0, an FEA program. Cognitive function will be tested with Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) version 4.

3.1. Participants

This study involves ten collegiate athletes from the Western Carolina University football team, a NCAA Division I FCS school. Players' ages range from 20-24 (mean age 21.6, SD 1.55). Participants are selected by the probability of receiving impacts during play. The study includes three tight ends, four offensive linemen, two defensive linemen, and one linebacker/special teams player. According to a study done by the Journal of Athletic Training, the number of impacts per game is ranked as follows: (1) Defensive Line, (2) Offensive Line, (3) Linebacker, (4) Special Teams, (5) Defensive Back, (6) Running Back, (7) Quarterback, (8) Wide Receiver [54]. Player intensity and style of play are also considered; football players often have psychological differences in aggressiveness, causing an increased probability of high-velocity impacts. To acquire the most relevant and frequent data, players who fit the aggressive and impact frequency criteria were selected for the study. Before enrolling participants in the study, study details were explained to the potential participants including, the nature of the study, what data will be collected, how they will be involved, what they will be required to do, and what kind of results are looking to be obtained. Participants were also given the ability to ask any questions and present concerns before beginning their involvement in the study; following any questions that needed to be answered, players were given the IRB participant consent form enrolling them into the data collection process during the 2023 football season.

Participants		
Player #	Age	Position
Player 1	23	Tight End
Player 2	23	Offensive line
Player 3	21	Offensive line
Player 4	20	Tight End
Player 5	20	Offensive line
Player 6	23	Offensive line
Player 7	21	Defensive Line
Player 8	21	Defensive Line
Player 9	23	Tight End
Player 10	22	Linebacker/Special Teams

Table 3: Player Identified Numbers and Positions

3.2. Testing Protocol

Data was collected for the duration of the 2023-2024 season. participants were issued a custom fit Prevent Biometric instrumented mouthguard before the start of the 2023 season, August 1st, 2023. Participants are required to take a baseline ImPACT test before beginning the study. Players are required to wear the custom-fit Prevent Biometrics iMG during games. The iMGs are transported in the Prevent Biometrics charging chase to practices and games. Before all practices and games, the mouthguards are passed out to the players before activity. Following practice and or games the iMGs are collected and placed back in the charging case. These iMGs were fitted with dental impression kits to ensure a comfortable fit and accurate results. The iMGs use Bluetooth to transmit impacts from each player to the Prevent Biometrics impact portal; when an impact is recorded over 30Gs of linear acceleration, participants are required to retake the ImPACT test (post impact test) to search for possible cognitive dysfunction. Due to travel, practice, and data processing time, the participants have 48 hours to complete the post-impact examination; falling within the testing window suggested by ImPACT of 72 hours [55]. Each iMG records a 50ms impact of linear and angular accelerations and velocities for all 6 DOF. The 50ms recordings are broken down into time steps every 0.03125ms with data for all linear and angular accelerations and velocities on the X, Y, and Z axis. All time steps are imported to three post-processing platforms: Brain Simulation (Brain Modeling), ParaView 5.11. 0.(FEA), and MATLAB (Statistical Processing). Figure 28 shows the flow of data from impact recorded from iMGs to MATLAB post-processing.

3.3. Dental Impressions

Players were then fitted for iMGs using Luckin Smile® Si-Impression Material dental kits. The impression kits have a base and catalyst puddy that are combined to create a soft material that hardens over time for teeth impressions. After combining the two materials the puddy is then inserted into the putty guard, and players bite down on the putty for two minutes, giving the puddy time to solidify. Once the dental impressions were finished, the casts were sent to Pennsylvania State University to make plaster molds for each dental impression. These plaster molds were then sent to Prevent Biometrics® to generate custom fit instrumented mouthguards.

Figure 8: Dental Mold Cast from Dental Impressions

3.4. Cognitive Data Collection

To begin the data collection process each participant must take a baseline ImPACT exam. The baseline exam is sent to each player via email and includes all the modules seen in Chapter 2.5. The baseline exam tests each player's cognitive ability unimpaired. All cognitive data is analyzed for dysfunction based on baseline testing scores. The post-impact version of the test mirrors the baseline exam; this exam includes six modules: word memory, design memory, X's and O's, symbol match, color match, and three letters. After a player receives a 30G linear acceleration impact, recorded by the iMG, a post impact test is sent to their email to evaluate for possible cognitive dysfunction. Each module by ImPACT evaluates the brain's cognitive function distinctly. Once the post-impact examination is finished, the participants' clinical report was downloaded from ImPACT's online platform.

The clinical report (Table 4) records the results of each test from the examination; this study will concentrate on the composite scores for each brain function, which comprise of verbal memory, visual memory, visual motor speed, reaction time, and impulse control. The composite scores represent a mathematical combination of the scores from the six modules; this combines the modules in a way that evaluates specific brain functions. Of the five composite scores four of them have a percentage score representing the composite score based on a percentage of function. This percentage is not different in value, it is only different in the representation of possible dysfunction. The composite percentages are added to post-processing as their own individual parameters. The data from the composite scores are then imported into MATLAB for post-processing.

ImPACT APPLICATIONS, INC.

ImPACT Clinical Report

[redacted]

Exam Type	Baseline	Post-Injury 1	Post-Injury 2	Post-Injury 3	Post-Injury 4
Age When Tested	22	22	22	22	22
Date Tested	Aug 24, 2023	Sep 04, 2023	Sep 11, 2023	Oct 10, 2023	Nov 06, 2023
Concussion Date					
Exam Language	English	English	English	English	English
Test Version	4.6.0	4.6.0	4.6.0	4.7.0	4.8.0
Pointing Device	Mouse	Mouse	Mouse	Mouse	Mouse

COMPOSITE SCORE

Memory composite (verbal)	87	46%	82	32%	74	14%	89	55%	86	44%
Memory composite (visual)	80	56%	72	32%	76	44%	95	93%	94	91%
Visual motor speed composite	31.67	11%	32.58	15%	33.05	16%	34.55	23%	37.63	38%
Reaction time composite	0.60	52%	0.61	47%	0.59	57%	0.57	66%	0.51	91%
Impulse control composite	0		1		4		1		1	

Table 4: ImPACT Report

In MATLAB, graphs are created to visualize deficits in cognitive function according to composite scores, seen in Figure 7. The first column in each graph is the baseline exam; every bar after the baseline represents a post impact test compared to the baseline. In the bar graphs, any post-impact score that shows a possible dysfunction is highlighted in red. Each bar is labeled by the numerical amount of how far the score is from the baseline (Post Impact score – Baseline).

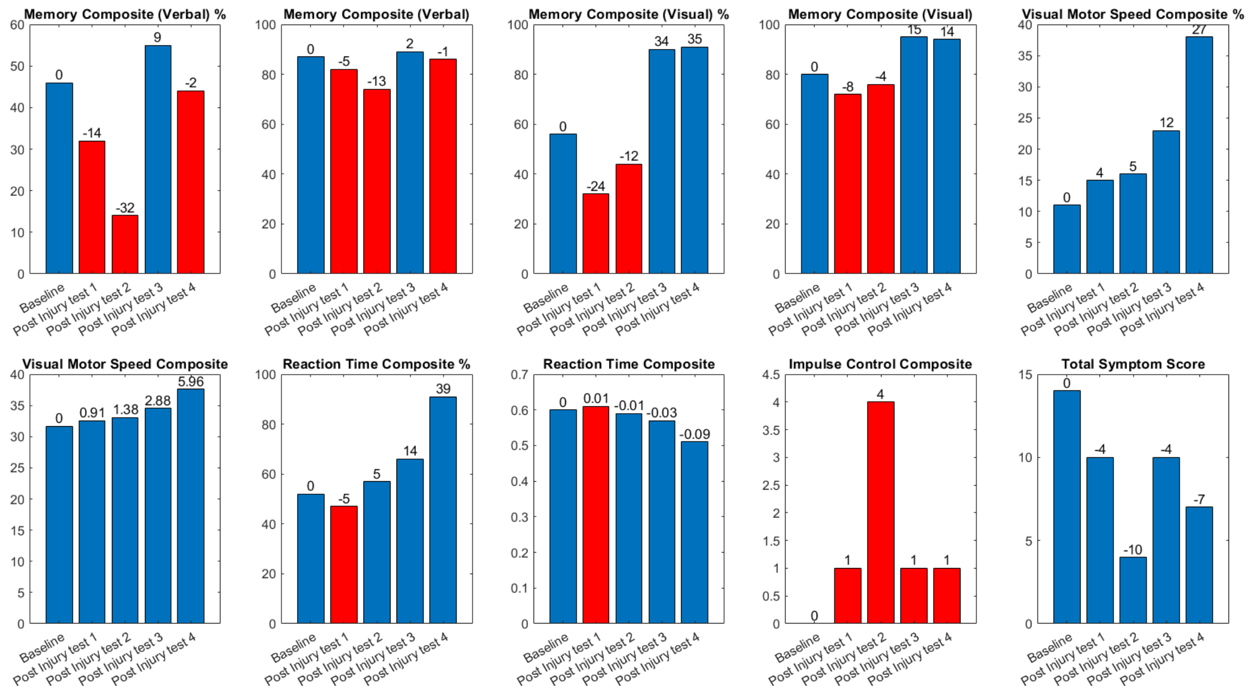


Figure 9: Composite Scores from ImPACT in MATLAB

Post impact scores were compared to baseline values to detect cognitive dysfunction, Equation 1. Creating the composite ratio ensures a constant evaluation of cognitive dysfunction in post processing. Every player's baseline score varies, giving some players a higher ceiling than others. If raw scores were used rather than the composite ratio, this would assume that all players have the same baseline score. To establish a constant variable that can be standardized across participants, the amount of dysfunction that occur is analyzed rather than raw score. For most composite scores higher values indicate better performance (e.g. improved memory). However, three of the composite scores are inversely represented in impact; (reaction time, impulse control, and symptom score) meaning, that lower values indicate better performance rather than worse (e.g. faster reaction time is better). To ensure consistency in the Composite Ratio, these three composite metrics were inversely represented, following Equation 2. Using this approach, any composite ratios less than one indicate dysfunction.

$$Composite\ Ratio = \frac{Post\ Impact\ Score}{Basline\ Score}$$

Equation 1: Composite Ratio

$$Composite\ Ratio' = \left(\frac{Post\ Impact\ Score}{Basline\ Score}\right)^{-1}$$

Equation 2: Inverse Composite Ratio

	Post Injury test 1	Post Injury test 2	Post Injury test 3	Post Injury test 4
Memory Composite (Verbal) %	0.6957	0.3043	1.1957	0.9565
Memory Composite (Verbal)	0.9425	0.8506	1.0230	0.9885
Memory Composite (Visual) %	0.5714	0.7857	1.6071	1.6250
Memory Composite (Visual)	0.9000	0.9500	1.1875	1.1750
Visual Motor Speed Composite %	1.3636	1.4545	2.0909	3.4545
Visual Motor Speed Composite	1.0287	1.0436	1.0909	1.1882
Reaction Time Composite %	0.9038	1.0962	1.2692	1.7500
Reaction Time Composite	0.9836	1.0169	1.0526	1.1765
Impulse Control Composite	1	4	1	1
Total Symptom Score	1.4000	3.5000	1.4000	2

Table 5: Composite Ratios from ImPACT in MATLAB

3.5. Brain Strain Data Collection

3.5.1. *Instrumented Mouthguards*

IMGs record seven data metrics that are visible in the prevent portal: impact number, peak linear acceleration (PLA), peak angular acceleration (PAA), peak linear velocity (PLV), peak angular velocity (PAV), workload (.OAD), and impact location (Figure 10). Peak linear acceleration is the primary concern in this study because it is used to determine if a severe impact of 30Gs is experienced. Following detection of an impact, a 50-millisecond data set is saved for PLA, PAA, PLV, and PAV in all 6-DOF, this includes impact metrics before and after the impact's occurrence. Only impacts of 30Gs or greater will be post processed. These data are broken into 0.03125 millisecond time steps as shown in Table 6.


IMPACTS FOR 2023-11-18
Western Carolina Football 2023

38 impacts between 12:03PM and 3:14PM EST (-05:00)

Filter

IMPACT TIME	#	PLAYER NAME	POSITION	DEVICE	IMPACT	PLA	PAA	PAV	PLV	.OAD	LOCATION
12:12:50 PM		Player 3	OL	81661	2313	34	2,227	20.0	2.8	22.3	Front Low
1:22:53 PM		Player 3	OL	81661	2378	25	1,559	13.0	1.9	10.3	Front Low
12:44:59 PM		Player 1	TE	80569	3832	20	827	5.0	1.5	5.4	Bottom Front
2:39:19 PM		Player 3	OL	81661	2419	18	1,321	11.0	1.6	7.5	Front Low

Figure 10: Seven Data Metrics Collected from Prevent Biometrics Online Portal

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	T.ms	PAA.X.rads	PAA.Y.rads	PAA.Z.rads	PAA.R.rads	PAV.X.rads	PAV.Y.rads	PAV.Z.rads	PAV.R.rads	PLA.X.mse	PLA.Y.mse	PLA.Z.mse	PLA.R.mse	PLV.X.mse	PLV.Y.mse	PLV.Z.mse	PLV.R.mse
2	0	52.6	32.083	21.35	65.207	0.369	0.362	-0.744	0.905	-2.993	2.961	-5.253	6.732	0	0	0	0
3	0.3125	54.515	33.715	17.236	66.375	0.373	0.365	-0.748	0.912	-2.535	3.245	-5.747	7.07	0	0	0	0
4	0.625	54.614	34.366	11.036	65.464	0.378	0.368	-0.753	0.919	-1.955	3.576	-6.442	7.623	0	0	0	0
5	0.9375	52.321	33.702	2.348	62.28	0.383	0.372	-0.759	0.928	-1.243	3.955	-7.37	8.456	0	0	0	0
6	1.25	46.998	31.348	-9.265	57.248	0.389	0.377	-0.766	0.938	-0.383	4.382	-8.566	9.629	0	0	0	0
7	1.5625	37.955	26.9	-24.272	52.472	0.396	0.381	-0.775	0.95	0.633	4.855	-10.059	11.187	0	0	0	0
8	1.875	24.465	19.929	-43.164	53.468	0.401	0.386	-0.786	0.963	1.816	5.372	-11.878	13.162	0	0	0	0

Table 6: Time Step Data from iMGs Downloaded from Prevent Portal

All Impacts collected from the ten participants are downloaded from the Prevent Portal via CSV (comma-separated values) files. Impacts per player were tracked, as well as impacts per player over the duration of the season (Figure 11 and Figure 12). Too help understand the possible risk factors of each position involved in the study, the impacts were also separated by position (Figure 13 and Figure 14). MATLAB code was written to separate players and positions. In these graphs, the red line indicates an impact over the testing threshold of 30Gs. All CSV files were converted to xlsx (excel workbook) files then imported into MATLAB for graph generation.

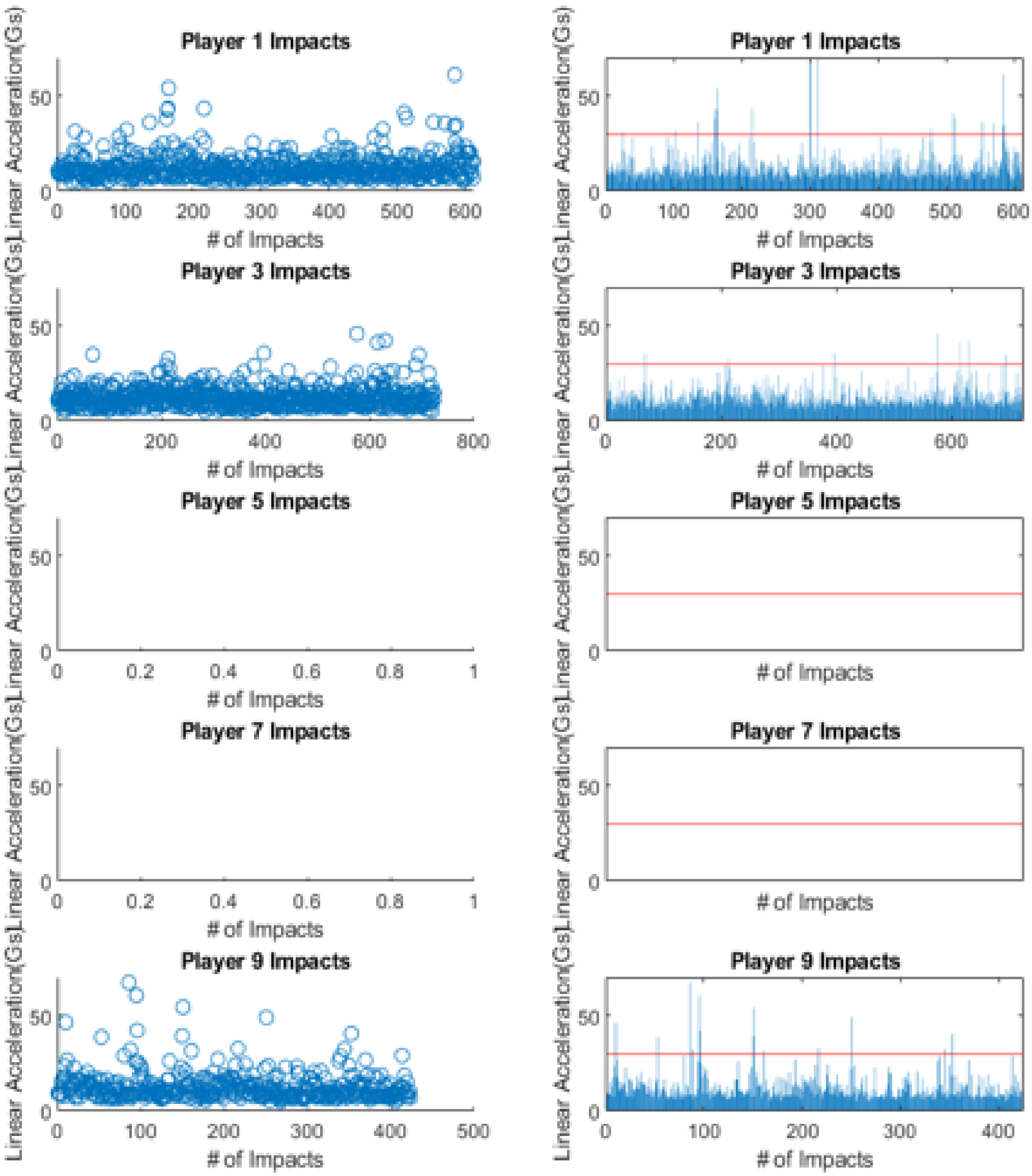


Figure 11: All Impacts from 2023 Season Recorded by iMGs for Players 1, 3, 5, 7, 9

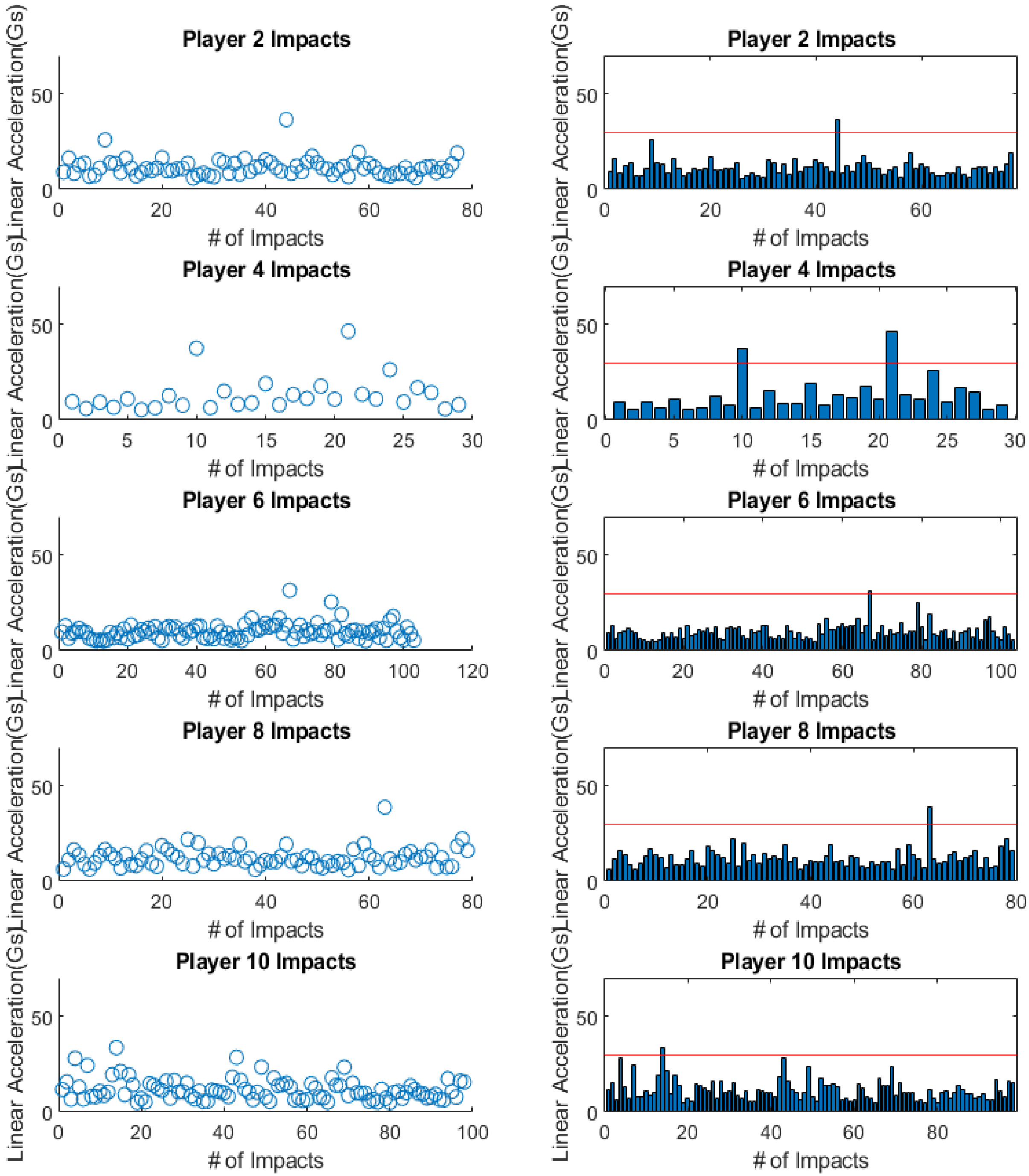


Figure 12: All Impacts from 2023 Season Recorded by iMGs for Players 2, 4, 6, 8, 10

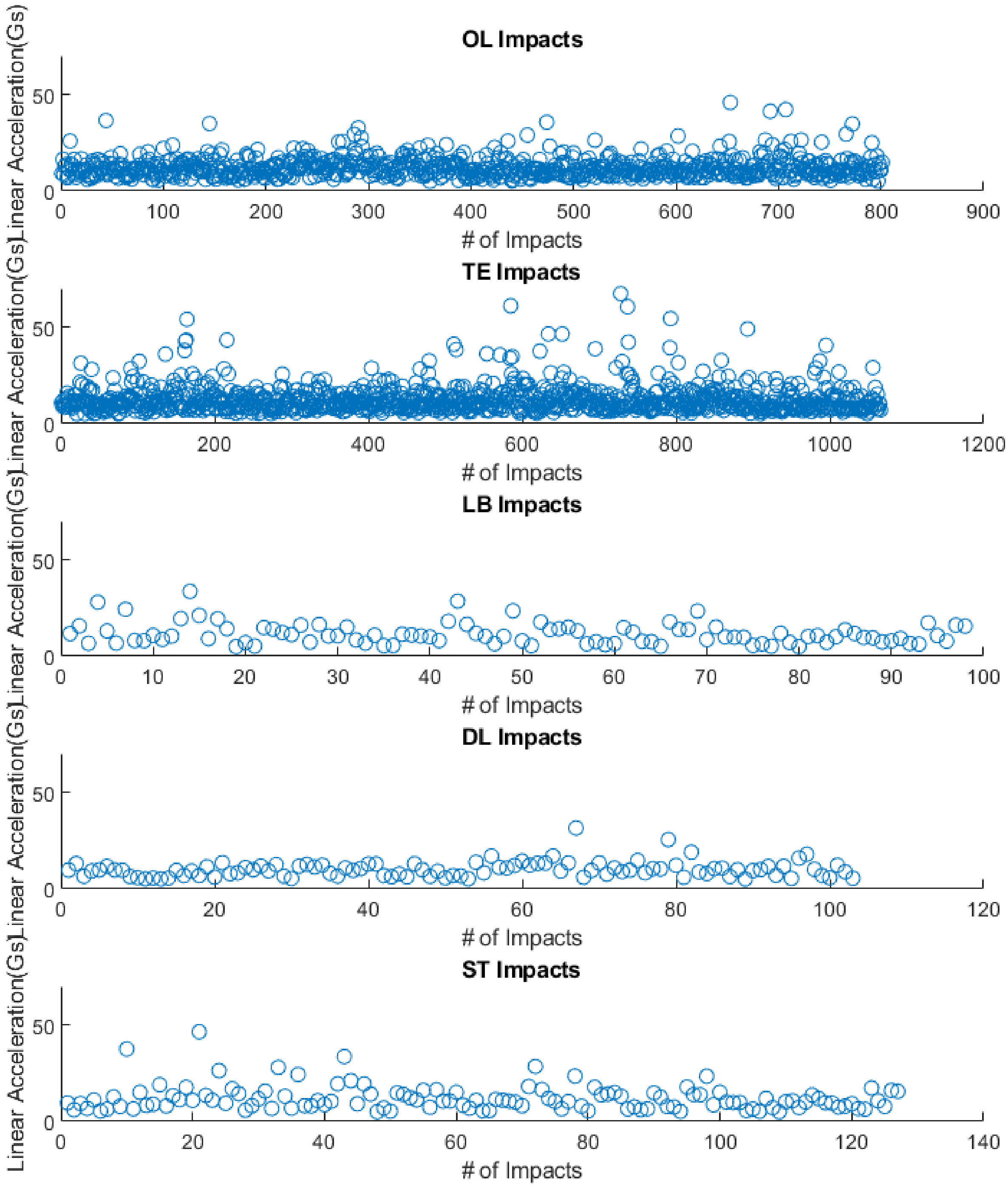


Figure 13: All Impacts for all Players from the 2023 Season by Position

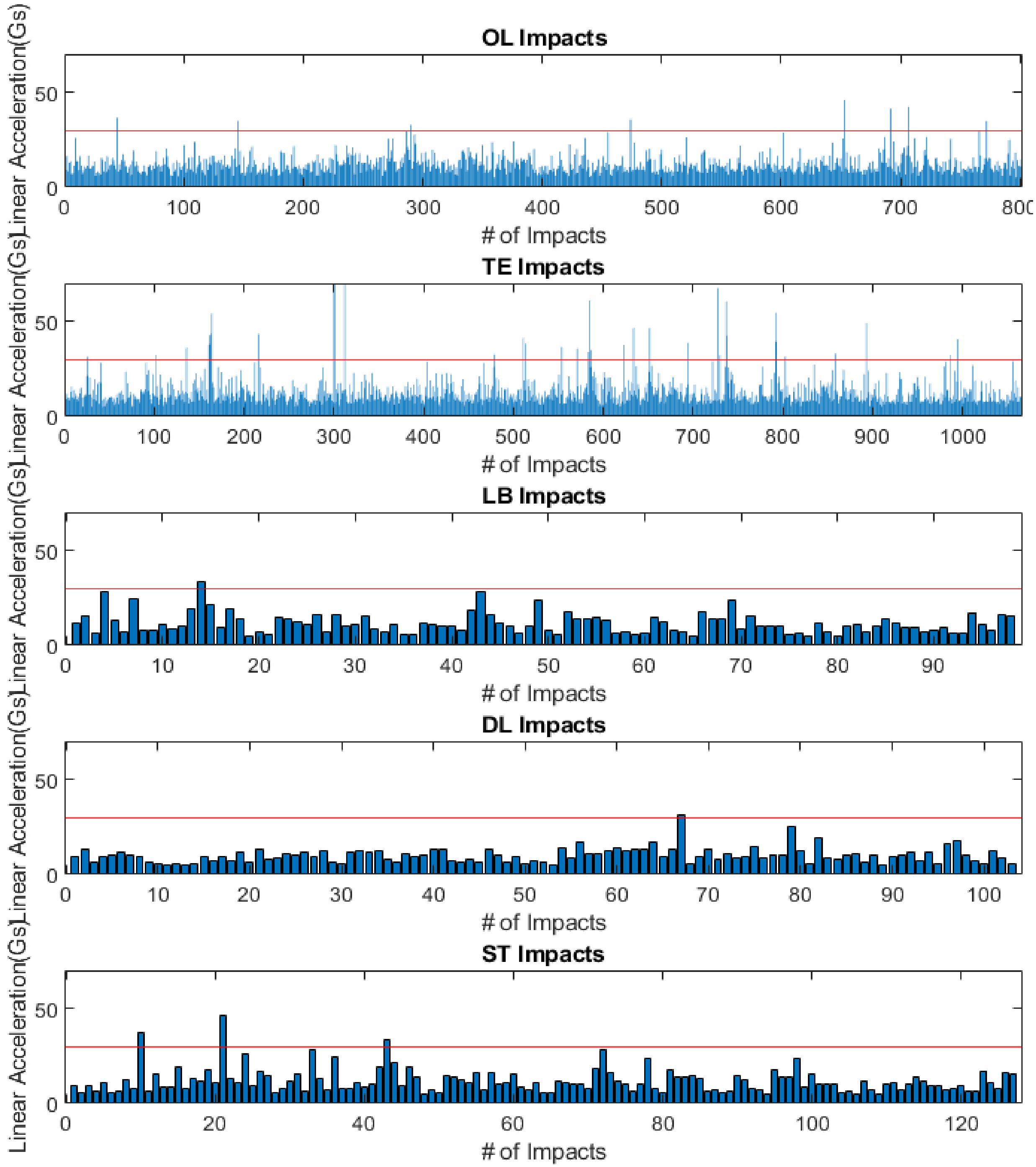


Figure 14: All Impacts for all Players from the 2023 Season by Position: Bar Graphs with 30G testing threshold marked in red

Issues arose with iMG data such as injury and iMG malfunction causing some impact data to not be collected. New iMGs were ordered from Prevent Biometrics for player 4, 5, and 7, but only player 4 was able to use the new iMG before injury, shortly after player 4 received their 2nd iMG, it lost charging capacity again. Player, date, and issues are recorded in Table 7.

Player #	Date	Issue
Player 1	8/10/2023	Injury, out 4 weeks
Player 2	No Issues	
Player 3	No Issues	
Player 4	9/2/2023	Lost charging capacity
Player 4	9/21/2023	2nd iMG lost charging capacity
Player 4	10/21/20223	Mental health, no longer with team
Player 5	8/19/2023	Lost charging capacity
Player 5	9/9/2023	Season ending injury
Player 6	9/16/2023	Lost charging capacity
Player 7	8/17/2023	Lost charging capacity
Player 7	9/2/2023	Season ending injury
Player 8	No Issues	
Player 9	No Issues	
Player 10	No Issues	

Table 7: Issues with iMGs Data Collection

3.5.2. *Brain Simulation*

Brain Simulation is a FE modeling software that uses iMG data to model brain kinematics and strain. Every participant had a Brain Simulation Dashboard that recorded all brain strain on the brain throughout the season. Brain Simulation tracked the loading (strain) on the brain over the duration of the season. Strain plots, 3D models, and 3D video strain simulations were generated to interpret the possible brain damage. All the data produced by the Brain

Simulation Platform was extrapolated from the kinematic data from the 50ms data sets as seen in Table 6. Impact time traces seen in Table 6, were uploaded to Brain Simulation for every impact from the iMGs record, no matter the linear acceleration value. For impacts that were greater than 30Gs, collaborators at Pennsylvania State send back the model files in the form of PVD, PTVU, and VTU files. These files together are all the elements in the FE model.

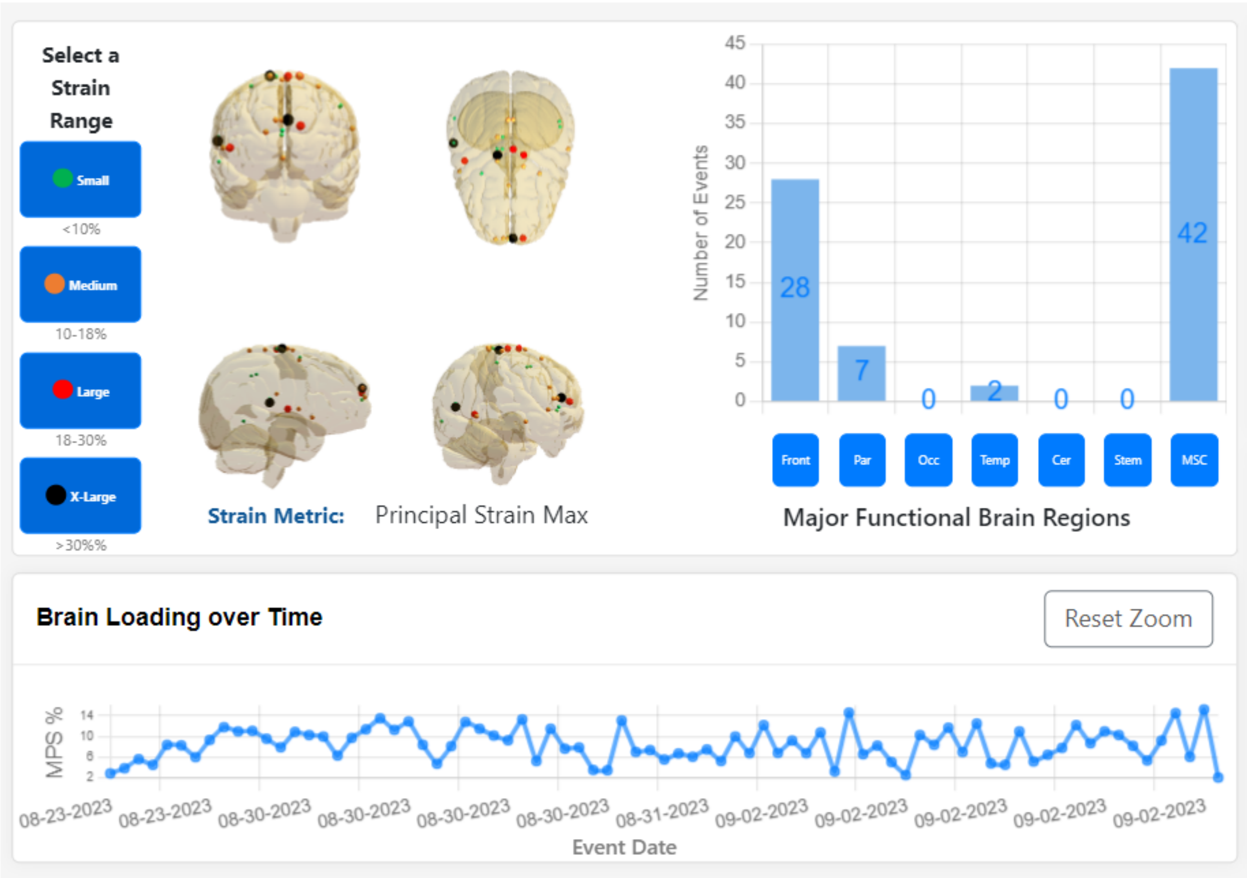
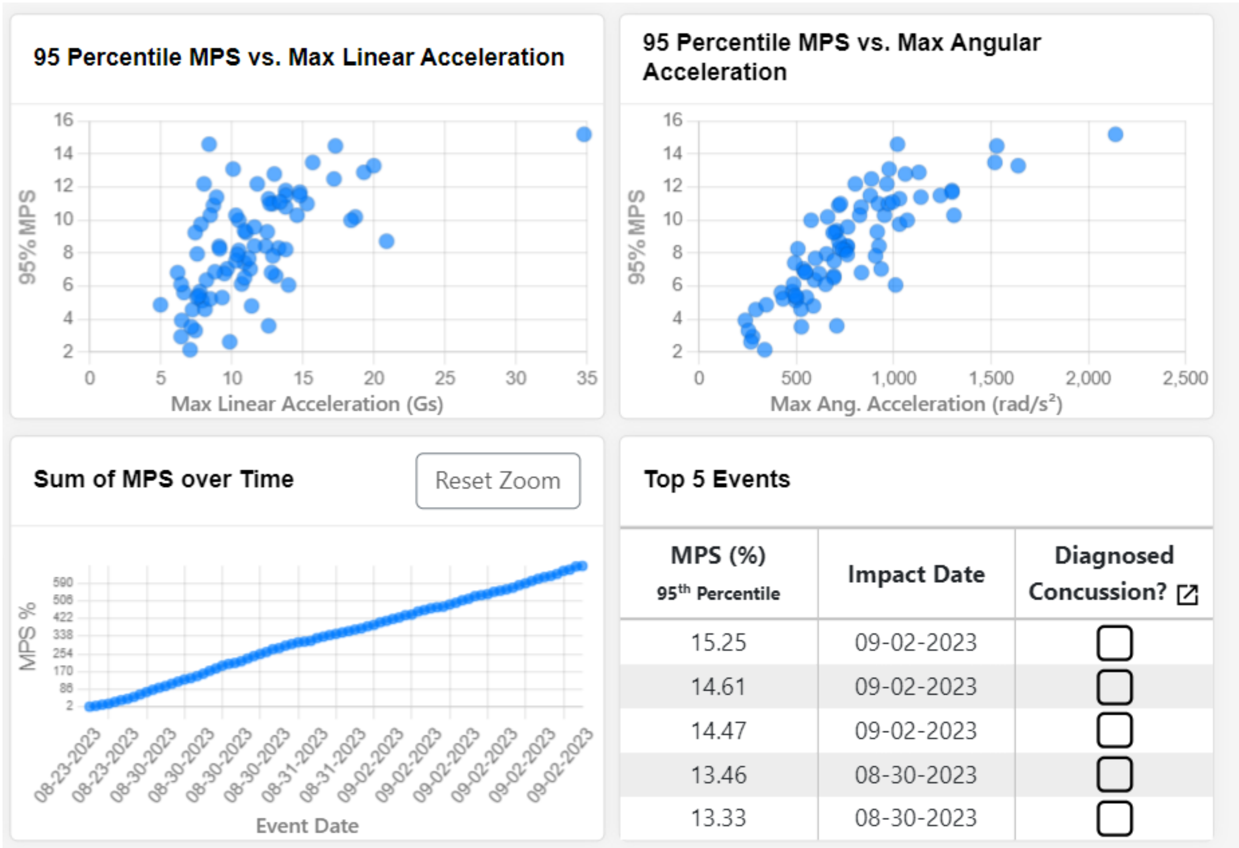


Figure 15: Brain Simulation Player Dashboard (Strain Location and Brain Loading)



MPS (%) 95th Percentile	Impact Date	Diagnosed Concussion?
15.25	09-02-2023	☐
14.61	09-02-2023	☐
14.47	09-02-2023	☐
13.46	08-30-2023	☐
13.33	08-30-2023	☐

Figure 16: Brain Simulation Player Dashboard (MPS95 and Angular Acceleration Plots)

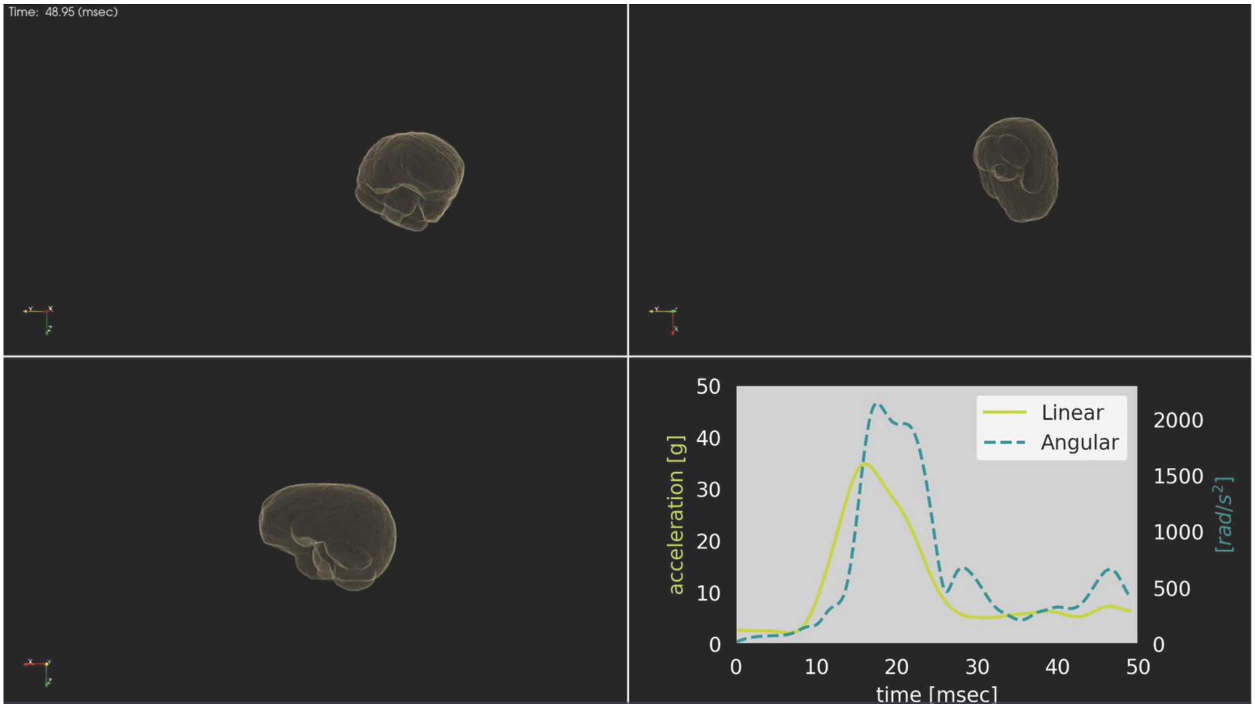


Figure 17: Head Kinematics Video Upon Impact from Brain Simulation

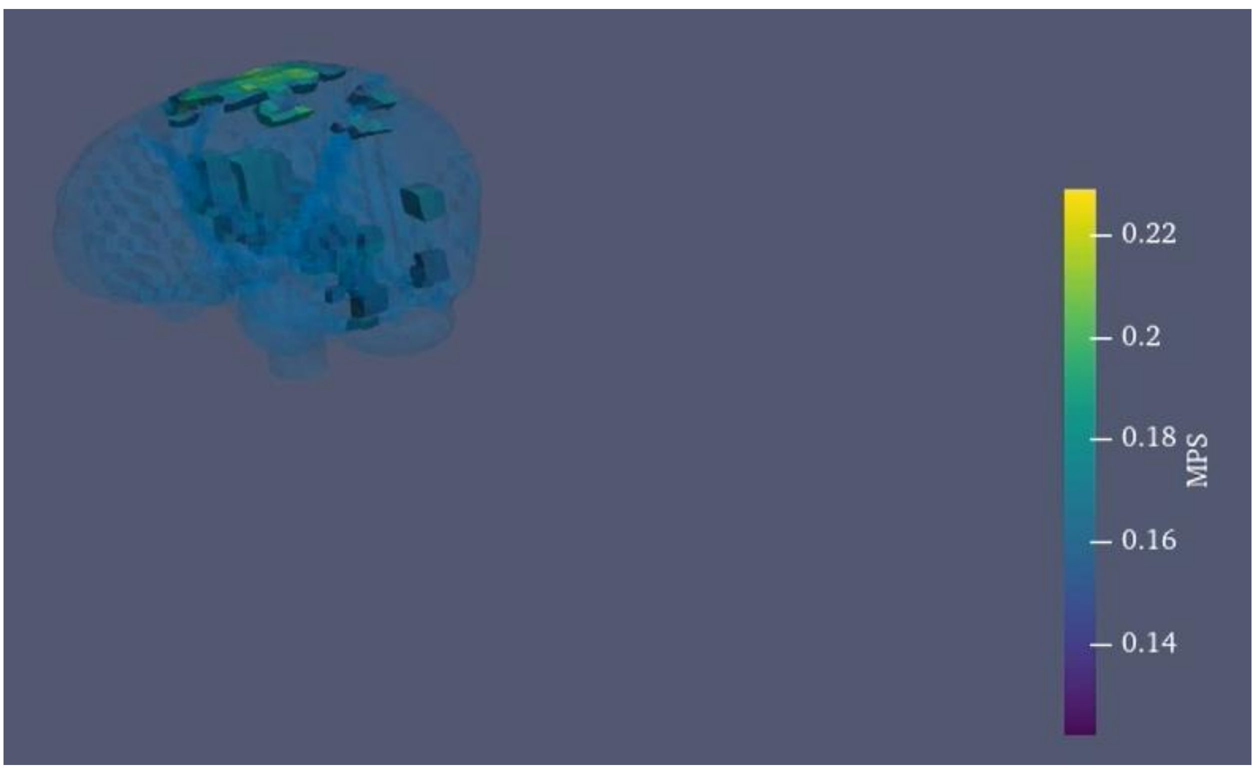


Figure 18: Brain Strain Moving Through Finite Element Model from Brain Simulation

3.5.3. *ParaView 5.11.0*

The model files, generated at PSU through brain simulations, were sent to WCU. Afterward, these data files were uploaded into ParaView for analysis. ParaView (© 2023 kitware,, Park, NY) generates a 3D interactive ~105,000-element model to analyze MPS95. The 105,000 elements are broken down into two different brain categories. The first brain category is related to the anatomical location of brain regions; the brain regions in this category are basal ganglia, thalamus, hippocampus, ventricles, corpus callosum, brainstem, cerebellum, and cerebral hemispheres (Table 8). The second brain category is separated into brain function regions; this category includes the frontal lobe, temporal lobe, parietal lobe, occipital lobe, motor and sensory cortex, cerebellum, and brain stem (Table 9).

Anatomical Region IDs	
1	Skull
2	Basal Ganglia
3	Thalamus
4	Hippocampus
5	Ventricles
6	Corpus Collosum
7	Brainstem
8	Cerebellum
9	Cerebral Hemispheres

Table 8: Region IDs for Anatomical Brain Regions

Functional Region IDs	
1	Cerbral Spinal Fluid
2	Skull
3	Frontal Lobe
4	Temporal Lobe
5	Parietal Lobe
6	Occipital Lobe
7	Motor Sensory Cortex
8	Cerebellum
9	Brainstem

Table 9: Region IDs for Functional Brain Regions

Using two separate categories for brain regions enables cognitive performance test results to be correlated with both anatomical regions and functional regions of the brain. This will also further our understanding of how iMGs can help determine which areas of the brain affect different cognitive functions. The interactive capabilities of ParaView allow for the FE model to be visualized in multiple ways. This study will use slices, transparency, and brain region isolation to assess the possible axonal damage to the brain. The capabilities of ParaView can be seen in Figure 19 and Figure 20.

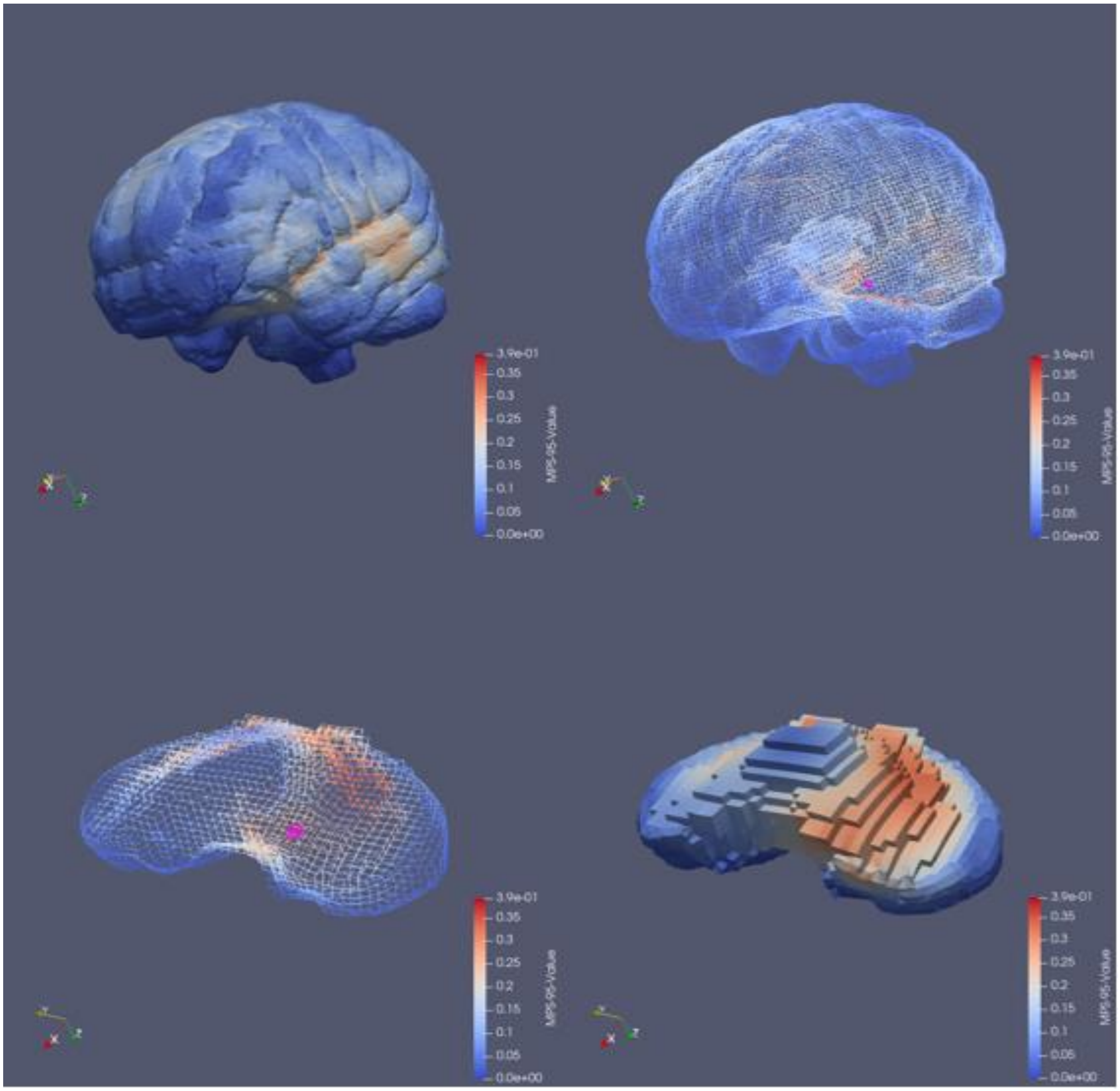


Figure 19: Finite Element Model from ParaView – Surface (TL), Wireframe (TR), Brain Region Wire Frame (BL), Brain Region Surface Views (BR)

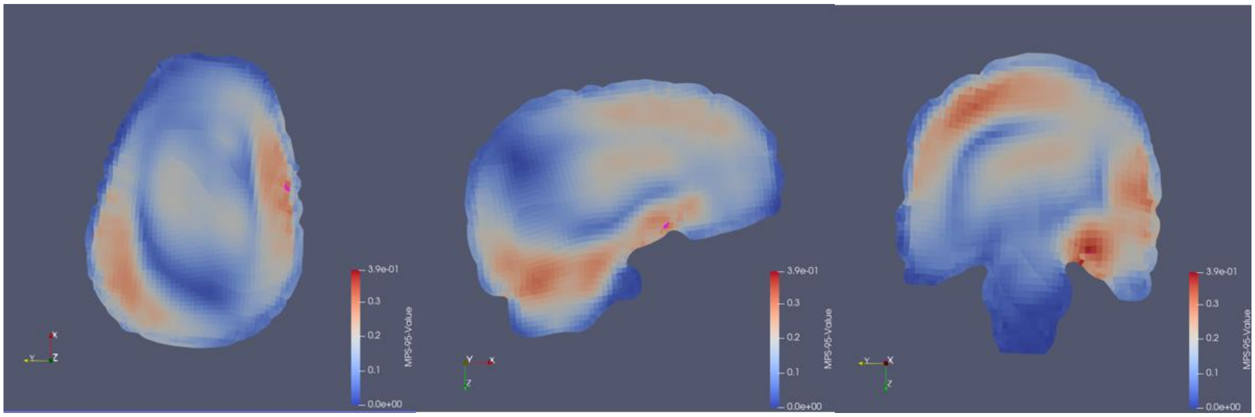


Figure 20: Slices of Finite Element Model From ParaView: Top (1), Side(2), Front(3)

Upon rendering the 3D model, all elements of the FE model in the time step with the highest MPS95 value were exported into MATLAB for statistical analysis. The highest MPS95 time step is determined from the MPS95 vs. Time plot generated by Brain Simulation Platform. The MPS95 vs. Time plot predominantly produces two peaks, known as the coup and contrecoup of impact. The coup represents the brain's initial physical response to the impact, and the contrecoup represents the brain's counter-reaction force to the initial impact, similar to the concept of Newton's third law. For example, if a player receives a whiplash-style impact on the back of the head, the brain would be forced to the back of the skull; this would be the coup motion of the brain. The contrecoup motion would be the brain's reaction force reflecting off the back of the head, moving to the front of the skull.

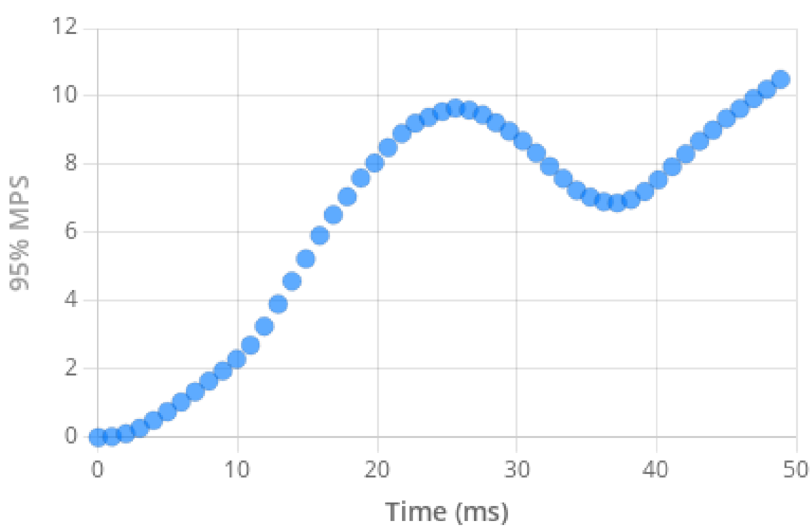


Figure 21: MPS95 vs. Time Plot - Brain Simulation

Of the ~ 105,000 elements in the model, ~ 77,000 of those elements are separated into their own individual brain part IDs to assess MPS95 of those brain regions in four different ways. (1) The maximum value of MPS95 in each region of the brain. (2) The average value of all strain in all elements of each region of the brain. (3) The average value of all strain in each part ID with removing all values of MPS95 that are less than 0.14, and (4) the average of the top 100 values of strain in each brain region. MALTAB code was written to remove strain values below 0.14, average the top 100 values, and locate the maximum strain element for each brain region. Looking at the top 100 values of strain in each brain region gives a better representation of how high strain values are in each brain region. Removing values of brain strain that are lower than 0.14 gives a better understanding of which regions had higher strain, because some brain regions have significantly more elements, due to size, many data points of low strain can miss represent overall strain in that region. Research has shown that a conservative threshold for strain and axonal damage to white matter in the brain is 0.14 [56]. Box and Whisker plots were made to identify average strain and which brain region received the most damage from impact, Figure 23 through Figure 27. The box plots are repeated for all four of the strain variables. It is hypothesized that average MPS95>0.14 (1) will produce the most significant results, followed by, average top 100 MPS95 (2), average MPS (3), and maximum element MPS95 (4).

		Avg_MPS95	MPS95wThresh	MaxMPS95	Top100Avg
1	basal ganglia(2)	0.1894	0.1901	0.5528	0.3462
2	thalamus(3)	0.1773	0.2061	0.3642	0.2112
3	hippocampus(4)	0.2062	0.2111	0.3989	0.3331
4	ventricles(5)	0.2157	0.2157	0.2836	0.2576
5	corpus callosum(6)	0.2028	0.2086	0.3235	0.2996
6	brain stem(7)	0.1190	0.1901	0.4455	0.3129
7	cerebellum(8)	0.1832	0.2251	0.4546	0.4681
8	cerebral hemispheres(9)	0.2001	0.2276	0.5351	0.4681

Table 10: MPS95 Variables for Anatomical Brain Regions

		Avg_MPS95	MPS95wThresh	MaxMPS95	Top100Avg
1	frontal lobe(3)	0.1843	0.2527	0.5528	0.3851
2	temporal lobe(4)	0.2214	0.2796	0.5046	0.4377
3	parietal lobe(5)	0.2225	0.2902	0.4779	0.4502
4	occipital lobe(6)	0.1877	0.2601	0.3922	0.3485
5	motor and sensory cortex(7)	0.1951	0.2721	0.4045	0.3773
6	cerebellum(8)	0.1728	0.2398	0.3968	0.3112
7	brain stem(9)	0.1653	0.2542	0.3586	0.3069

Table 11: MPS95 Variables for Functional Brain Regions

MATLAB code was developed to dissect each element of the brain regions portrayed in Table 8 and Table 9. Approximately 77,000 elements were imported into MATLAB and sorted according to their respective part IDs, which were assigned by ParaView in the exported data file for anatomical brain regions. However, for functional brain regions, ParaView did not automatically allocate region ID values. To segment the data file according to functional regions, an element key obtained from Pennsylvania State University was utilized, linking individual elements to specific functional regions. This necessitated the implementation of two separate codes—one for anatomical and another for functional brain regions. For impacts exceeding 30Gs, both codes were executed to allocate elements to their appropriate brain region based on anatomical or functional location. Despite utilizing the same dataset from ParaView, these codes differentiated between different brain regions.

In Figure 22 through Figure 27, element strain value is separated for each brain region via box and whisker plots. It consists of several components: The whiskers of the plot extend from the minimum to the maximum values of the dataset, representing the range of the data. A red line inside the box represents the median value of strain, which divides the data into two equal halves. The bottom edge of the box marks the first quartile, representing the 25th percentile of strain, while the top edge of the box marks the third quartile, representing the 75th percentile. These quartiles present the spread of the middle 50% of the data, known as the interquartile range (IQR). Any data points that fall outside the range defined by the whiskers are considered outliers, indicating potentially unusual or extreme values. They are particularly effective for comparing multiple brain regions simultaneously. Analyzing strain data sets with box and whisker plots can help identify how concentrated the strain is for each brain region.

Figure 24 and Figure 27 visually demonstrate the impact of low strain values on the overall averages of strain across brain regions. With a specific focus on the thalamus in Figure 27, removing values of strain below 0.14 results in a significant ~52% increase in strain to this brain region. Initially ranked 5th in median strain before removing low strain values, the thalamus ascends to the first position in median strain by approximately 20% after their removal.

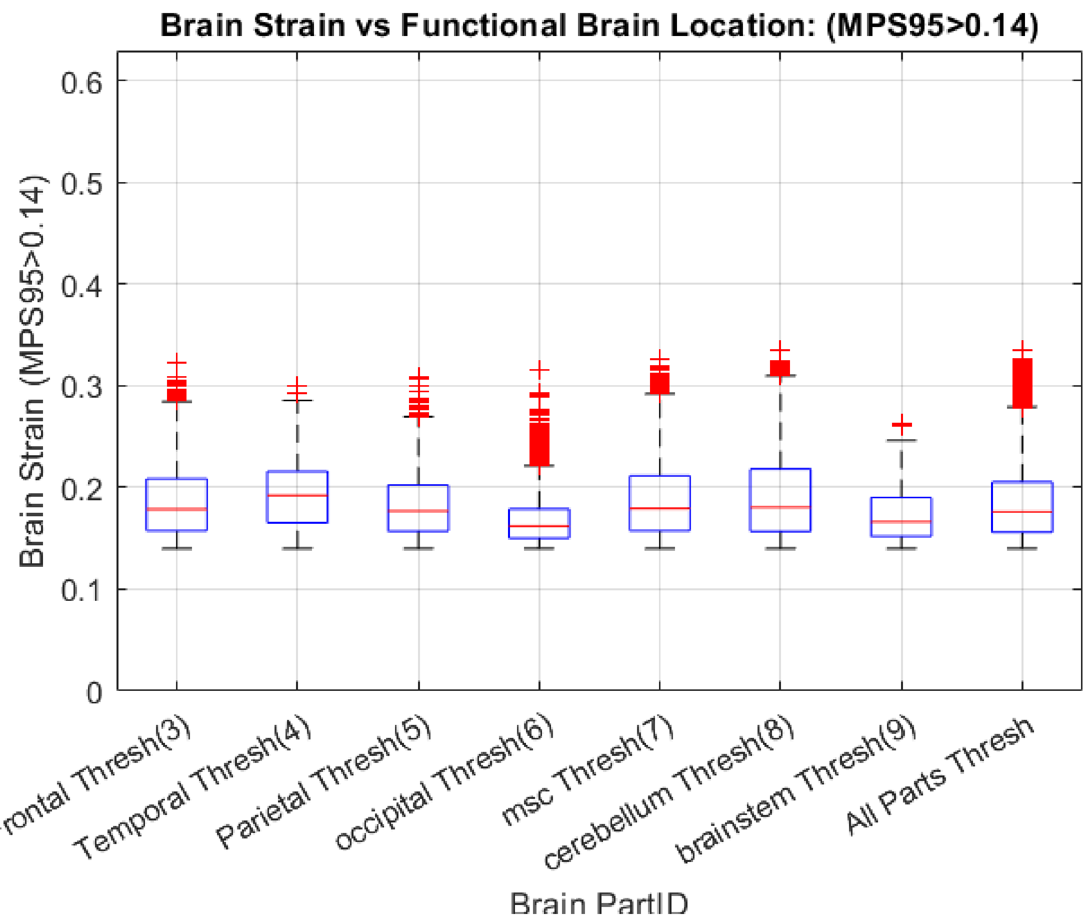


Figure 22: Brain Strain for Anatomical Regions (MPS95 >0.14)

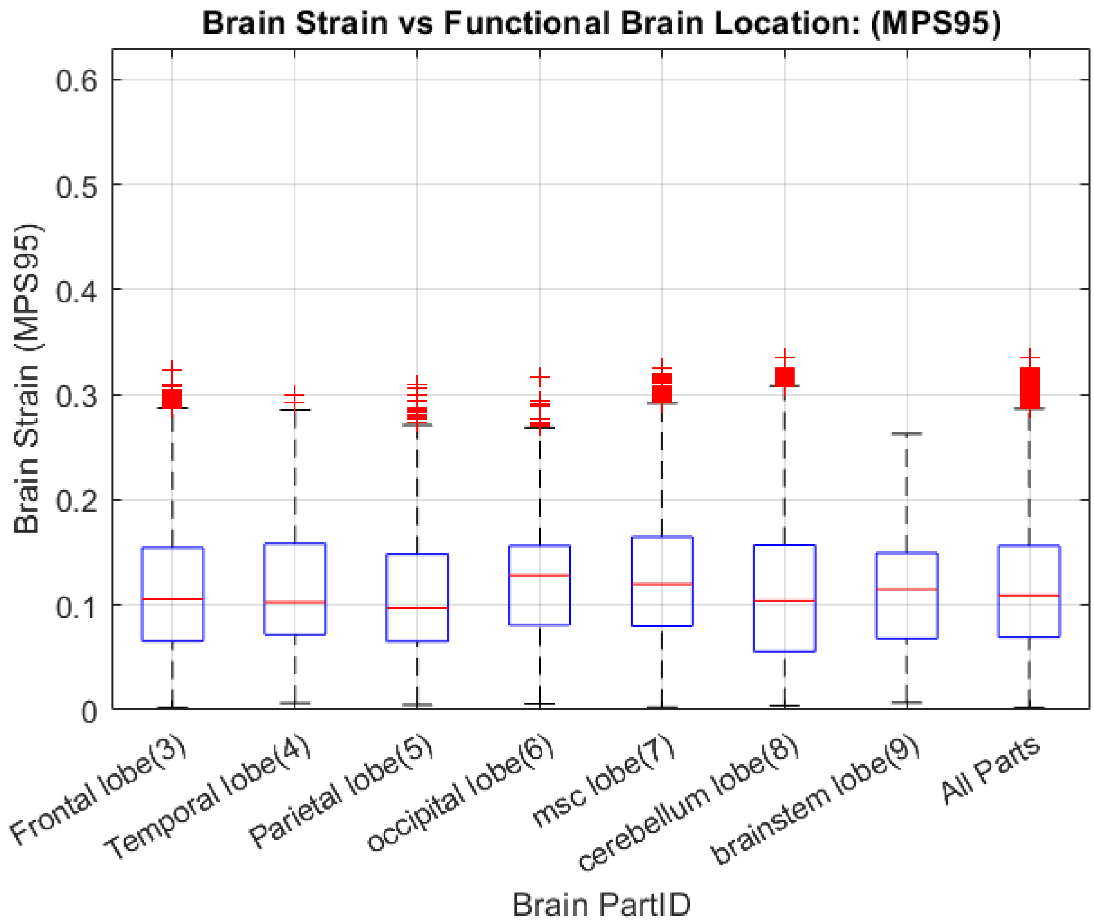


Figure 23: Brain Strain for Functional Regions of the Brain (All MPS95 Values)

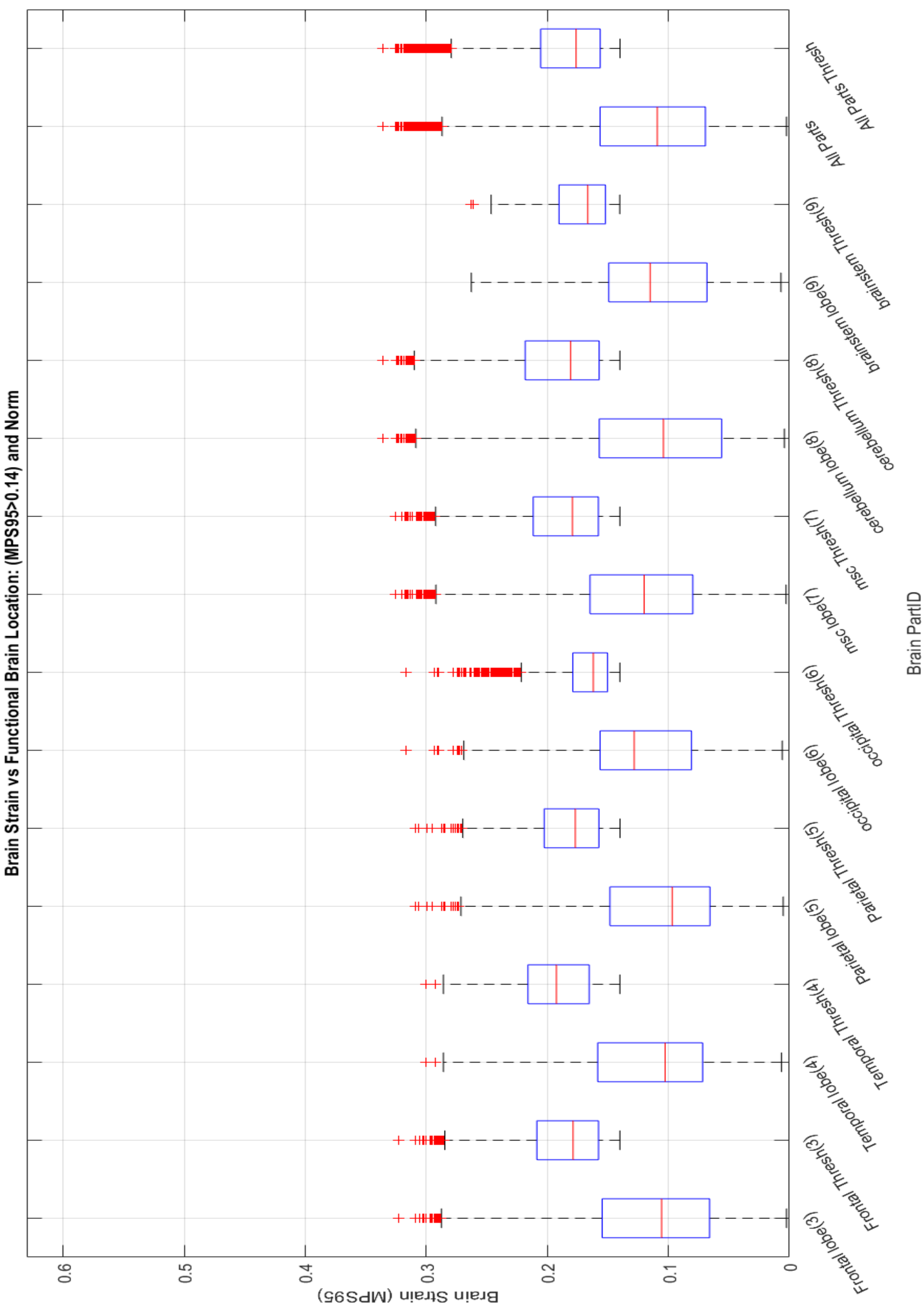


Figure 24: Brain Strain for Functional Brain Regions (All MPS95 values and MPS95 > 0.14)

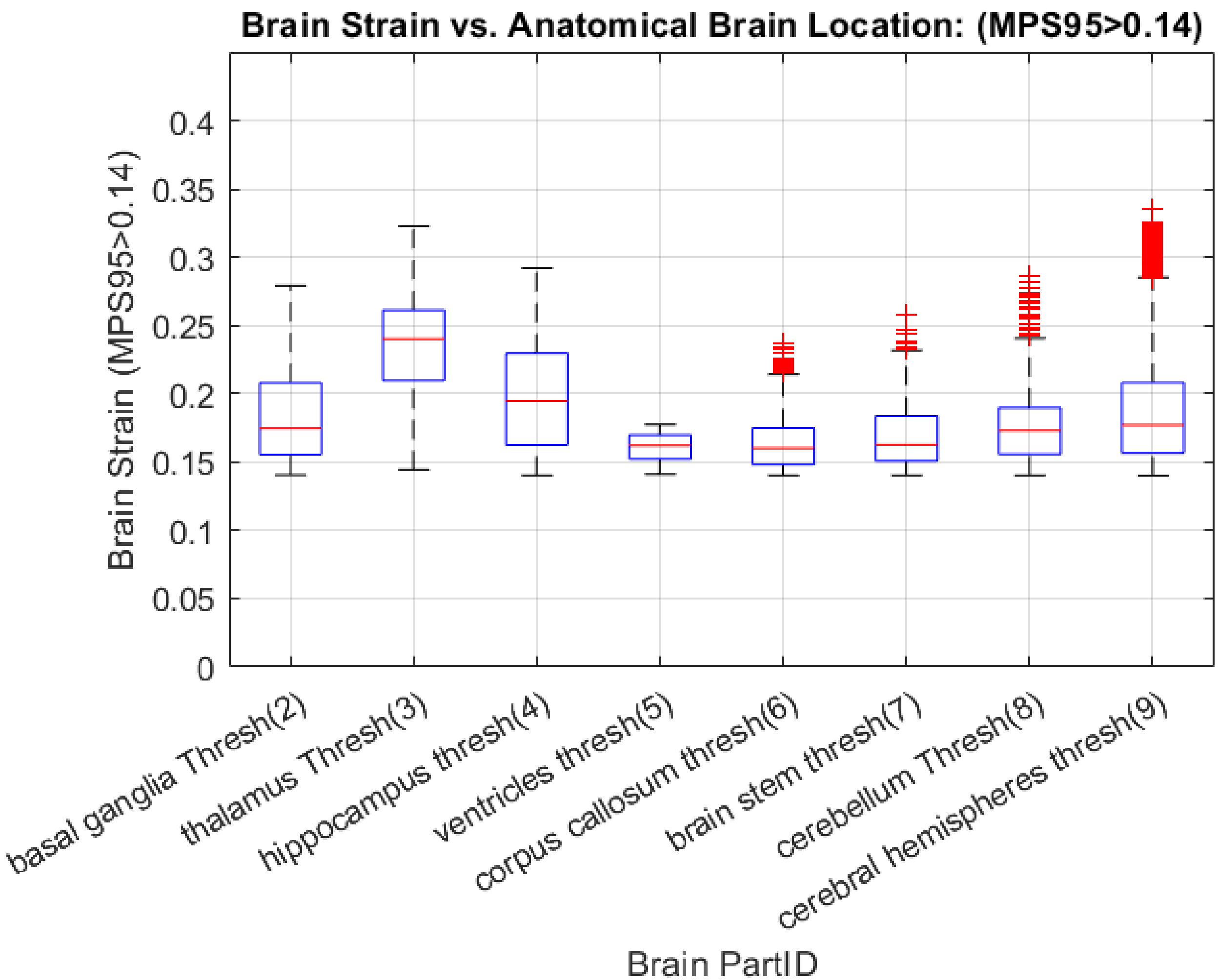


Figure 25: Brain Strain for Anatomical Brain Regions (MPS95 > 0.14)

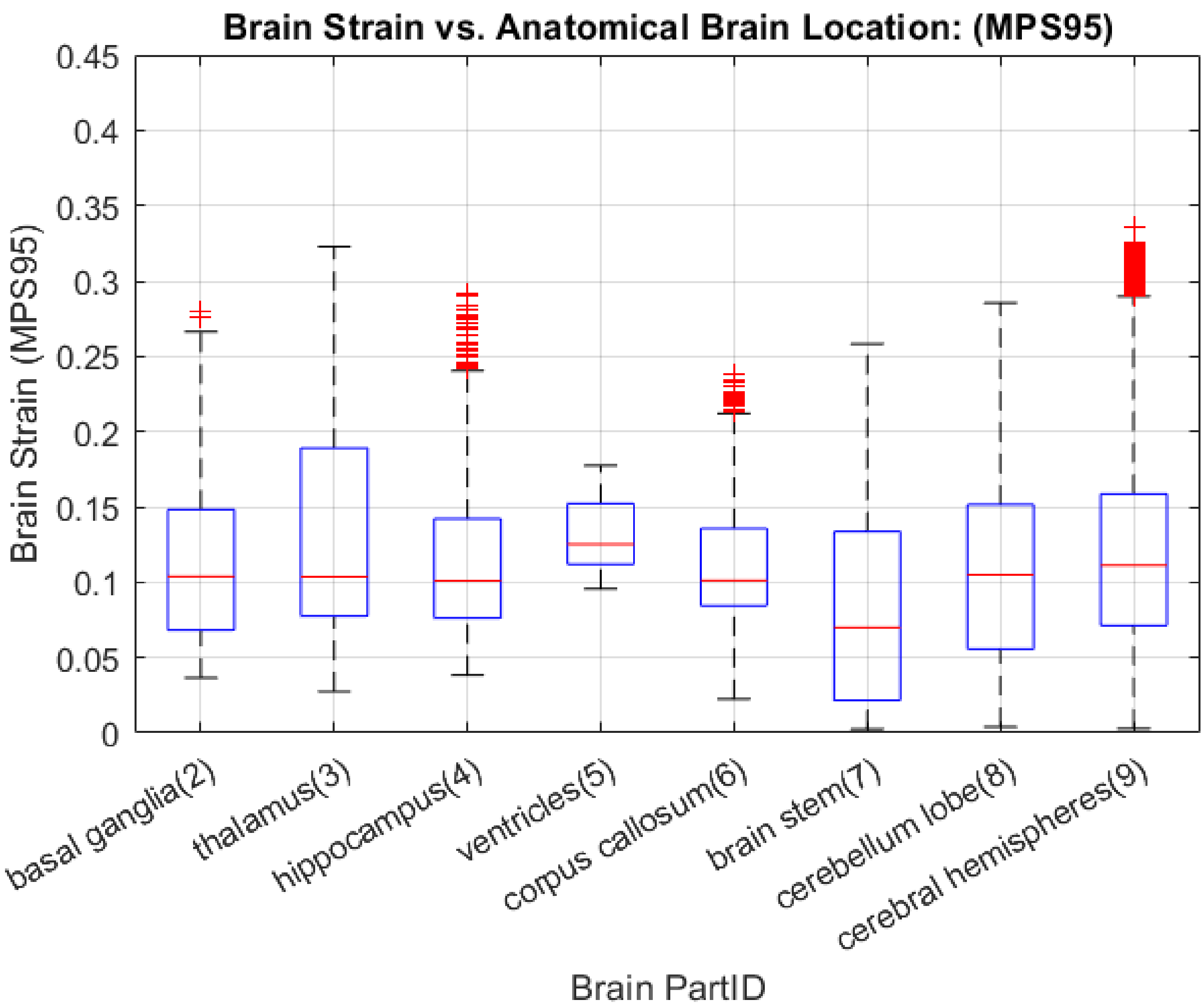


Figure 26: Brain Strain for Anatomical Brain Regions (All MPS95 Values)

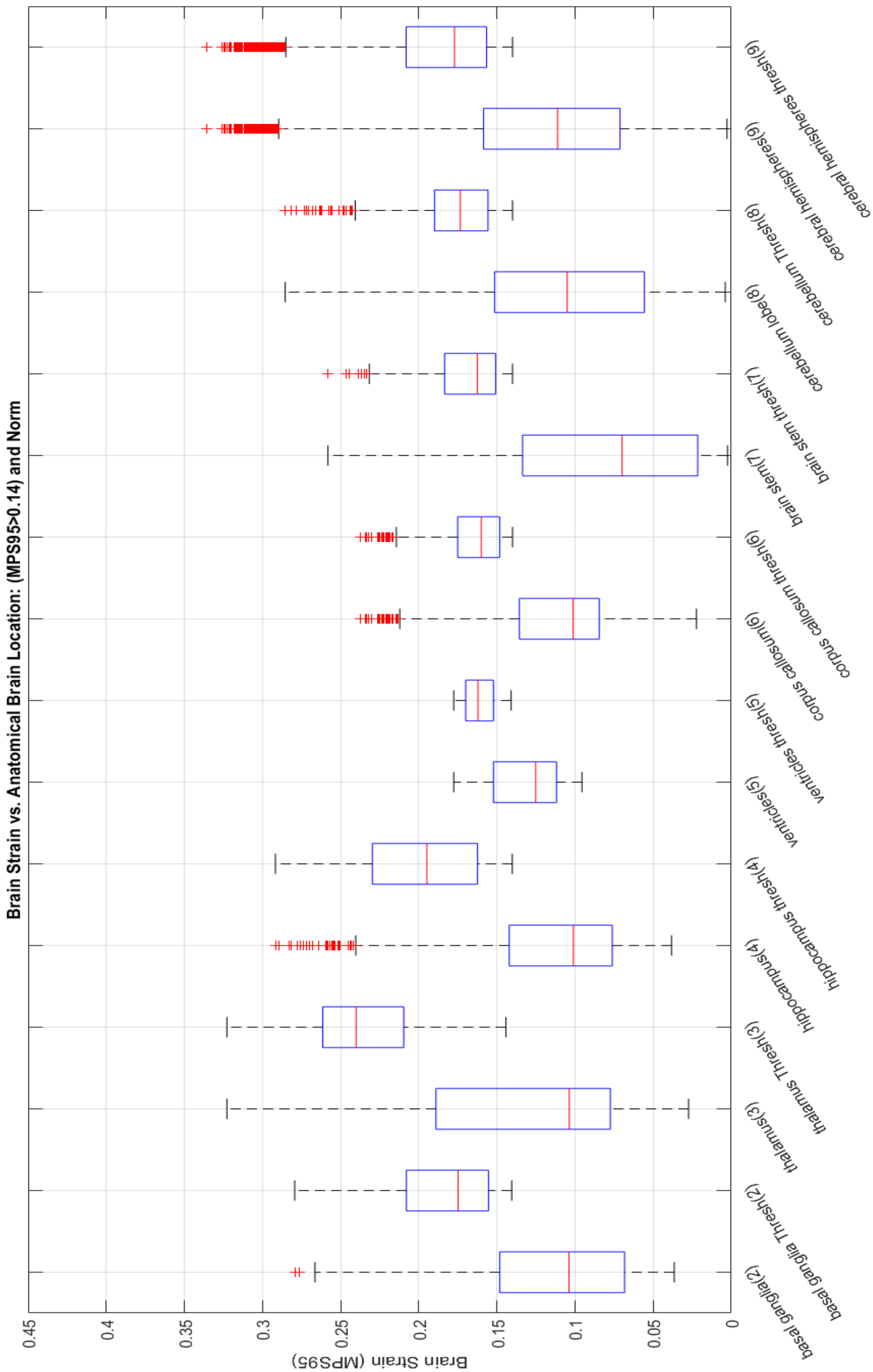


Figure 27: Brain Strain for Anatomical Brain Regions (All MPS95 Values and MPS95 > 0.14)

3.6. Prediction Values and Prediction Percentage

Two variables were devised to assess the efficacy of brain region strain in predicting deficiencies in composite scores. First, the Prediction Percentage (PP) evaluates the extent to which the anticipated composite scores, as per Table 1, align with the observed brain strain results. If the slope values of composite scores within a brain region from the linear regression plots in Chapter 4.1 are positive, it indicates that the composite scores are not accurately predicted, as the anticipated relationship between strain and cognitive function should be negative. The Prediction Percentage is computed using Equation 3: Prediction Percentage Equation, providing an overall indication of whether brain regions can effectively predict composite scores based on strain. Second, the Prediction Value (PdV) determines the relevance of the forecasted composite scores. The magnitude of results is determined by the slope values of the linear regression plots in Chapter 4.1. PdV evaluates how many predicted composite scores fall among the highest negative slope values. Each composite variable is assigned a value from 1 to 9 based on its position in ascending slope rankings, with nine denoting the highest correlated slope and one representing the lowest correlated slope. Subsequently, the Prediction Value is calculated using Equation 4, providing insights into the significance of the predicted composite scores.

$$Prediciton\ Percentage(PP) = \frac{\#\ of\ Composite\ Scores\ Seen\ From\ Brain\ Strain}{Total\ \#\ of\ Possible\ Composite\ scores}$$

Equation 3: Prediction Percentage Equation

$$Prediciton\ Value(PdV) = Predicition\ Percentage(PP) * \sum(Ranked\ Composite\ Score\ values)$$

Equation 4: Prediction Value Equation

3.7. Linear Regression Fits on Data Sets (Slope)

Scatter plots of nine points were generated in MATLAB when analyzing cognitive function and strain data. The ten points represent the ten instances where an impact recorded from the iMG elicited a post impact test. The composite ratio for each test was then set at the dependent variable (y-axis), and the brain strain value was set as the independent variable (x-axis). Giving each instance a coordinate location to represent the cognitive function and the amount of brain strain in each region of the brain. Linear regression models were fit to the data set in MATLAB using the four different strain variables (Average Strain, Average Strain <0.14, Maximum Strain, Top 100 Average of strain). Eight different MATLAB codes were written to analyze the four strain parameters for the anatomical and functional brain regions. The composite ratio was constant through the different linear regression models, where the strain values varied with the variables being used and quantity of strain in each brain area being analyzed.

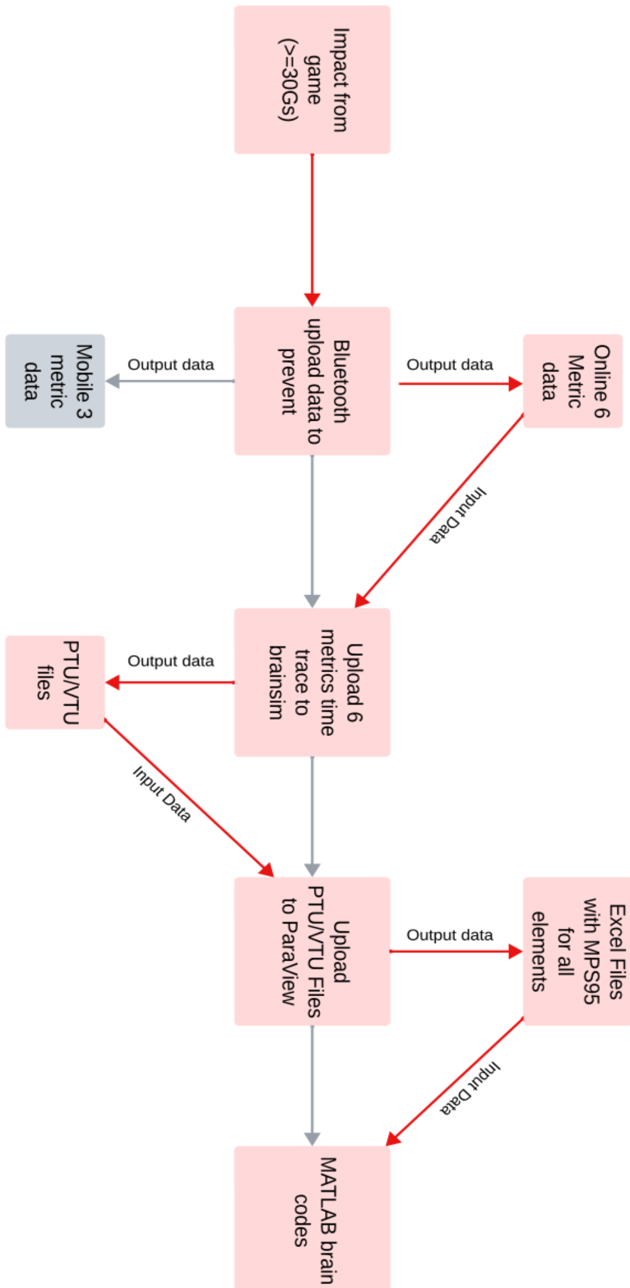


Figure 28: Study Data Flowchart

CHAPTER 4: RESULTS

4.1. Composite Results

4.1.1. *Memory Composite (Verbal) Percentage*

Figure 29 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Percentage vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, three brain regions had a negative relationship denoted by slope values: Ventricles, Brainstem, and Cerebellum.

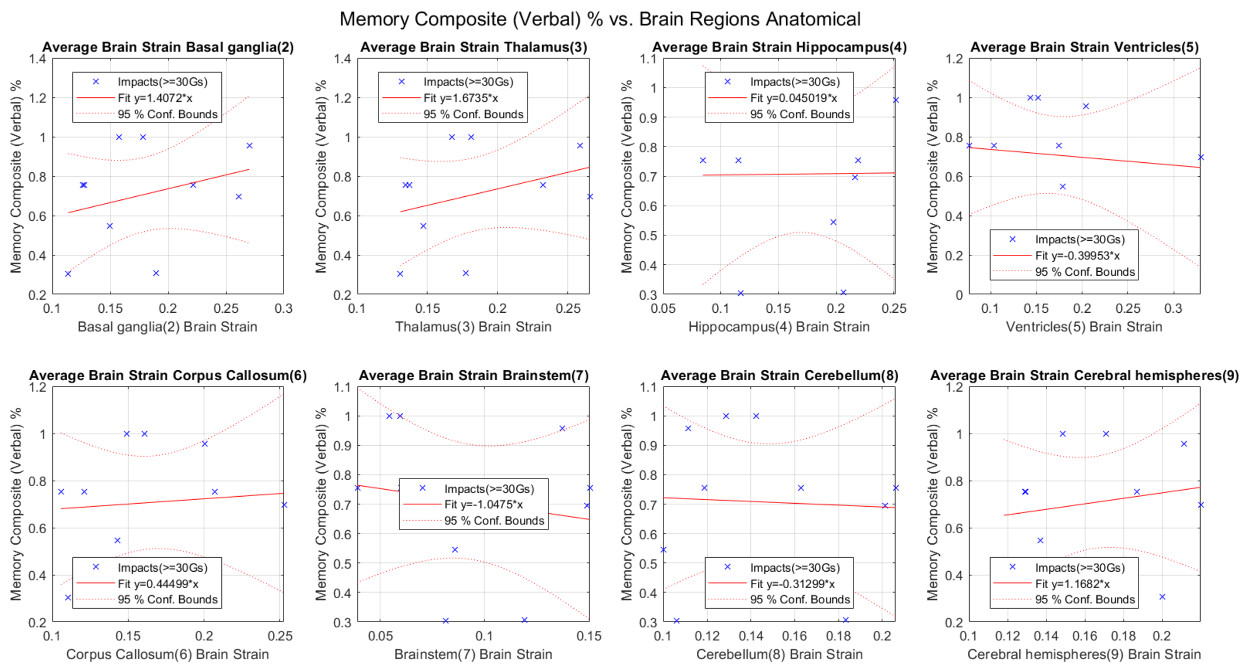


Figure 29: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95

		Memory Composite (Verbal) %
1	Basal ganglia(2)	1.4072
2	Thalamus(3)	1.6735
3	Hippocampus(4)	0.0450
4	Ventricles(5)	-0.3995
5	Corpus Callosum(6)	0.4450
6	Brainstem(7)	-1.0475
7	Cerebellum(8)	-0.3130
8	Cerebral hemispheres(9)	1.1682

Table 12: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) - Average MPS95 – Slopes

Figure 30: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average MPS95 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Percentage vs. Functional Brain Regions using Average MPS95 as the strain parameter, two brain regions have a negative slope indicating possible correlation: Frontal Lobe and Brainstem.

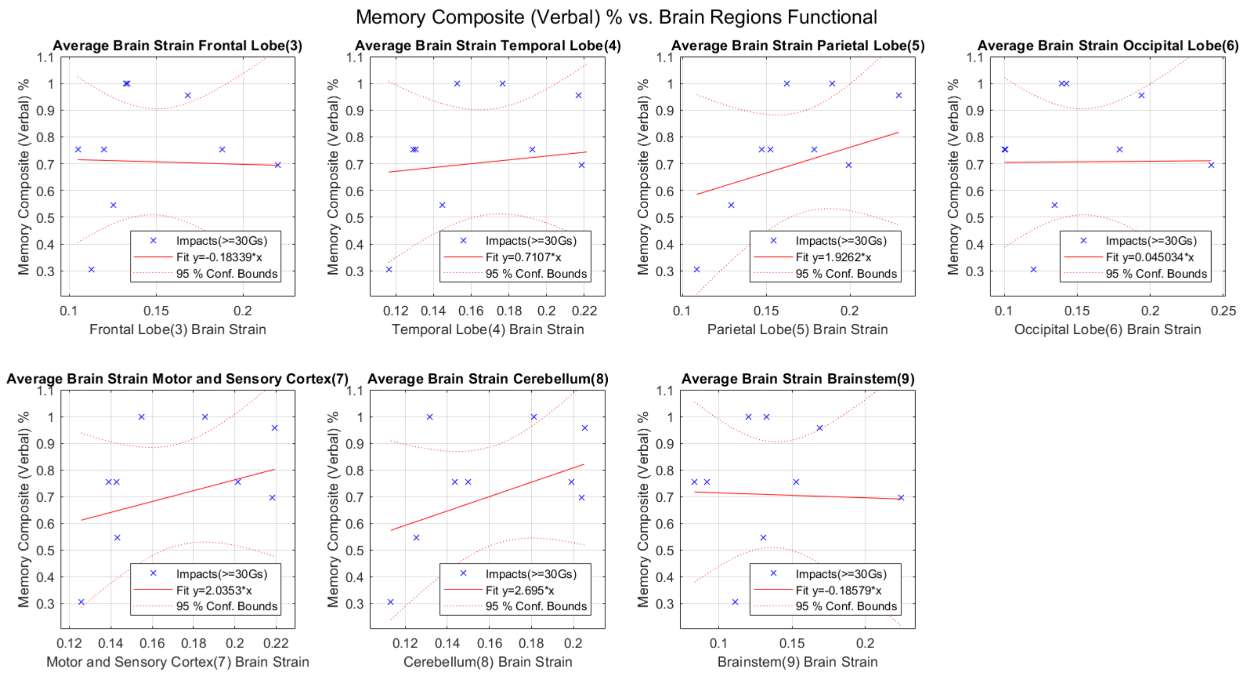


Figure 30: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average MPS95

		Memory Composite (Verbal) %
1	Frontal Lobe(3)	-0.1834
2	Temporal Lobe(4)	0.7107
3	Parietal Lobe(5)	1.9262
4	Occipital Lobe(6)	0.0450
5	Motor and Sensory Cortex(7)	2.0353
6	Cerebellum(8)	2.6950
7	Brainstem(9)	-0.1858

Table 13: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average MPS95 – Slopes

Figure 31 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter, six brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, Ventricles, Corpus Collosum, Brainstem, and Cerebellum.

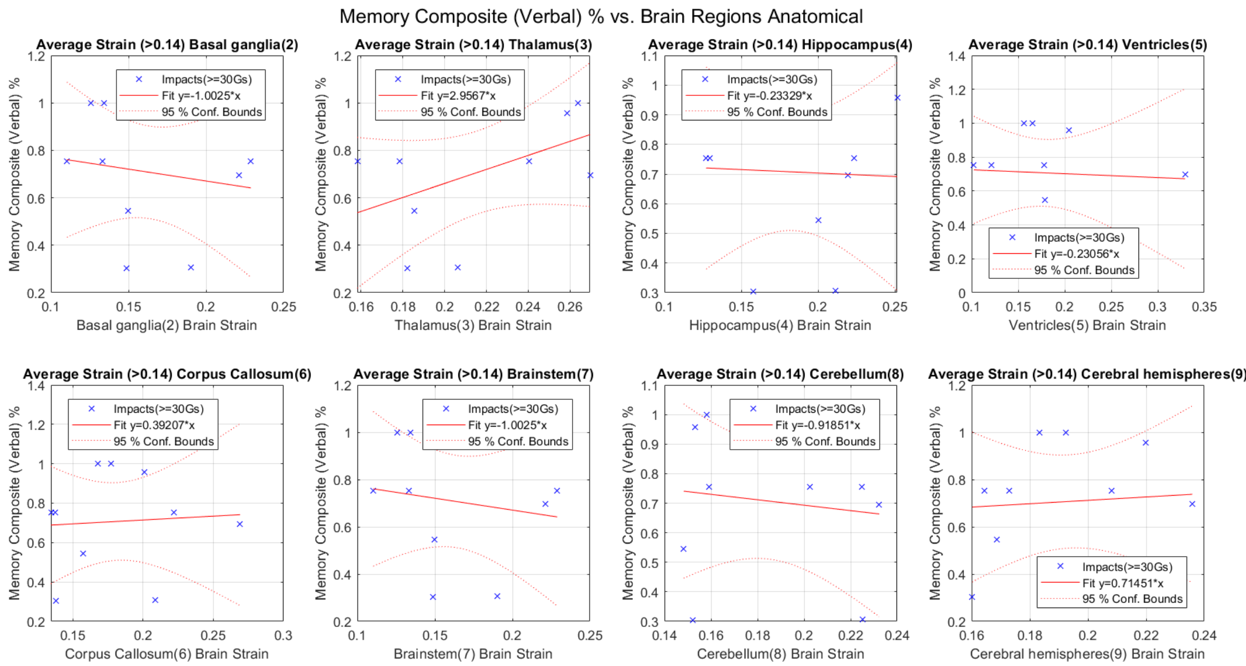


Figure 31: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Memory Composite (Verbal) %
1	**Basal ganglia(2)**	-1.0025
2	**Thalamus(3)**	2.9567
3	**Hippocampus(4)**	-0.2333
4	**Ventricles(5)**	-0.2306
5	**Corpus Callosum(6)**	0.3921
6	**Brainstem(7)**	-1.0025
7	**Cerebellum(8)**	-0.9185
8	**Cerebral hemispheres(9)**	0.7145

Figure 32: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 33 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; seven brain regions have a negative slope indicating possible correlation, no brain regions have a negative slope indicating no possible correlation.

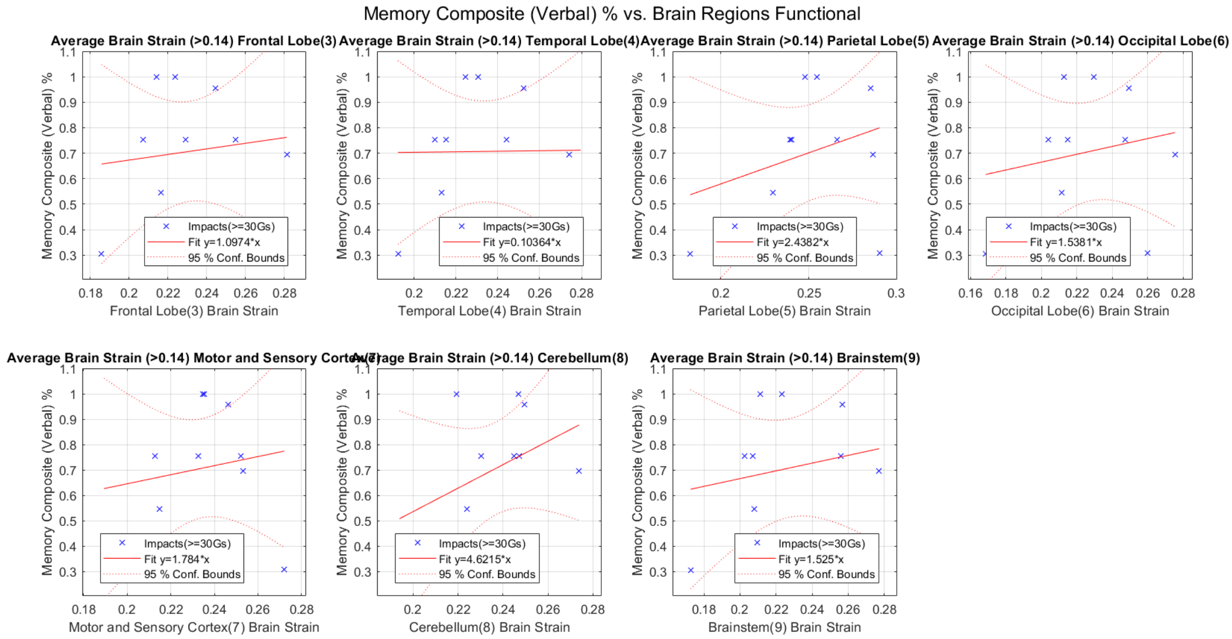


Figure 33: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Memory Composite (Verbal) %
1	Frontal Lobe(3)	1.0974
2	Temporal Lobe(4)	0.1036
3	Parietal Lobe(5)	2.4382
4	Occipital Lobe(6)	1.5381
5	Motor and Sensory Cortex(7)	1.7840
6	Cerebellum(8)	4.6215
7	Brainstem(9)	1.5250

Table 14: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 34 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; five brain regions have a negative slope indicating possible correlation: Hippocampus, Ventricles, Brainstem, Cerebellum, and Cerebral Hemispheres.

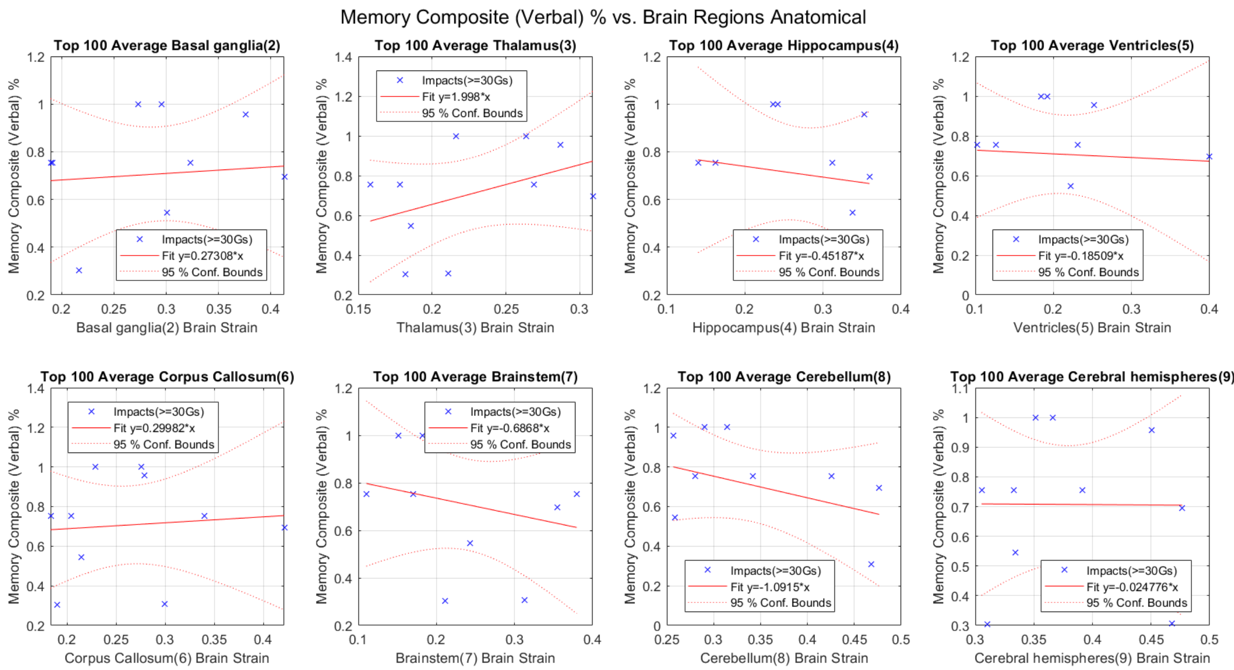


Figure 34: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average)

		Memory Composite (Verbal) %
1	Basal ganglia(2)	0.2731
2	Thalamus(3)	1.9980
3	Hippocampus(4)	-0.4519
4	Ventricles(5)	-0.1851
5	Corpus Callosum(6)	0.2998
6	Brainstem(7)	-0.6868
7	Cerebellum(8)	-1.0915
8	Cerebral hemispheres(9)	-0.0248

Table 15: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average) – Slopes

Figure 35 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, two regions have a negative slope indicating possible correlation: Frontal Lobe and Temporal Lobe.

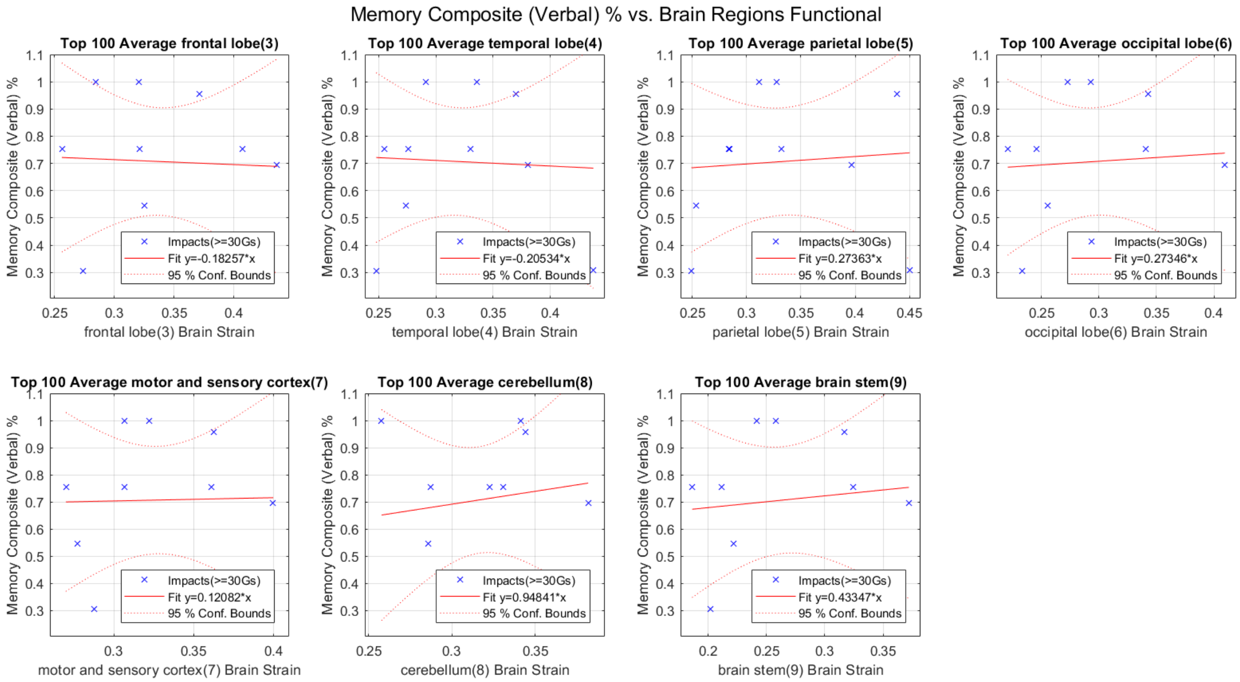


Figure 35: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Memory Composite (Verbal) %
1	frontal lobe(3)	-0.1826
2	temporal lobe(4)	-0.2053
3	parietal lobe(5)	0.2736
4	occipital lobe(6)	0.2735
5	motor and sensory cortex(7)	0.1208
6	cerebellum(8)	0.9484
7	brain stem(9)	0.4335

Table 16: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 36 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, six brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, Ventricles, Brainstem, Cerebellum, and Cerebral Hemispheres.

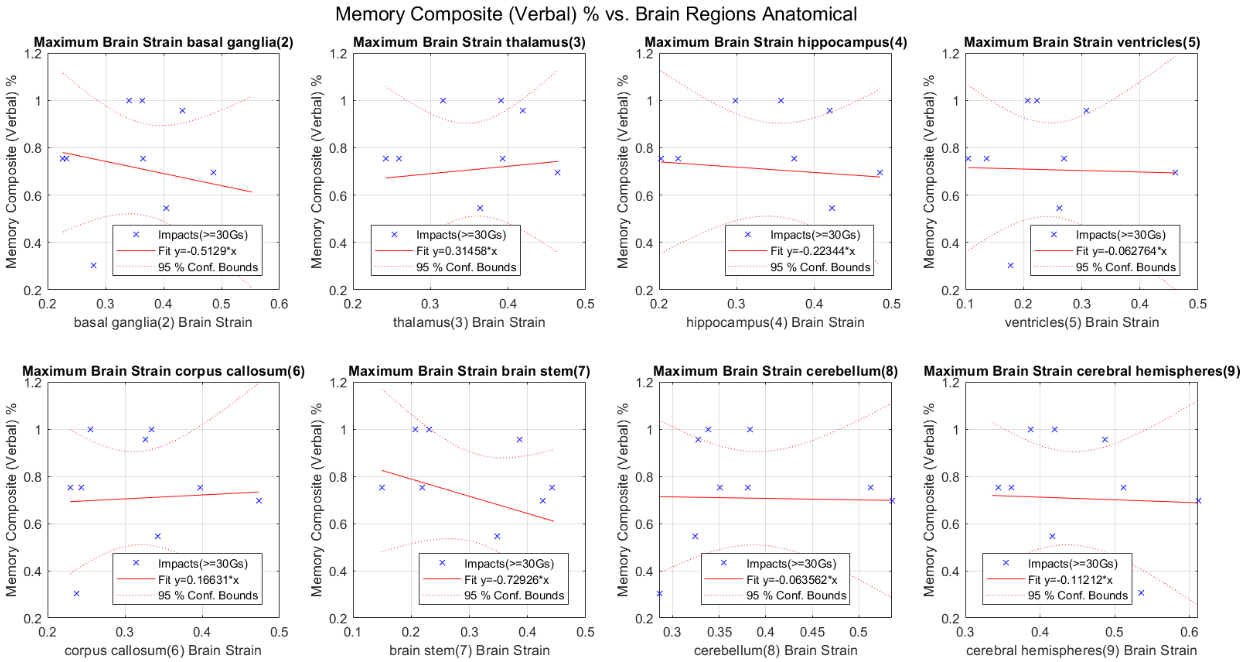


Figure 36: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Verbal) %
1	basal ganglia(2)	-0.5129
2	thalamus(3)	0.3146
3	hippocampus(4)	-0.2234
4	ventricles(5)	-0.0628
5	corpus callosum(6)	0.1663
6	brain stem(7)	-0.7293
7	cerebellum(8)	-0.0636
8	cerebral hemispheres(9)	-0.1121

Table 17: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 37 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite Percentage vs. Functional Brain Regions using Max Strain Value as the strain parameter, three brain regions have a negative slope indicating possible correlation: Frontal Lobe, Temporal Lobe, and Occipital Lobe.

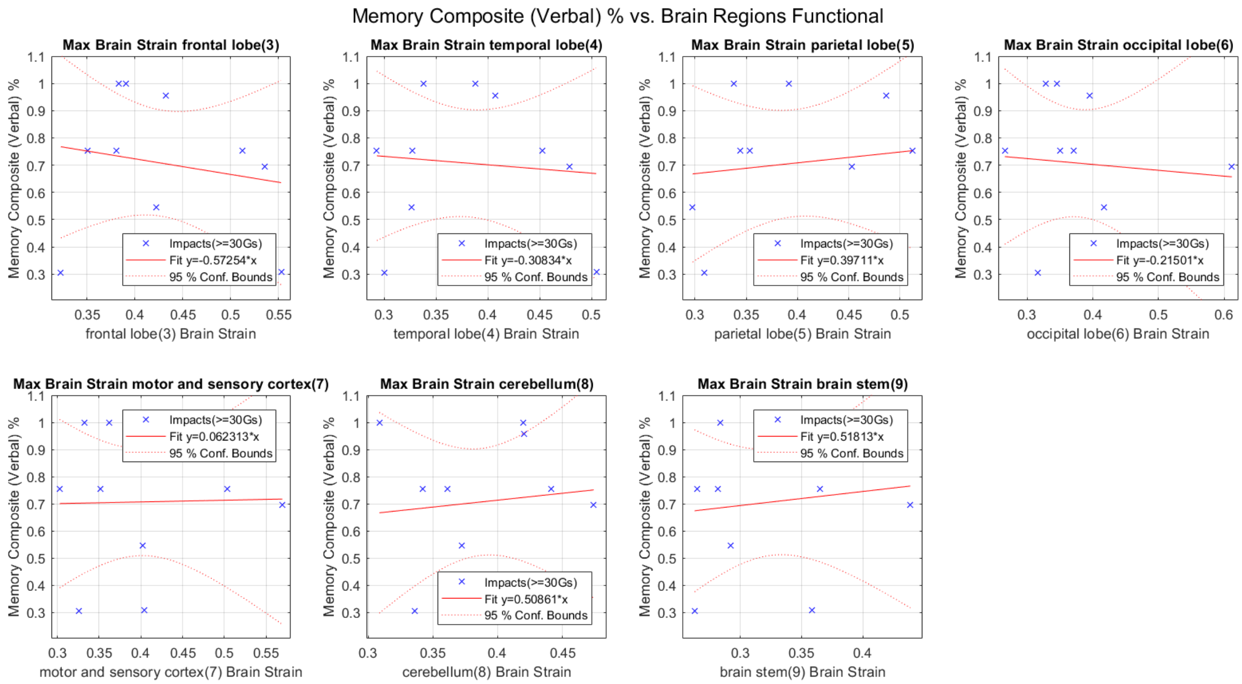


Figure 37: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Max Strain Value

		Memory Composite (Verbal) %
1	frontal lobe(3)	-0.5725
2	temporal lobe(4)	-0.3083
3	parietal lobe(5)	0.3971
4	occipital lobe(6)	-0.2150
5	motor and sensory cortex(7)	0.0623
6	cerebellum(8)	0.5086
7	brain stem(9)	0.5181

Table 18: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Max Strain Value – Slopes

4.1.2. *Memory Composite (Verbal)*

Figure 38 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, two brain regions had a negative relationship denoted by slope values: Ventricles and Brainstem .

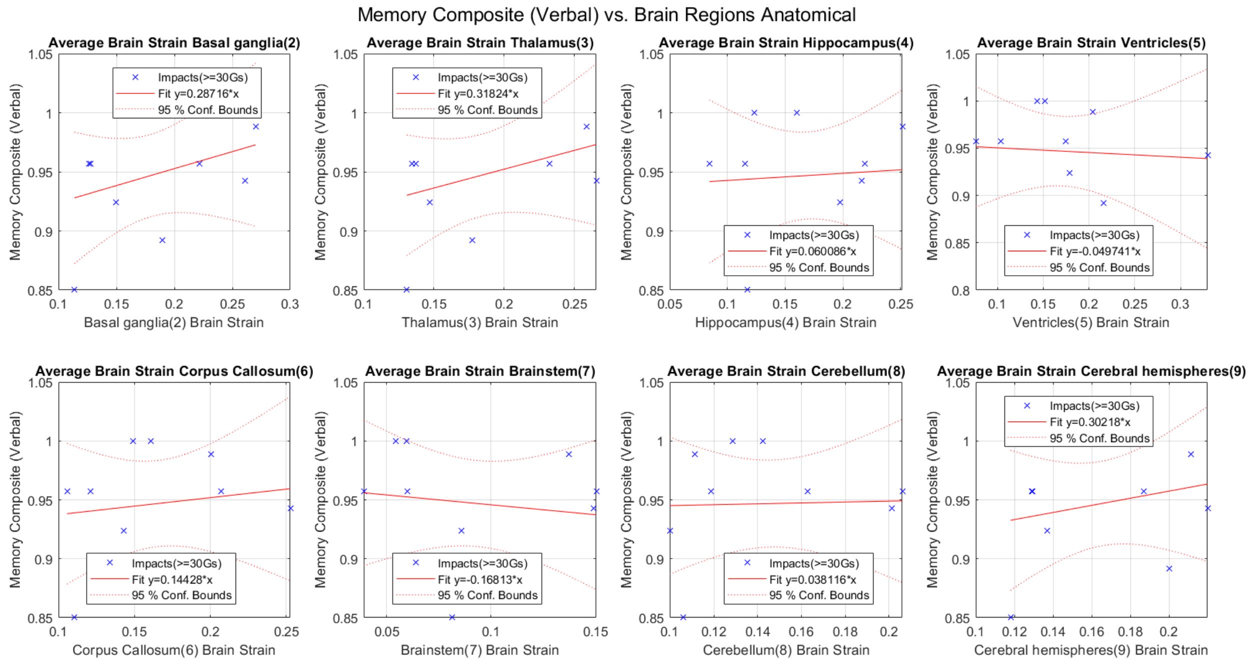


Figure 38: Verbal Memory Composite vs. Brain Regions (Anatomical) – Average MPS95

		Memory Composite (Verbal)
1	Basal ganglia(2)	0.2872
2	Thalamus(3)	0.3182
3	Hippocampus(4)	0.0601
4	Ventricles(5)	-0.0497
5	Corpus Callosum(6)	0.1443
6	Brainstem(7)	-0.1681
7	Cerebellum(8)	0.0381
8	Cerebral hemispheres(9)	0.3022

Table 19: Verbal Memory Composite vs. Brain Regions (Anatomical) - Average MPS95 – Slopes

Figure 39 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory vs. Functional Brain Regions using Average MPS95 as the strain parameter, no brain regions have a negative slope indicating no possible correlation.

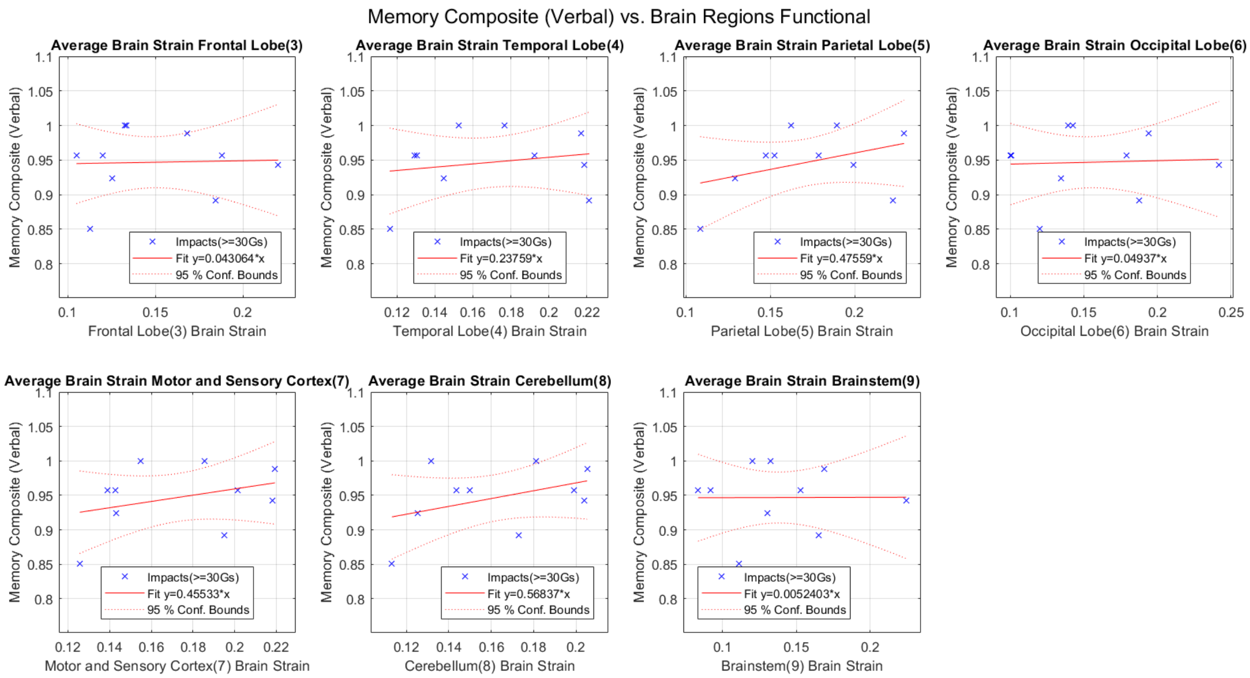


Figure 39: Verbal Memory Composite vs. Brain Regions (Functional) – Average MPS95

		Memory Composite (Verbal)
1	Frontal Lobe(3)	0.0431
2	Temporal Lobe(4)	0.2376
3	Parietal Lobe(5)	0.4756
4	Occipital Lobe(6)	0.0494
5	Motor and Sensory Cortex(7)	0.4553
6	Cerebellum(8)	0.5684
7	Brainstem(9)	0.0052

Table 20: Verbal Memory Composite vs. Brain Regions (Functional) – Average MPS95- Slopes

Figure 40 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter, four brain regions have a negative slope indicating possible correlation: Basal Ganglia, Ventricles, Brainstem, and Cerebellum.

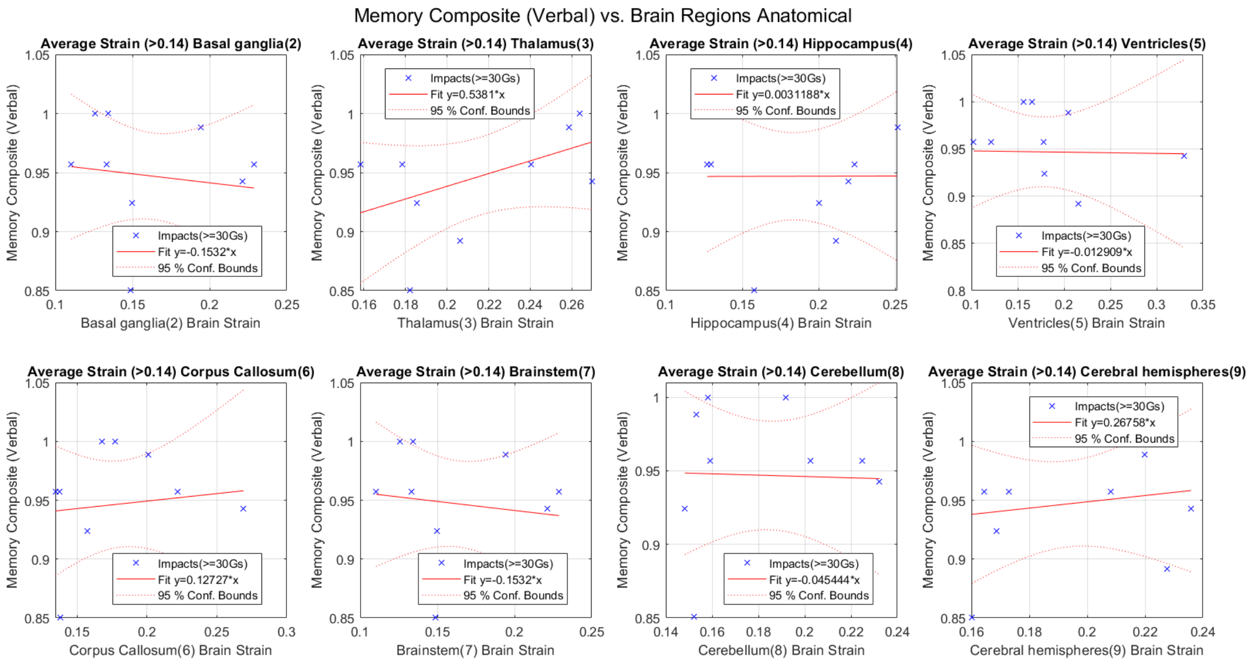


Figure 40: Verbal Memory Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Memory Composite (Verbal)
1	Basal ganglia(2)	-0.1532
2	Thalamus(3)	0.5381
3	Hippocampus(4)	0.0031
4	Ventricles(5)	-0.0129
5	Corpus Callosum(6)	0.1273
6	Brainstem(7)	-0.1532
7	Cerebellum(8)	-0.0454
8	Cerebral hemispheres(9)	0.2676

Table 21:Verbal Memory Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 41 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

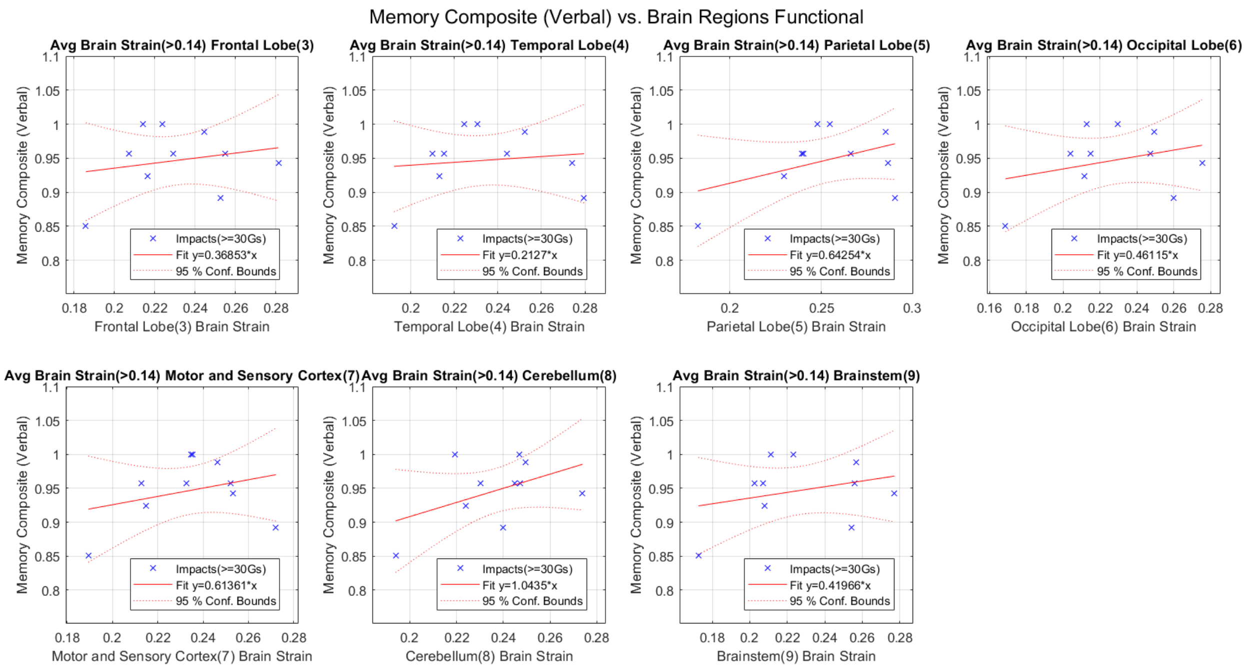


Figure 41: Verbal Memory Composite vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Memory Composite (Verbal)
1	Frontal Lobe(3)	0.3685
2	Temporal Lobe(4)	0.2127
3	Parietal Lobe(5)	0.6425
4	Occipital Lobe(6)	0.4611
5	Motor and Sensory Cortex(7)	0.6136
6	Cerebellum(8)	1.0435
7	Brainstem(9)	0.4197

Table 22: Verbal Memory Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14)- Slopes

Figure 42 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; four brain regions have a negative slope indicating possible correlation: Hippocampus, Ventricles, Brainstem, and Cerebellum.

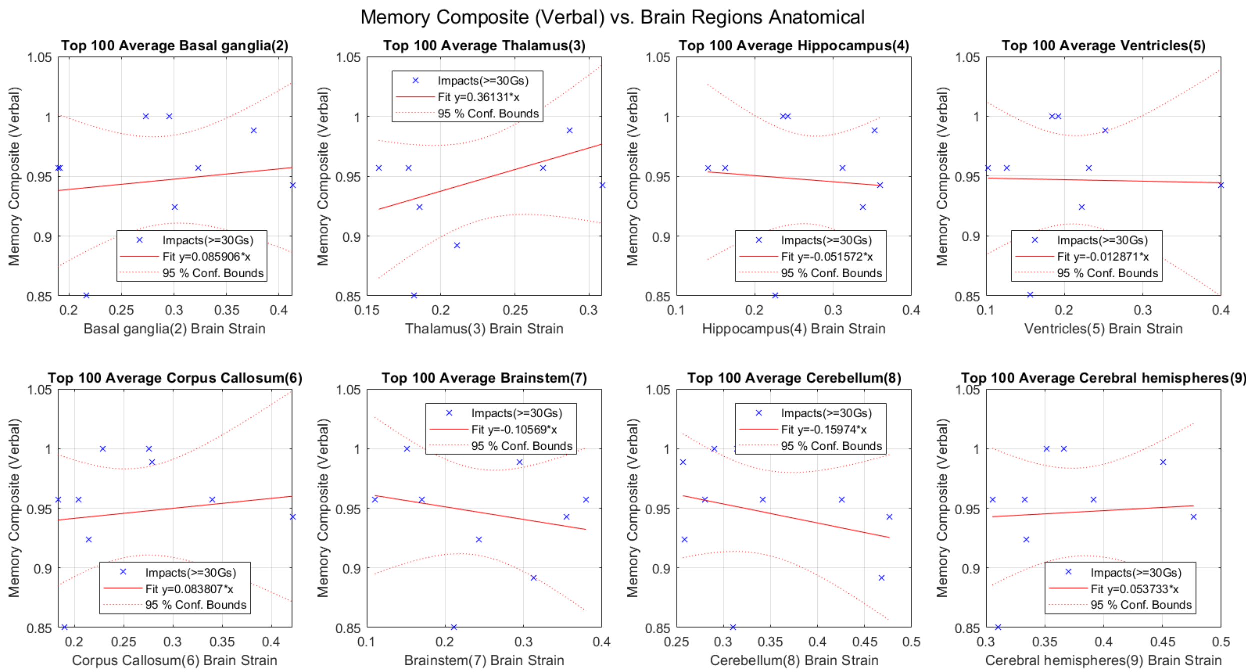


Figure 42: Verbal Memory Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Memory Composite (Verbal)
1	Basal ganglia(2)	0.0859
2	Thalamus(3)	0.3613
3	Hippocampus(4)	-0.0516
4	Ventricles(5)	-0.0129
5	Corpus Callosum(6)	0.0838
6	Brainstem(7)	-0.1057
7	Cerebellum(8)	-0.1597
8	Cerebral hemispheres(9)	0.0537

Table 23: Verbal Memory Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 43 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, no brain regions have a negative slope indicating possible correlation.

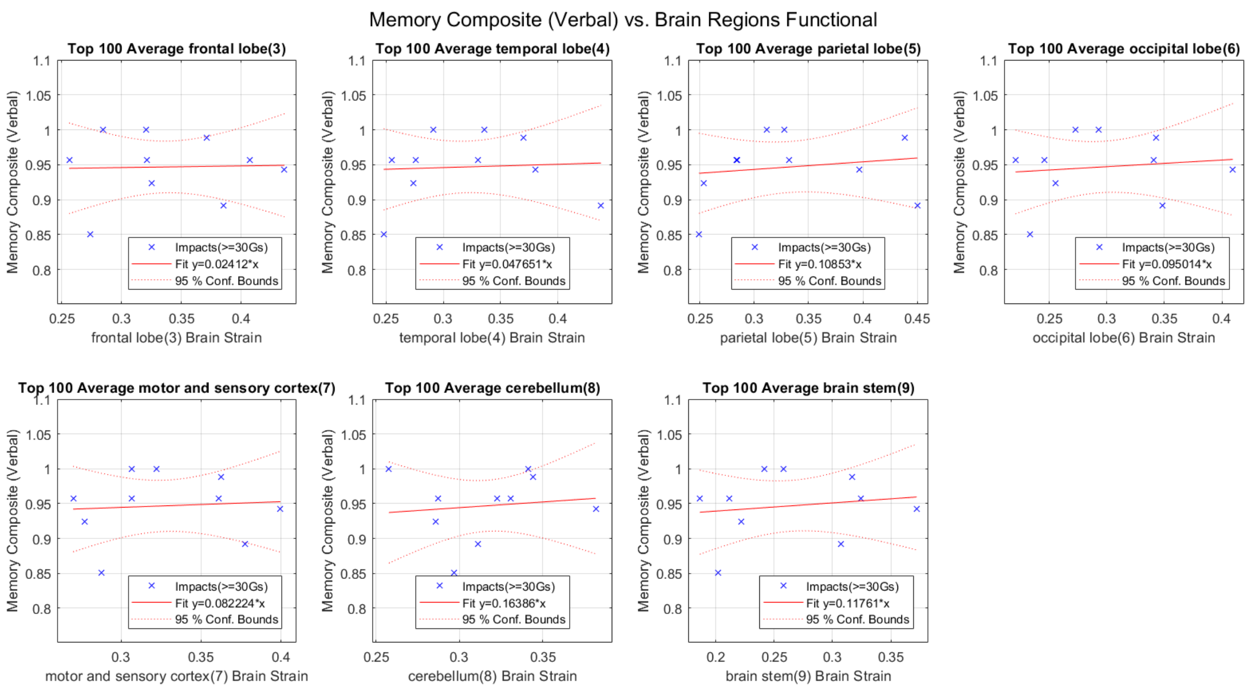


Figure 43: Verbal Memory Composite vs. Brain Regions (Functional) – Top 100 Strain Average

		Memory Composite (Verbal)
1	frontal lobe(3)	0.0241
2	temporal lobe(4)	0.0477
3	parietal lobe(5)	0.1085
4	occipital lobe(6)	0.0950
5	motor and sensory cortex(7)	0.0822
6	cerebellum(8)	0.1639
7	brain stem(9)	0.1176

Table 24: Verbal Memory Composite vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 44 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, three brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, and Brainstem.

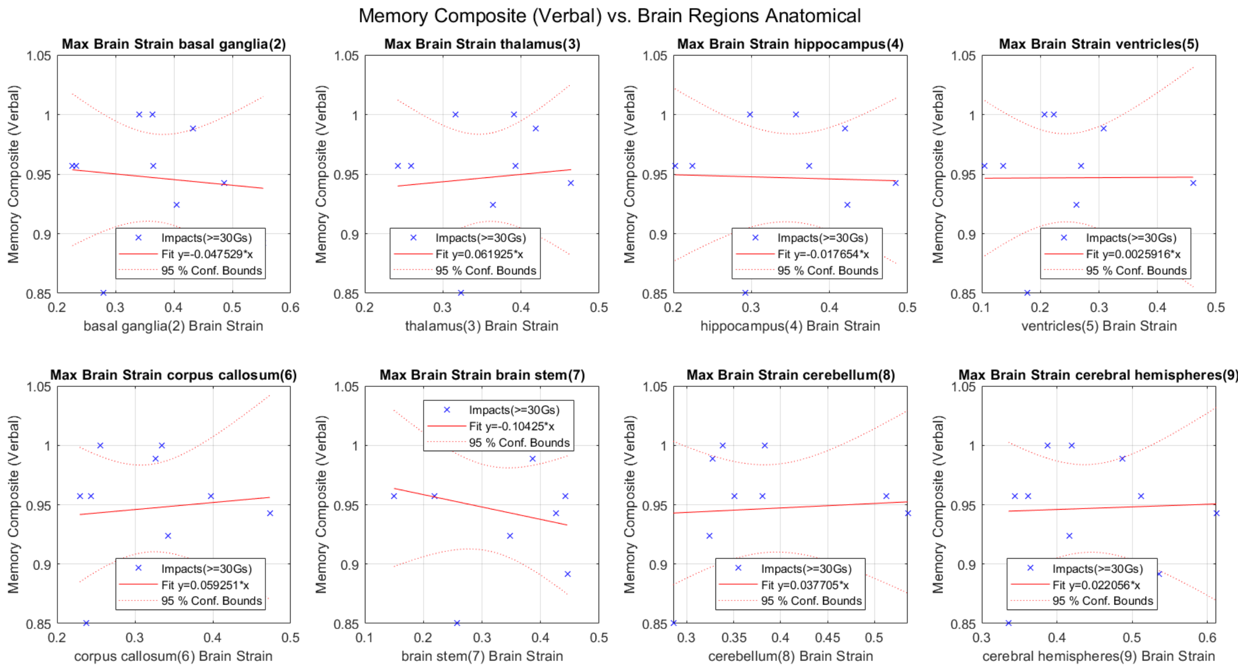


Figure 44: Verbal Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Verbal)
1	basal ganglia(2)	-0.0475
2	thalamus(3)	0.0619
3	hippocampus(4)	-0.0177
4	ventricles(5)	0.0026
5	corpus callosum(6)	0.0593
6	brain stem(7)	-0.1043
7	cerebellum(8)	0.0377
8	cerebral hemispheres(9)	0.0221

Table 25: Verbal Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 45 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Verbal Memory Composite vs. Functional Brain Regions using Max Strain Value as the strain parameter, two brain regions have a negative slope indicating possible correlation: Frontal Lobe and Occipital Lobe.

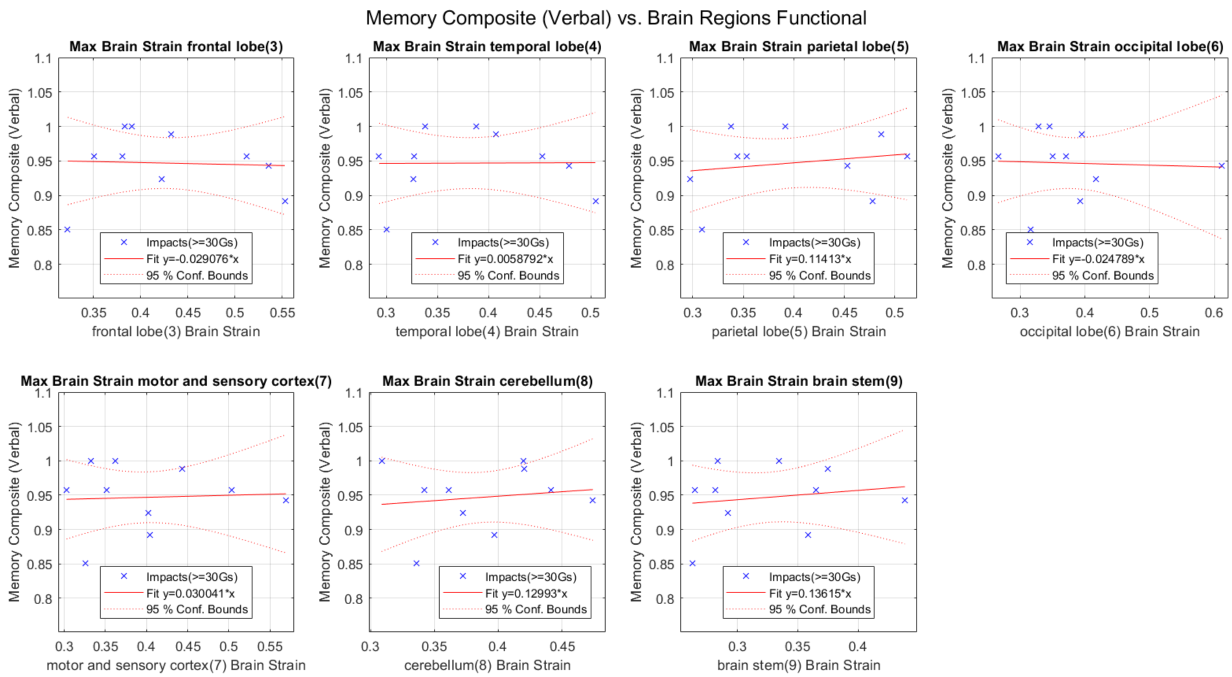


Figure 45: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Verbal)
1	frontal lobe(3)	-0.0291
2	temporal lobe(4)	0.0059
3	parietal lobe(5)	0.1141
4	occipital lobe(6)	-0.0248
5	motor and sensory cortex(7)	0.0300
6	cerebellum(8)	0.1299
7	brain stem(9)	0.1362

Table 26: Verbal Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.3. *Memory Composite (Visual) Percentage*

Figure 46 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, one brain region has a negative slope indicating possible correlation, Ventricles.

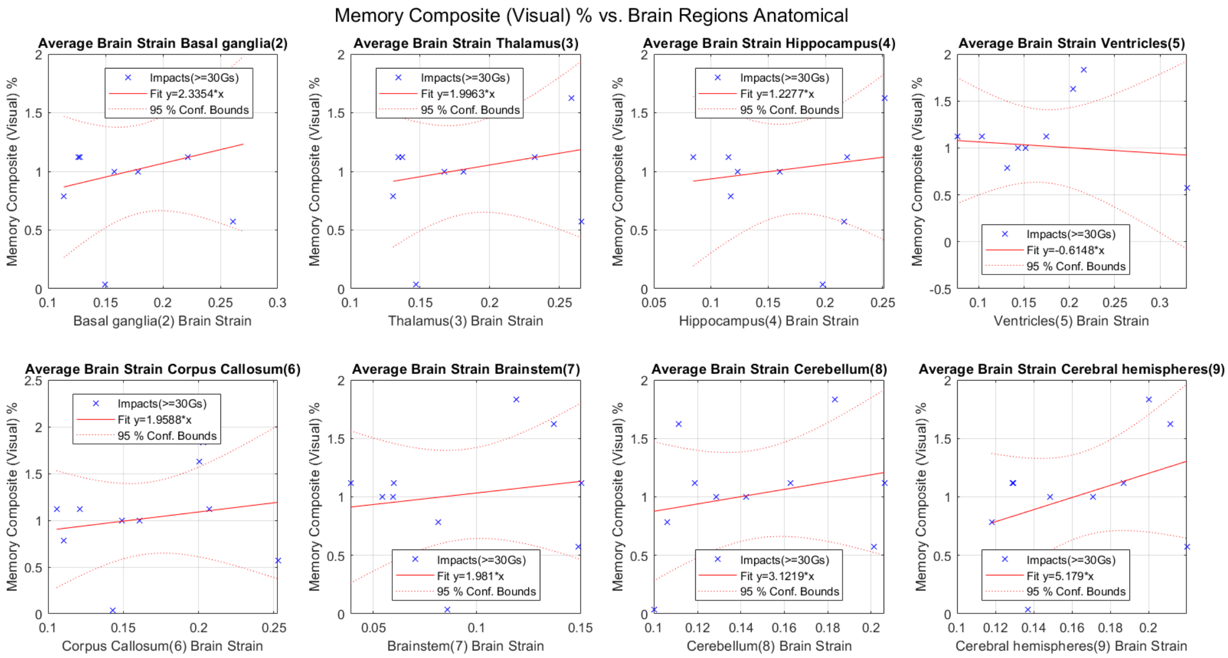


Figure 46: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95

		Memory Composite (Visual) %
1	**Basal ganglia(2)**	2.3354
2	**Thalamus(3)**	1.9963
3	**Hippocampus(4)**	1.2277
4	**Ventricles(5)**	-0.6148
5	**Corpus Callosum(6)**	1.9588
6	**Brainstem(7)**	1.9810
7	**Cerebellum(8)**	3.1219
8	**Cerebral hemispheres(9)**	5.1790

Table 27: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) - Average MPS95 – Slopes

Figure 47 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Percentage vs. Functional Brain Regions using Average MPS95 as the strain parameter, no brain regions have a negative slope indicating no possible correlation.

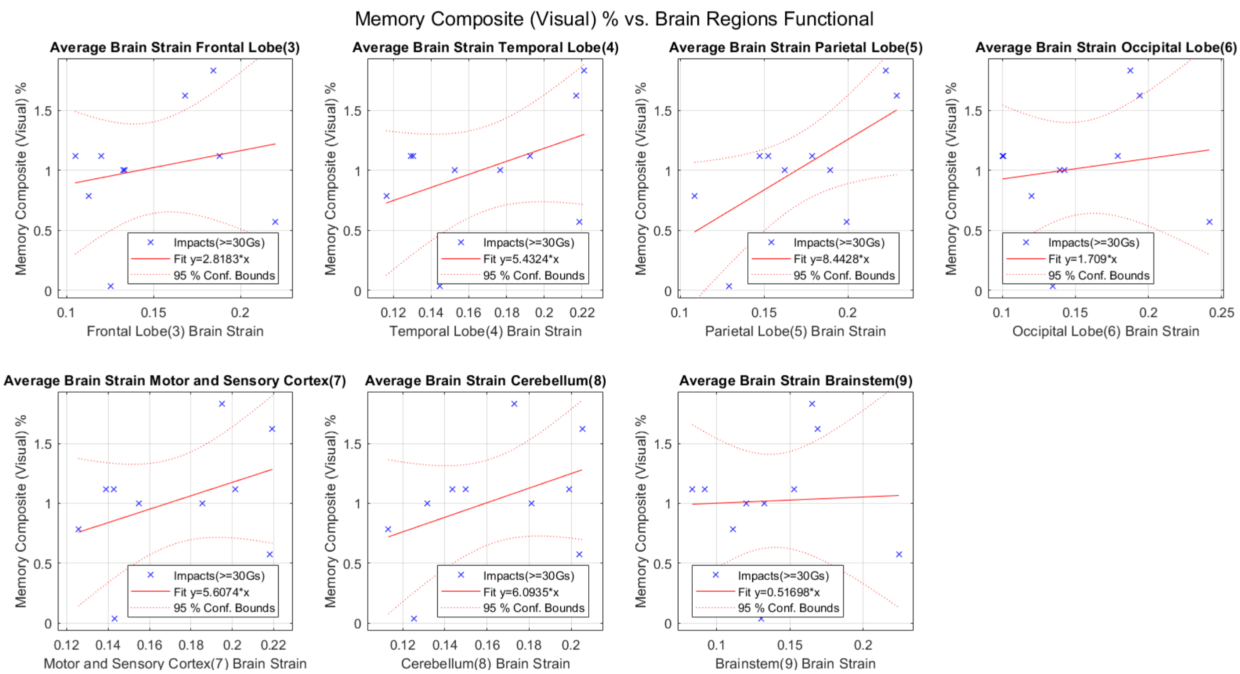


Figure 47: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Average MPS95

		Memory Composite (Visual) %
1	Frontal Lobe(3)	2.8183
2	Temporal Lobe(4)	5.4324
3	Parietal Lobe(5)	8.4428
4	Occipital Lobe(6)	1.7090
5	Motor and Sensory Cortex(7)	5.6074
6	Cerebellum(8)	6.0935
7	Brainstem(9)	0.5170

Table 28: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Average MPS95 – Slopes

Figure 48 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter, one brain regions had a negative slope indicating possible correlation, Ventricles.

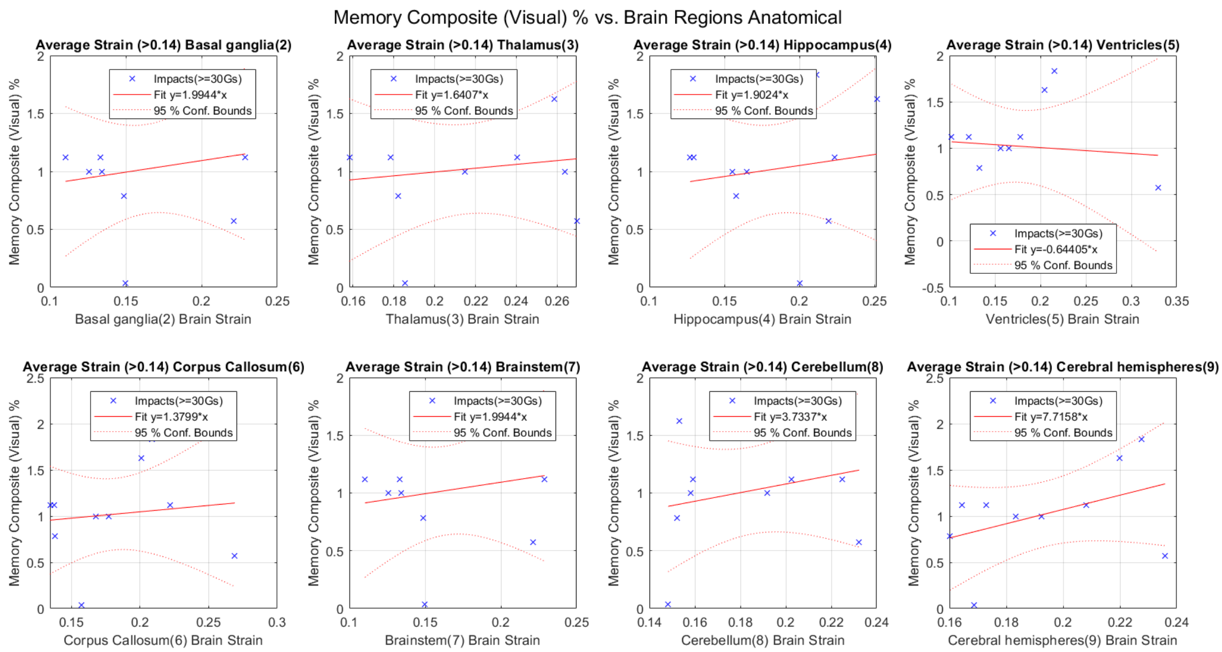


Figure 48: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Memory Composite (Visual) %
1	Basal ganglia(2)	1.9944
2	Thalamus(3)	1.6407
3	Hippocampus(4)	1.9024
4	Ventricles(5)	-0.6440
5	Corpus Callosum(6)	1.3799
6	Brainstem(7)	1.9944
7	Cerebellum(8)	3.7337
8	Cerebral hemispheres(9)	7.7158

Table 29: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 49 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Percentage Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

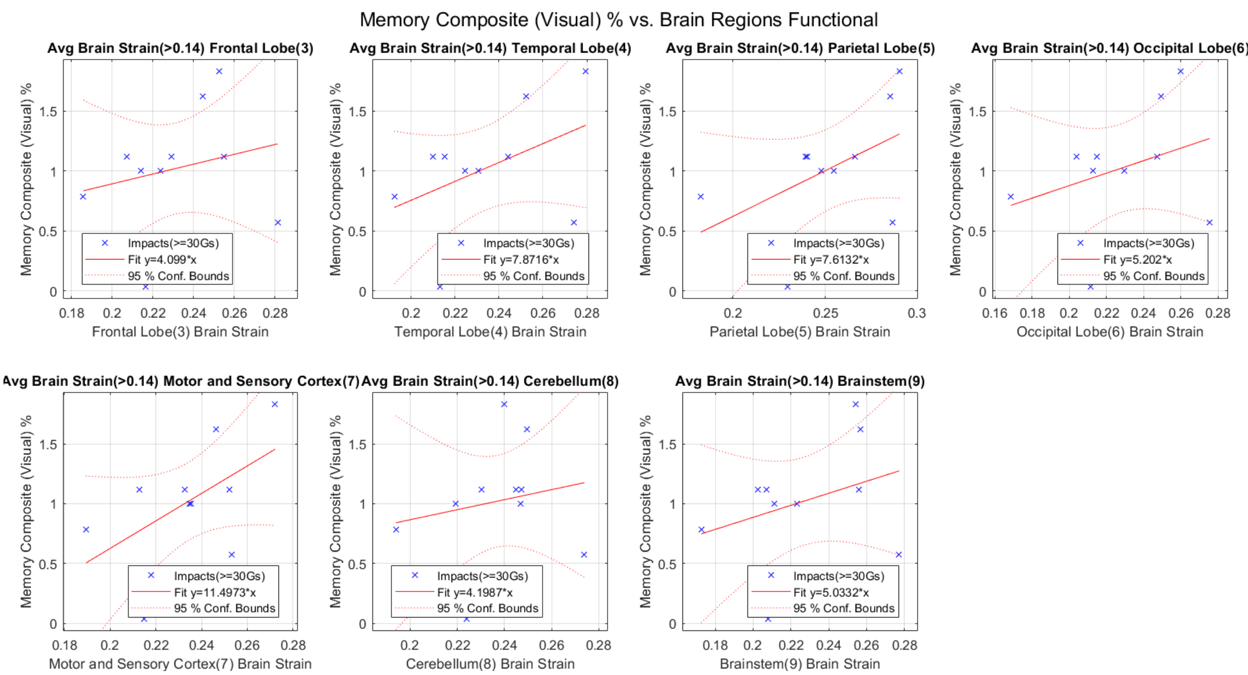


Figure 49: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Memory Composite (Visual) %
1	Frontal Lobe(3)	4.0990
2	Temporal Lobe(4)	7.8716
3	Parietal Lobe(5)	7.6132
4	Occipital Lobe(6)	5.2020
5	Motor and Sensory Cortex(7)	11.4973
6	Cerebellum(8)	4.1987
7	Brainstem(9)	5.0332

Table 30: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 50 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; two brain regions have a negative slope indicating possible correlation: Hippocampus and Ventricles.

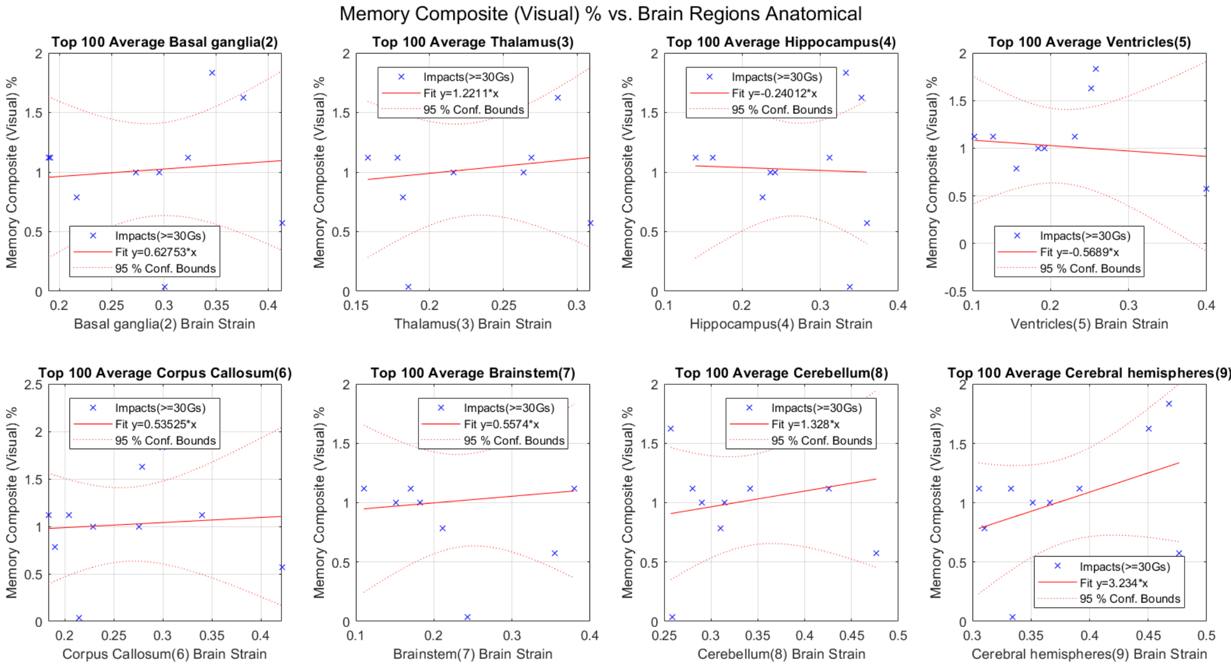


Figure 50: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Memory Composite (Visual) %
1	**Basal ganglia(2)**	0.6275
2	**Thalamus(3)**	1.2211
3	**Hippocampus(4)**	-0.2401
4	**Ventricles(5)**	-0.5689
5	**Corpus Callosum(6)**	0.5353
6	**Brainstem(7)**	0.5574
7	**Cerebellum(8)**	1.3280
8	**Cerebral hemispheres(9)**	3.2340

Table 31: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 51 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, no brain regions have a negative slope indicating possible correlation.

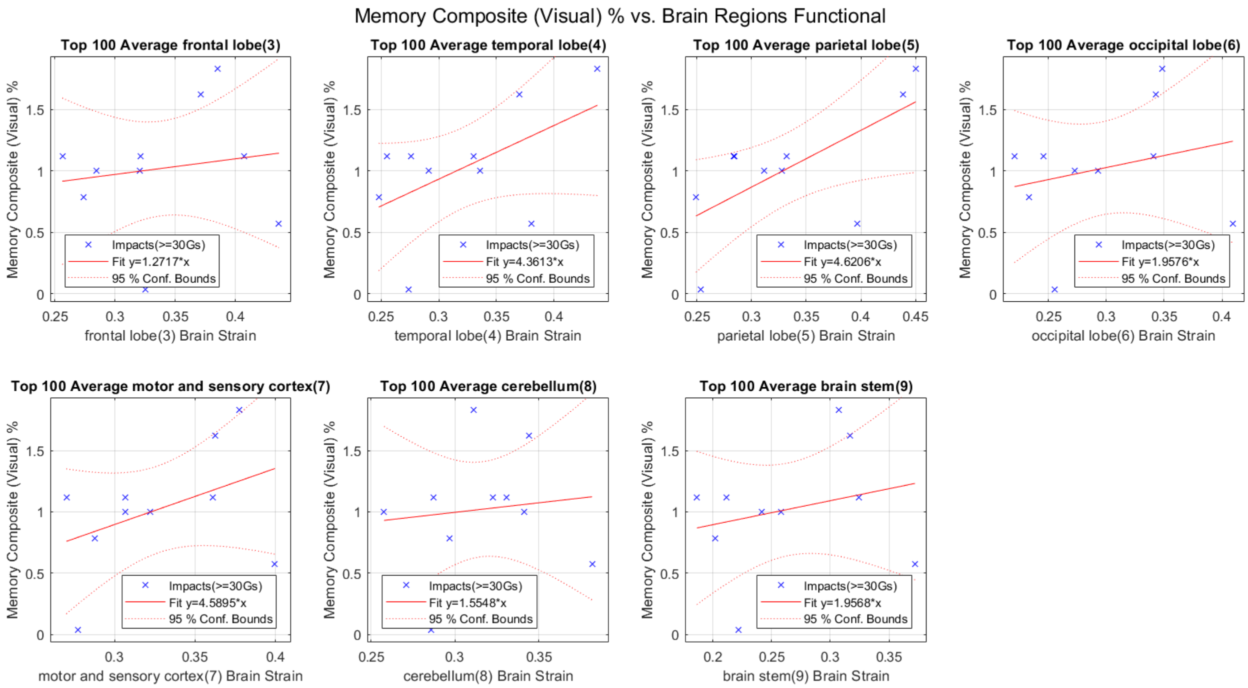


Figure 51: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average

		Memory Composite (Visual) %
1	frontal lobe(3)	1.2717
2	temporal lobe(4)	4.3613
3	parietal lobe(5)	4.6206
4	occipital lobe(6)	1.9576
5	motor and sensory cortex(7)	4.5895
6	cerebellum(8)	1.5548
7	brain stem(9)	1.9568

Table 32: Visual Memory Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 52 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, four brain regions have a negative slope indicating possible correlation: Thalamus, Hippocampus, Cerebellum, and Corpus Collosum.

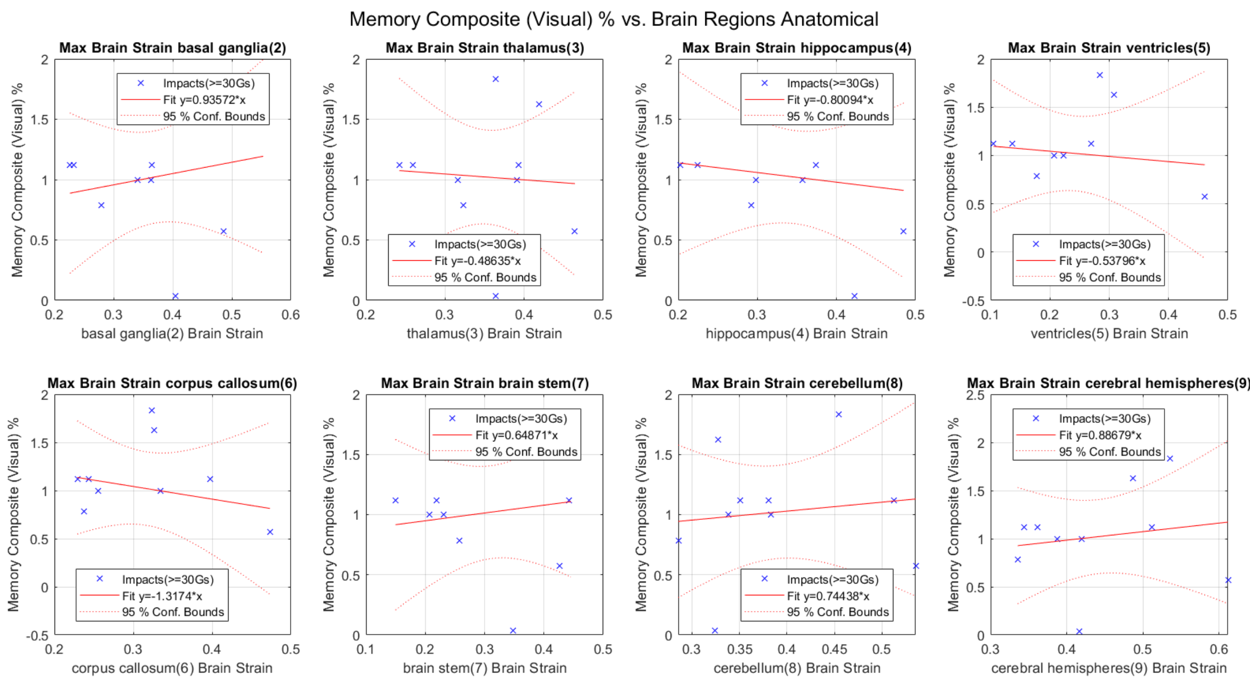


Figure 52: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Visual) %
1	basal ganglia(2)	0.9357
2	thalamus(3)	-0.4863
3	hippocampus(4)	-0.8009
4	ventricles(5)	-0.5380
5	corpus callosum(6)	-1.3174
6	brain stem(7)	0.6487
7	cerebellum(8)	0.7444
8	cerebral hemispheres(9)	0.8868

Table 33: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 53 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Functional Brain Regions using Max Strain Value as the strain parameter, two brain regions have a negative slope indicating possible correlation: Occipital Lobe and Motor and Sensory Cortex.

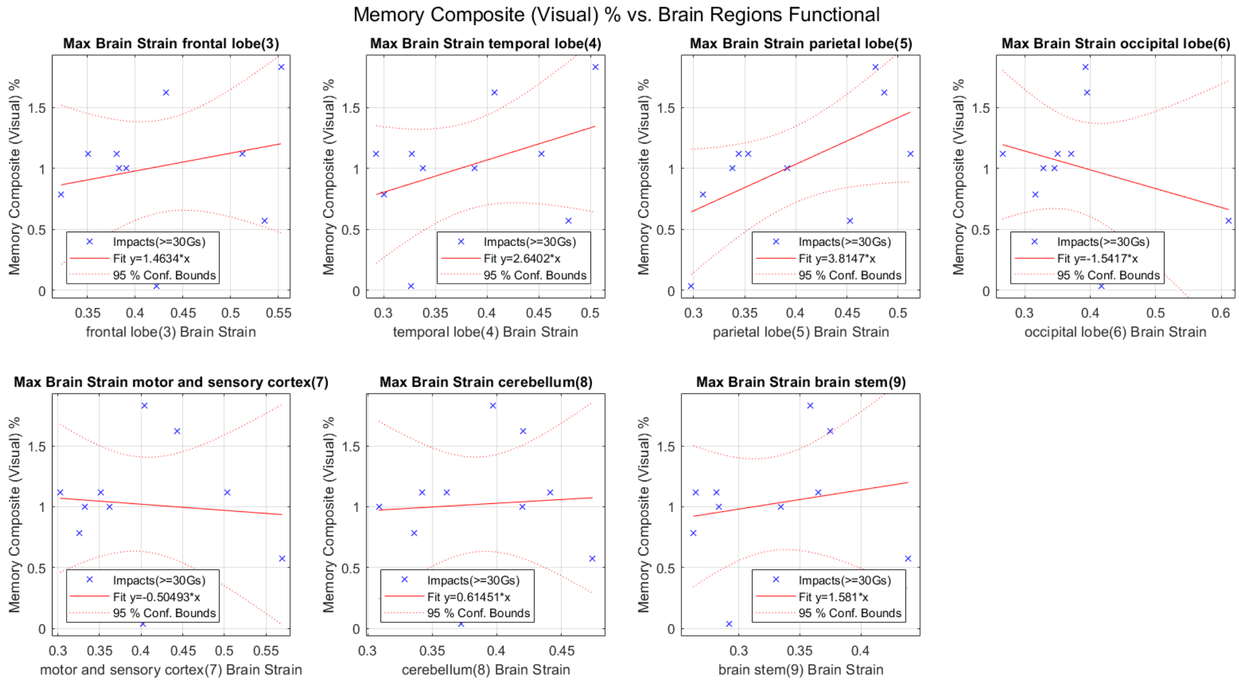


Figure 53: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Visual) %
1	frontal lobe(3)	1.4634
2	temporal lobe(4)	2.6402
3	parietal lobe(5)	3.8147
4	occipital lobe(6)	-1.5417
5	motor and sensory cortex(7)	-0.5049
6	cerebellum(8)	0.6145
7	brain stem(9)	1.5810

Table 34: Visual Memory Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.4. *Memory Composite (Visual)*

Figure 54 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, one brain region has a negative slope indicating possible correlation, Ventricles.

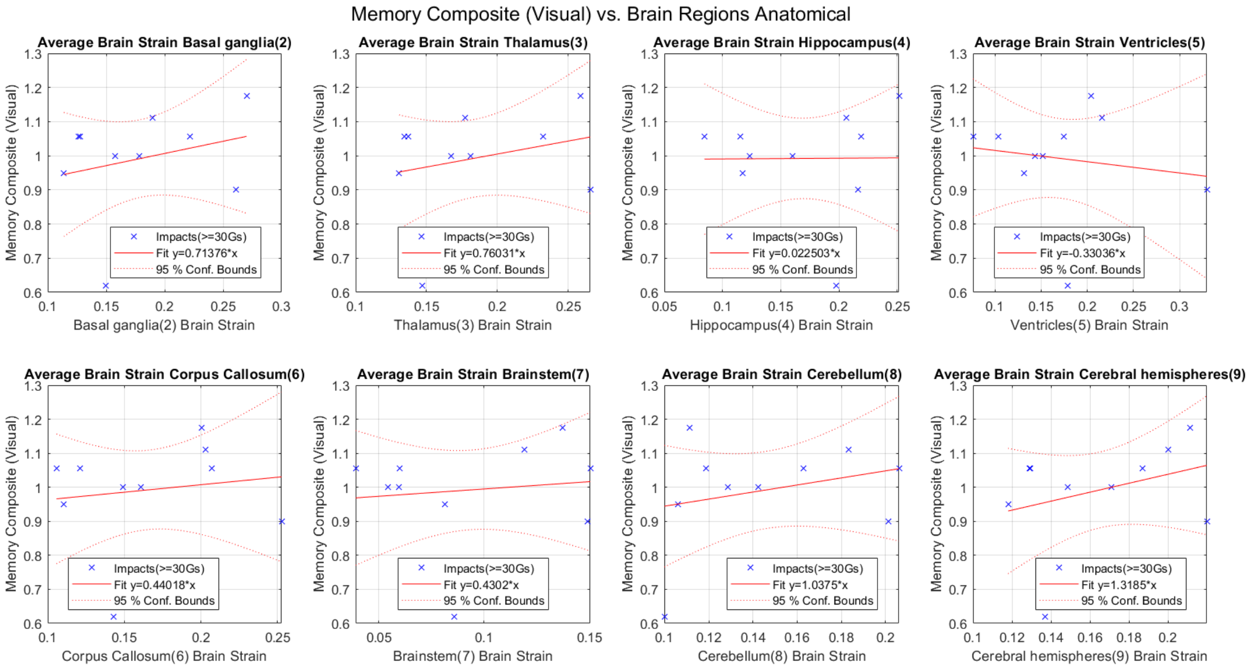


Figure 54: Visual Memory Composite vs. Brain Regions (Anatomical) – Average MPS95

		Memory Composite (Visual)
1	Basal ganglia(2)	0.7138
2	Thalamus(3)	0.7603
3	Hippocampus(4)	0.0225
4	Ventricles(5)	-0.3304
5	Corpus Callosum(6)	0.4402
6	Brainstem(7)	0.4302
7	Cerebellum(8)	1.0375
8	Cerebral hemispheres(9)	1.3185

Table 35: Visual Memory Composite vs. Brain Regions (Anatomical) - Average MPS95 - Slopes

Figure 55 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory vs. Functional Brain Regions using Average MPS95 as the strain parameter, one brain regions have a negative slope, Brainstem.

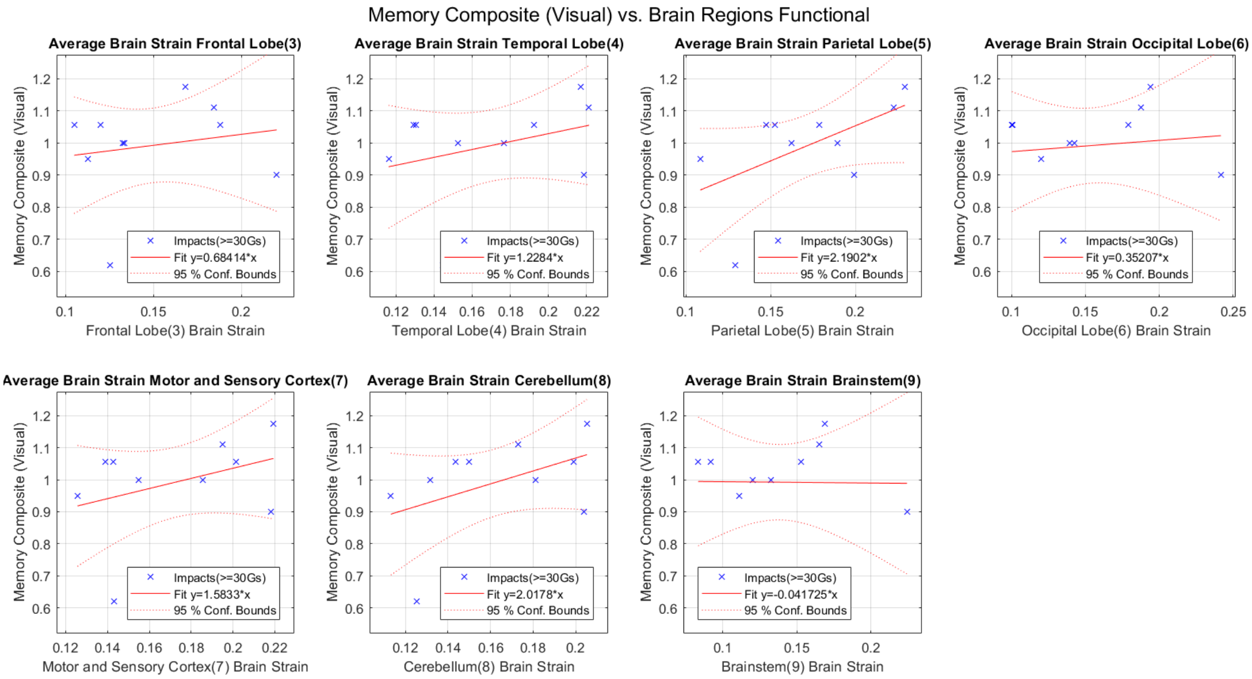


Figure 55: Visual Memory Composite vs. Brain Regions (Functional) – Average MPS95

		Memory Composite (Visual)
1	Frontal Lobe(3)	0.6841
2	Temporal Lobe(4)	1.2284
3	Parietal Lobe(5)	2.1902
4	Occipital Lobe(6)	0.3521
5	Motor and Sensory Cortex(7)	1.5833
6	Cerebellum(8)	2.0178
7	Brainstem(9)	-0.0417

Table 36: Visual Memory Composite vs. Brain Regions (Functional) – Average MPS95- Slopes

Figure 56 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; seven brain regions have a negative slope indicating possible correlation, one brain region has a negative slope indicating possible correlation, Ventricles.

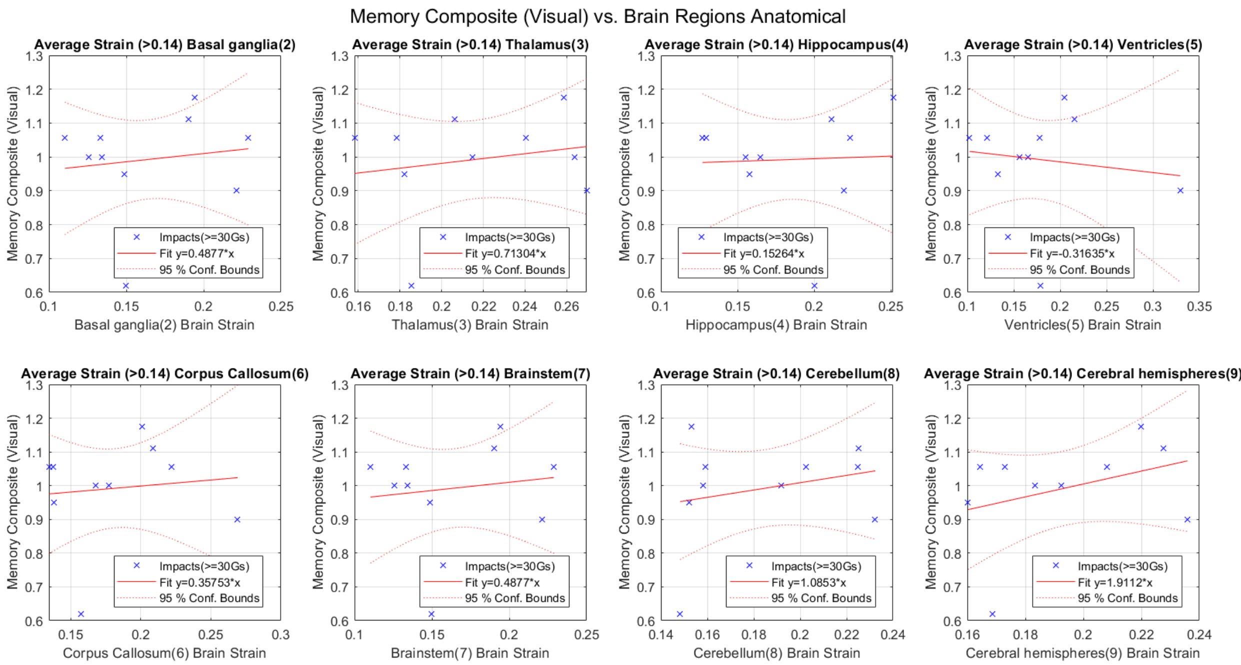


Figure 56: Visual Memory Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Memory Composite (Visual)
1	Basal ganglia(2)	0.4877
2	Thalamus(3)	0.7130
3	Hippocampus(4)	0.1526
4	Ventricles(5)	-0.3163
5	Corpus Callosum(6)	0.3575
6	Brainstem(7)	0.4877
7	Cerebellum(8)	1.0853
8	Cerebral hemispheres(9)	1.9112

Table 37: Visual Memory Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 57 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

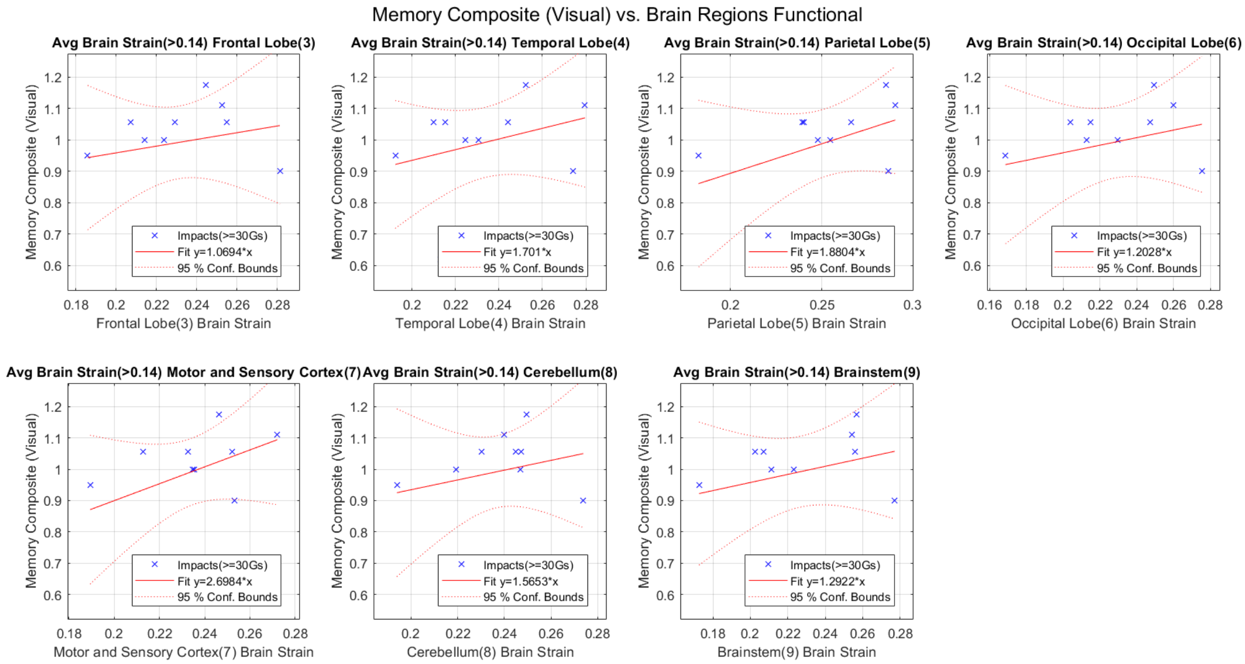


Figure 57: Visual Memory Composite vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Memory Composite (Visual)
1	Frontal Lobe(3)	1.0694
2	Temporal Lobe(4)	1.7010
3	Parietal Lobe(5)	1.8804
4	Occipital Lobe(6)	1.2028
5	Motor and Sensory Cortex(7)	2.6984
6	Cerebellum(8)	1.5653
7	Brainstem(9)	1.2922

Table 38: Visual Memory Composite vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 58 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; three brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, and Ventricles.

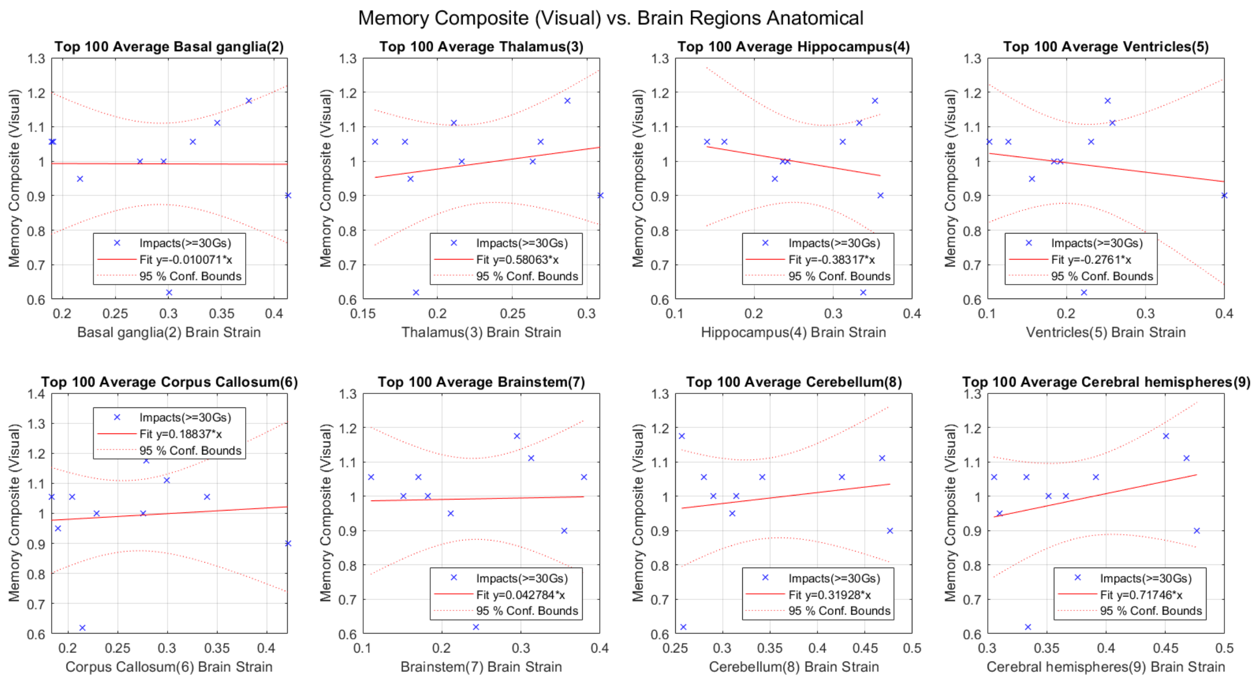


Figure 58: Visual Memory Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Memory Composite (Visual)
1	Basal ganglia(2)	-0.0101
2	Thalamus(3)	0.5806
3	Hippocampus(4)	-0.3832
4	Ventricles(5)	-0.2761
5	Corpus Callosum(6)	0.1884
6	Brainstem(7)	0.0428
7	Cerebellum(8)	0.3193
8	Cerebral hemispheres(9)	0.7175

Table 39: Visual Memory Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 59 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, no brain regions have a negative slope indicating possible correlation.

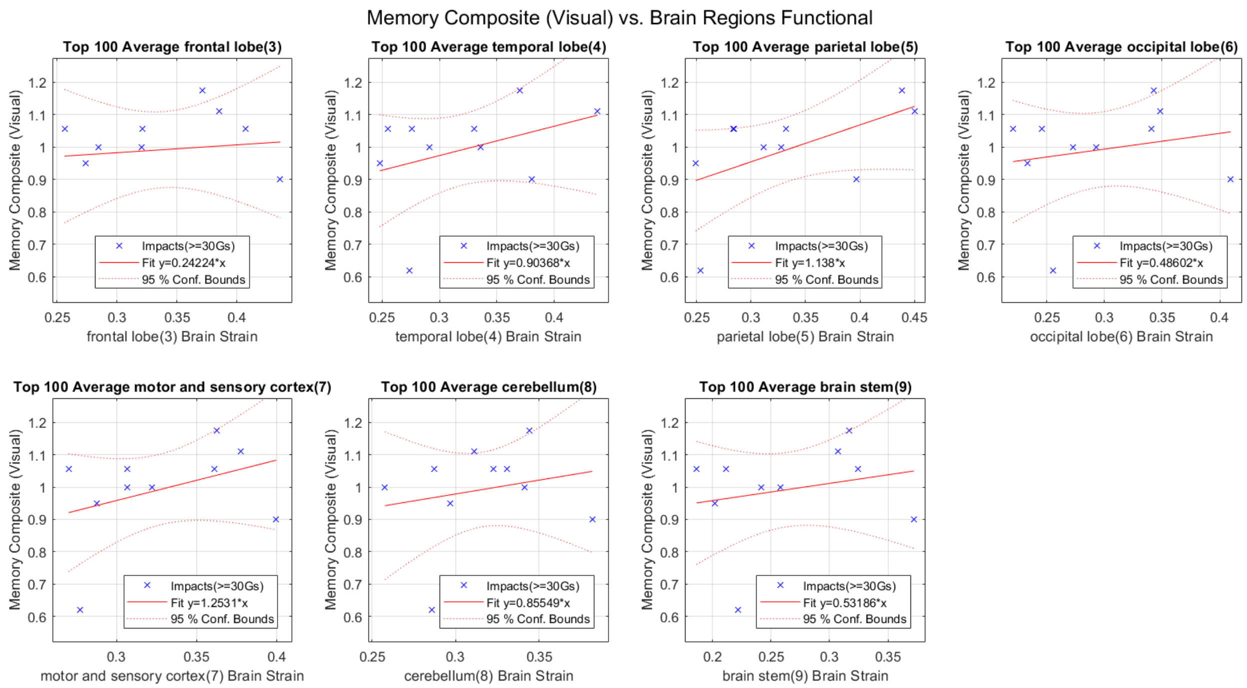


Figure 59: Visual Memory Composite vs. Brain Regions (Functional) – Top 100 Strain Average

		Memory Composite (Visual)
1	frontal lobe(3)	0.2422
2	temporal lobe(4)	0.9037
3	parietal lobe(5)	1.1380
4	occipital lobe(6)	0.4860
5	motor and sensory cortex(7)	1.2531
6	cerebellum(8)	0.8555
7	brain stem(9)	0.5319

Table 40: Visual Memory Composite vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 60 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, six brain regions have a negative slope indicating possible correlation: Basal Ganglia, Thalamus, Hippocampus, Ventricles, Corpus Collosum, and Brainstem.

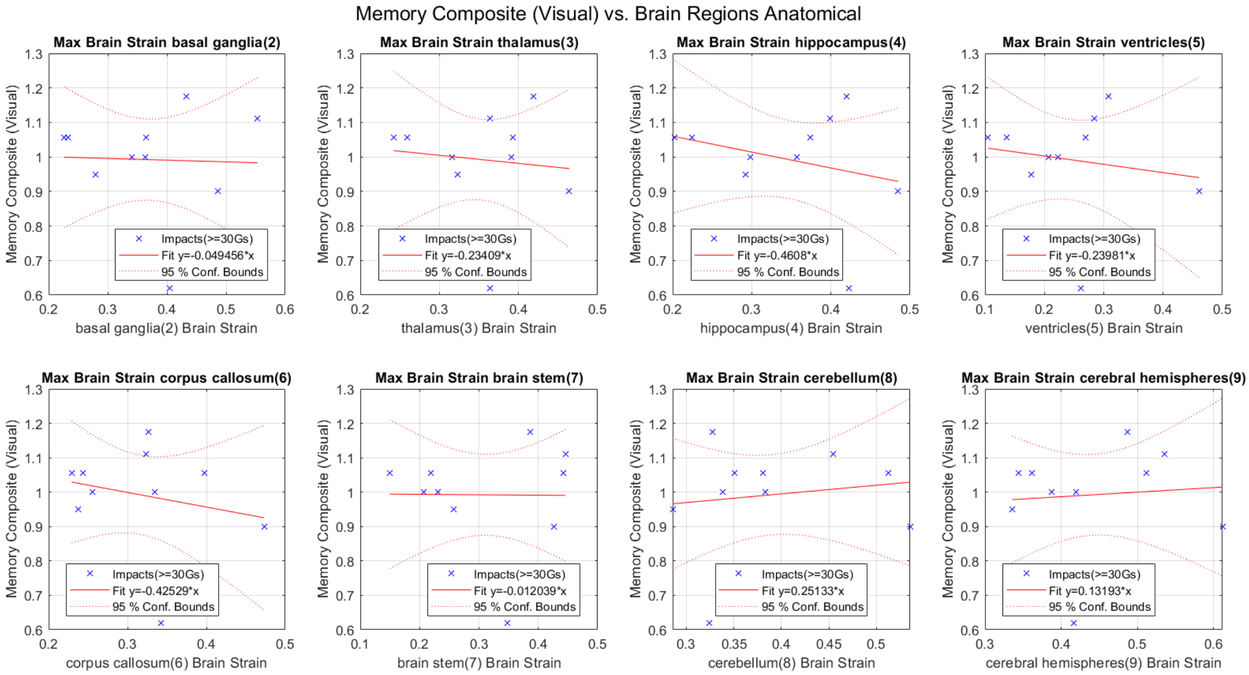


Figure 60: Visual Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Visual)
1	basal ganglia(2)	-0.0495
2	thalamus(3)	-0.2341
3	hippocampus(4)	-0.4608
4	ventricles(5)	-0.2398
5	corpus callosum(6)	-0.4253
6	brain stem(7)	-0.0120
7	cerebellum(8)	0.2513
8	cerebral hemispheres(9)	0.1319

Table 41: Visual Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 61 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Functional Brain Regions using Max Strain Value as the strain parameter, two brain regions have a negative slope indicating possible correlation: Occipital Lobe and Motor and Sensory Cortex.

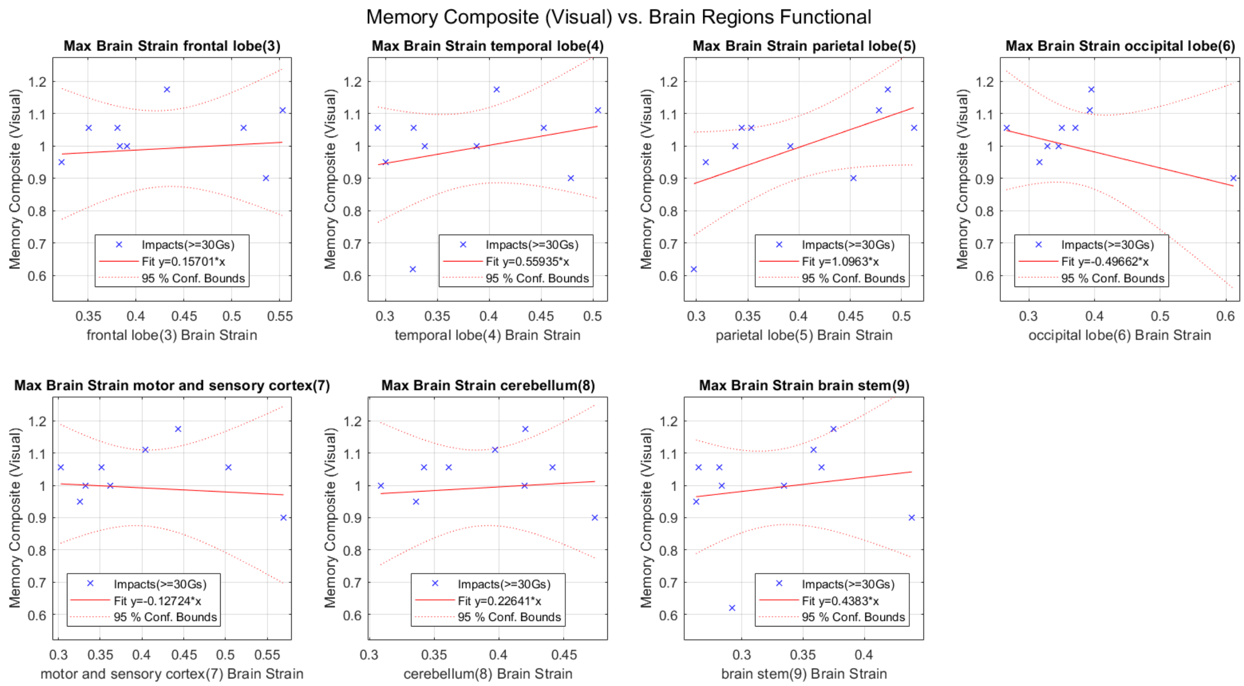


Figure 61: Visual Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Memory Composite (Visual)
1	frontal lobe(3)	0.1570
2	temporal lobe(4)	0.5594
3	parietal lobe(5)	1.0963
4	occipital lobe(6)	-0.4966
5	motor and sensory cortex(7)	-0.1272
6	cerebellum(8)	0.2264
7	brain stem(9)	0.4383

Table 42: Visual Memory Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.5. *Visual Motor Speed Percentage*

Figure 62 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Percentage vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, one brain region has a negative slope indicating possible correlation, Cerebellum.

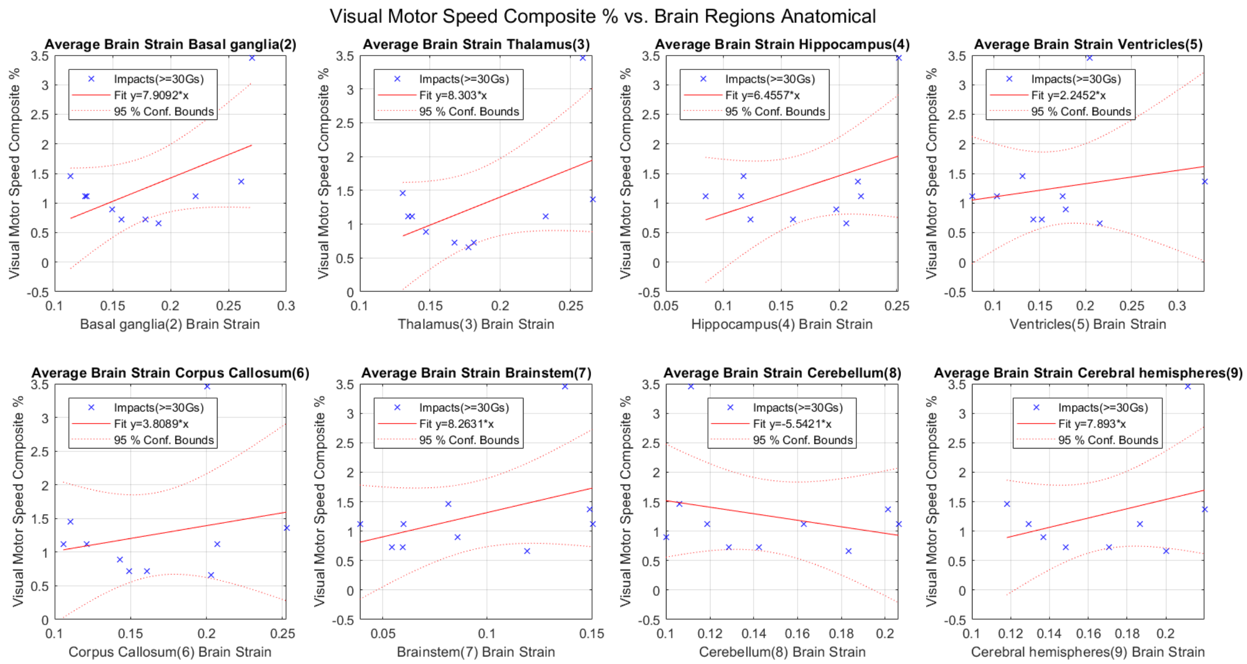


Figure 62: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95

		Visual Motor Speed Composite %
1	Basal ganglia(2)	7.9092
2	Thalamus(3)	8.3030
3	Hippocampus(4)	6.4557
4	Ventricles(5)	2.2452
5	Corpus Callosum(6)	3.8089
6	Brainstem(7)	8.2631
7	Cerebellum(8)	-5.5421
8	Cerebral hemispheres(9)	7.8930

Table 43: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95 - Slopes

Figure 63 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Percentage vs. Functional Brain Regions using Average MPS95 as the strain parameter, no brain regions have a negative slope indicating no possible correlation.

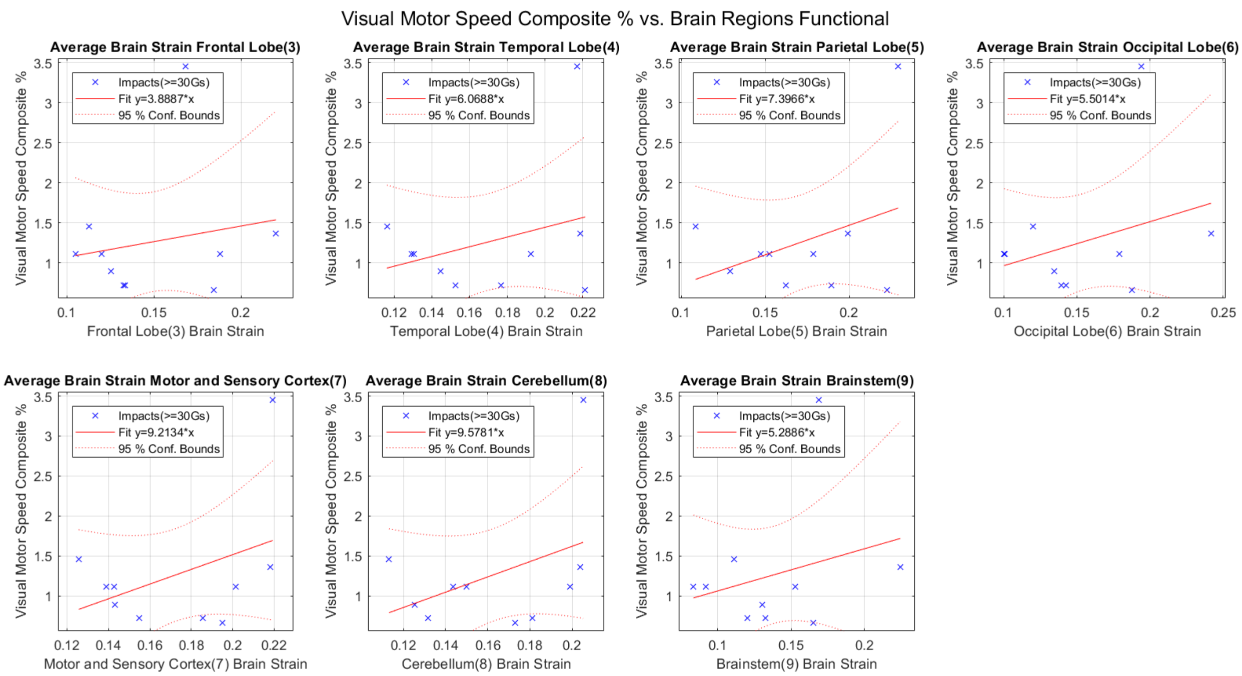


Figure 63: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Average MPS95

		Visual Motor Speed Composite %
1	Frontal Lobe(3)	3.8887
2	Temporal Lobe(4)	6.0688
3	Parietal Lobe(5)	7.3966
4	Occipital Lobe(6)	5.5014
5	Motor and Sensory Cortex(7)	9.2134
6	Cerebellum(8)	9.5781
7	Brainstem(9)	5.2886

Table 44: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Average MPS95-

Figure 64 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; seven brain regions have a negative slope indicating possible correlation, one brain region has a negative slope indicating possible correlation, Cerebellum.

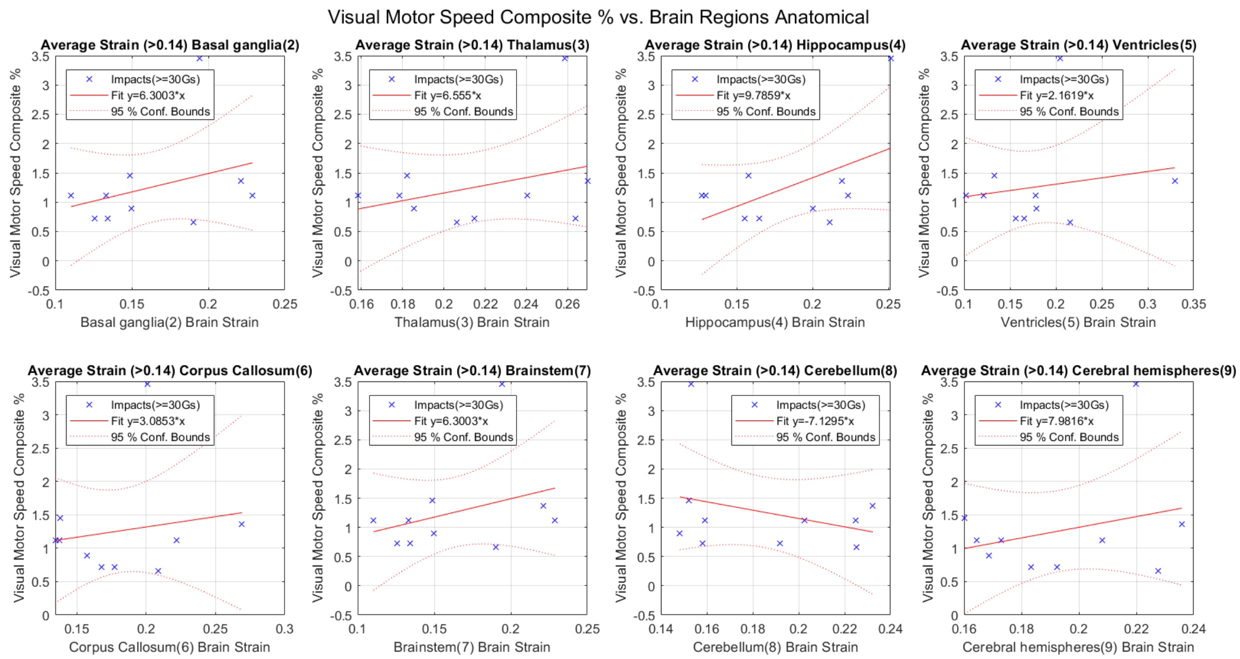


Figure 64: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Visual Motor Speed Composite %
1	Basal ganglia(2)	6.3003
2	Thalamus(3)	6.5550
3	Hippocampus(4)	9.7859
4	Ventricles(5)	2.1619
5	Corpus Callosum(6)	3.0853
6	Brainstem(7)	6.3003
7	Cerebellum(8)	-7.1295
8	Cerebral hemispheres(9)	7.9816

Table 45: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 65 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

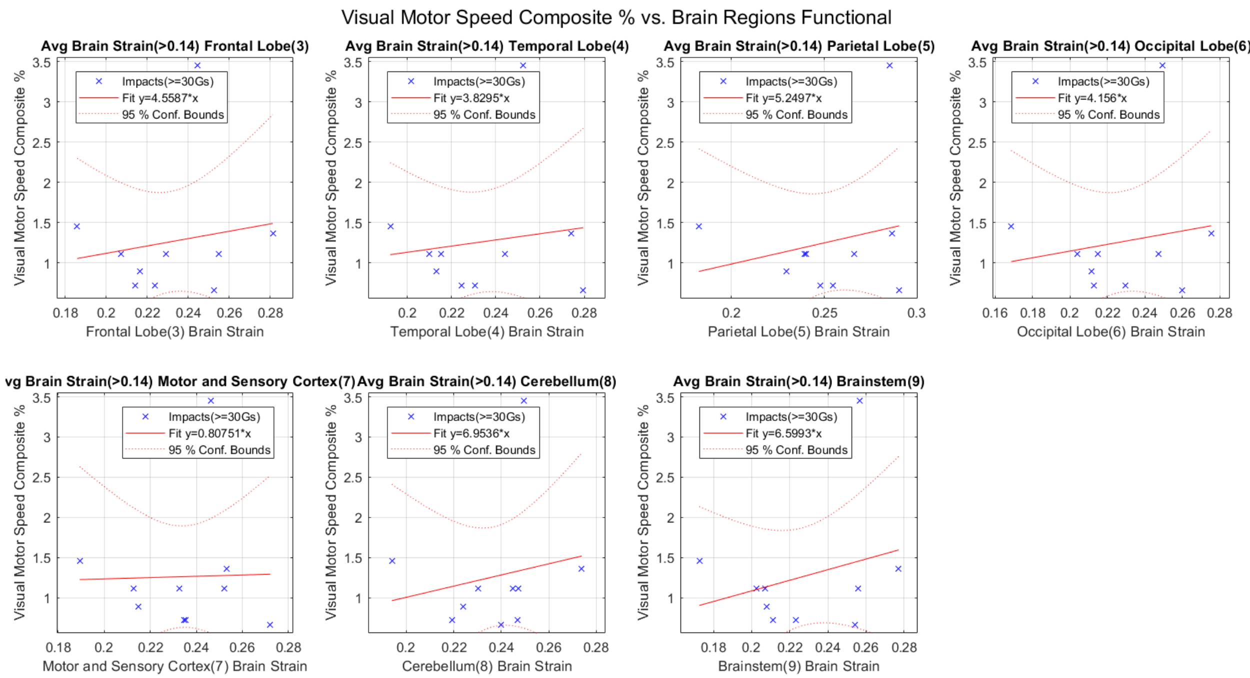


Figure 65: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Visual Motor Speed Composite %
1	Frontal Lobe(3)	4.5587
2	Temporal Lobe(4)	3.8295
3	Parietal Lobe(5)	5.2497
4	Occipital Lobe(6)	4.1560
5	Motor and Sensory Cortex(7)	0.8075
6	Cerebellum(8)	6.9536
7	Brainstem(9)	6.5993

Table 46: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 66 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; one brain region has a negative slope indicating possible correlation: Cerebellum.

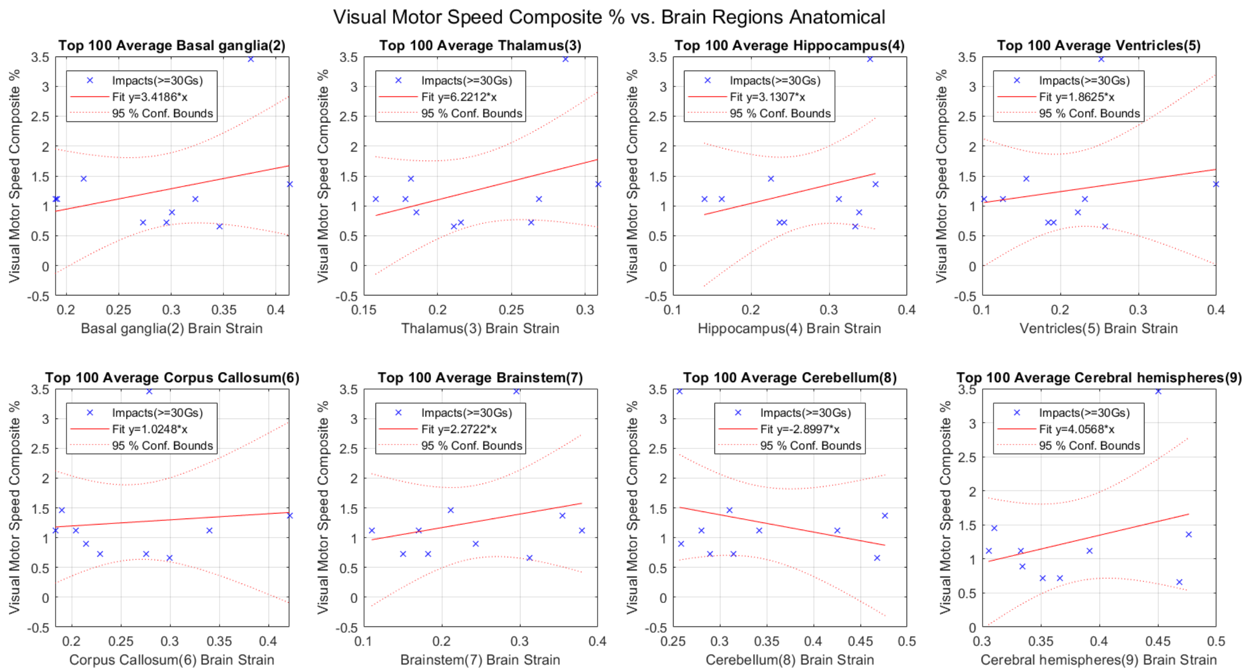


Figure 66: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Visual Motor Speed Composite %
1	Basal ganglia(2)	3.4186
2	Thalamus(3)	6.2212
3	Hippocampus(4)	3.1307
4	Ventricles(5)	1.8625
5	Corpus Callosum(6)	1.0248
6	Brainstem(7)	2.2722
7	Cerebellum(8)	-2.8997
8	Cerebral hemispheres(9)	4.0568

Table 47: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 67 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, no brain regions have a negative slope indicating possible correlation.

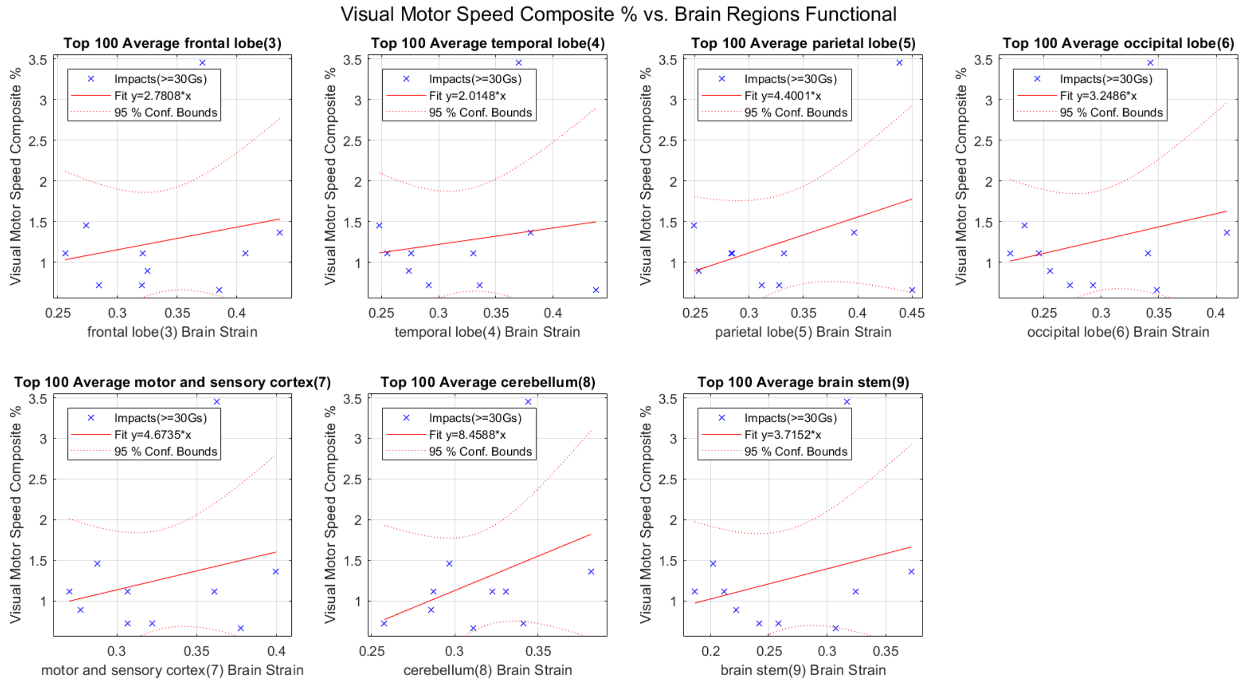


Figure 67: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average

		Visual Motor Speed Composite %
1	frontal lobe(3)	2.7808
2	temporal lobe(4)	2.0148
3	parietal lobe(5)	4.4001
4	occipital lobe(6)	3.2486
5	motor and sensory cortex(7)	4.6735
6	cerebellum(8)	8.4588
7	brain stem(9)	3.7152

Table 48: Visual Motor Speed Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 68 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, one brain region has a negative slope indicating possible correlation, Cerebellum.

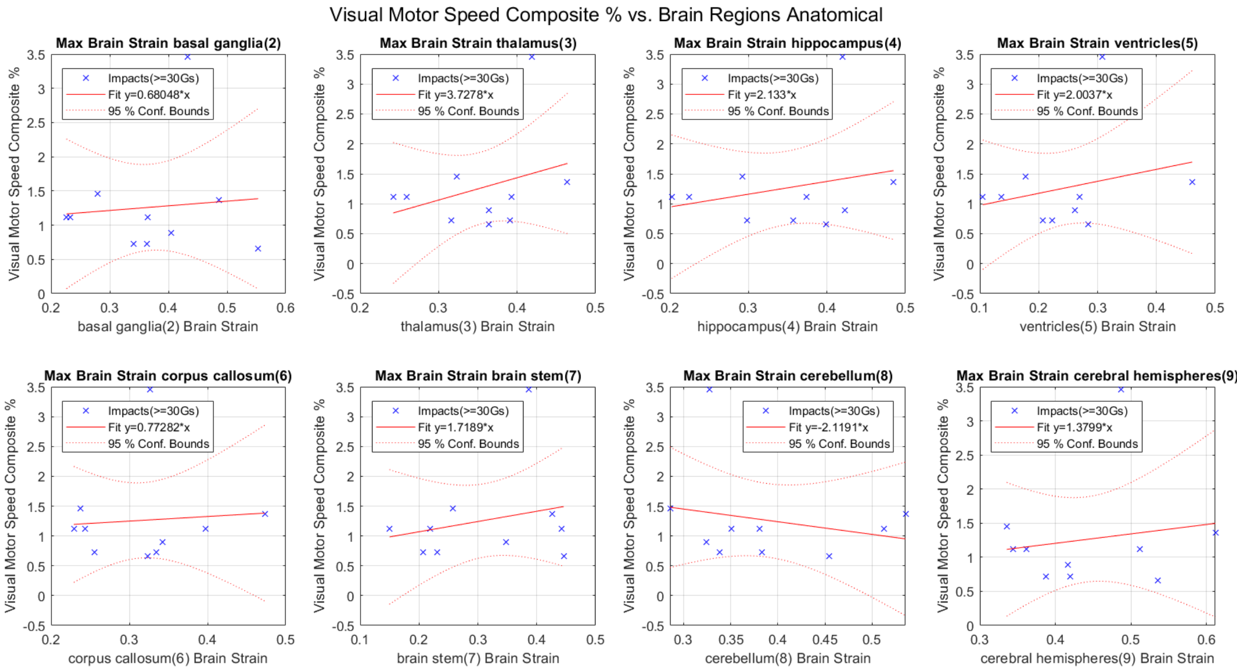


Figure 68: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Visual Motor Speed Composite %
1	basal ganglia(2)	0.6805
2	thalamus(3)	3.7278
3	hippocampus(4)	2.1330
4	ventricles(5)	2.0037
5	corpus callosum(6)	0.7728
6	brain stem(7)	1.7189
7	cerebellum(8)	-2.1191
8	cerebral hemispheres(9)	1.3799

Table 49: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 69 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite Percentage vs. Functional Brain Regions using Max Strain Value as the strain parameter, one brain region has a negative slope indicating possible correlation, Frontal Lobe.

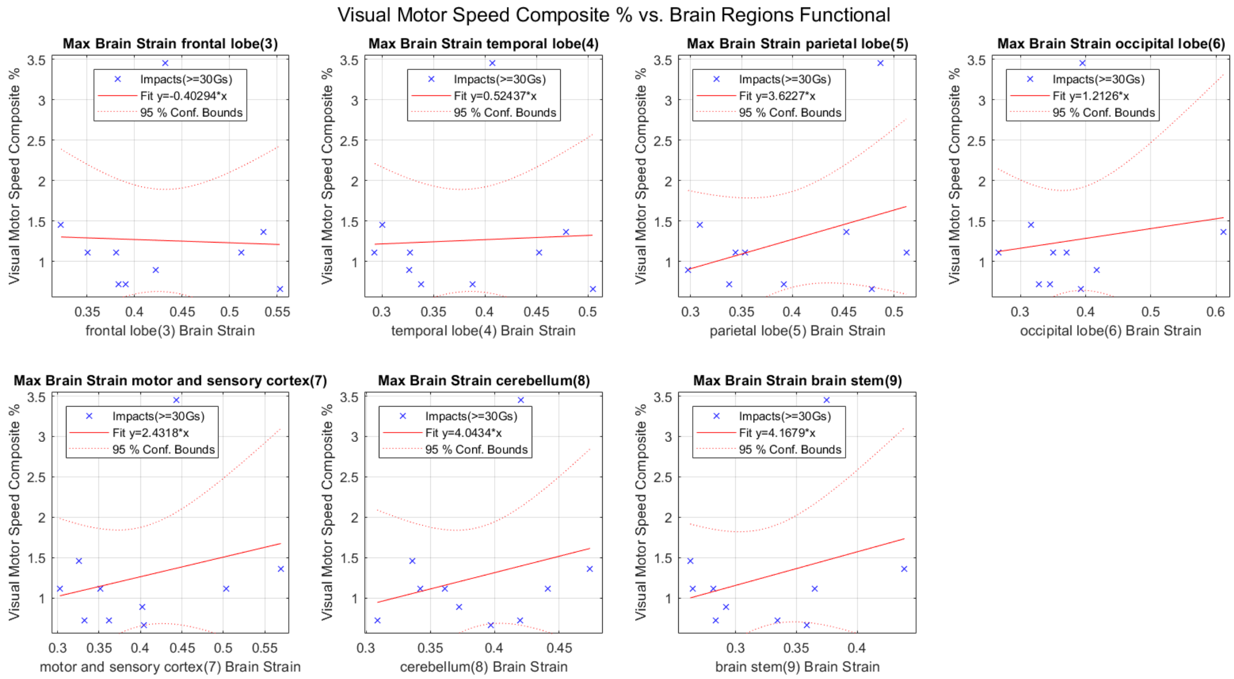


Figure 69: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Visual Motor Speed Composite %
1	frontal lobe(3)	-0.4029
2	temporal lobe(4)	0.5244
3	parietal lobe(5)	3.6227
4	occipital lobe(6)	1.2126
5	motor and sensory cortex(7)	2.4318
6	cerebellum(8)	4.0434
7	brain stem(9)	4.1679

Table 50: Visual Motor Speed Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.6. *Visual Motor Speed*

Figure 70 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, one brain region has a negative slope indicating possible correlation, Cerebellum.

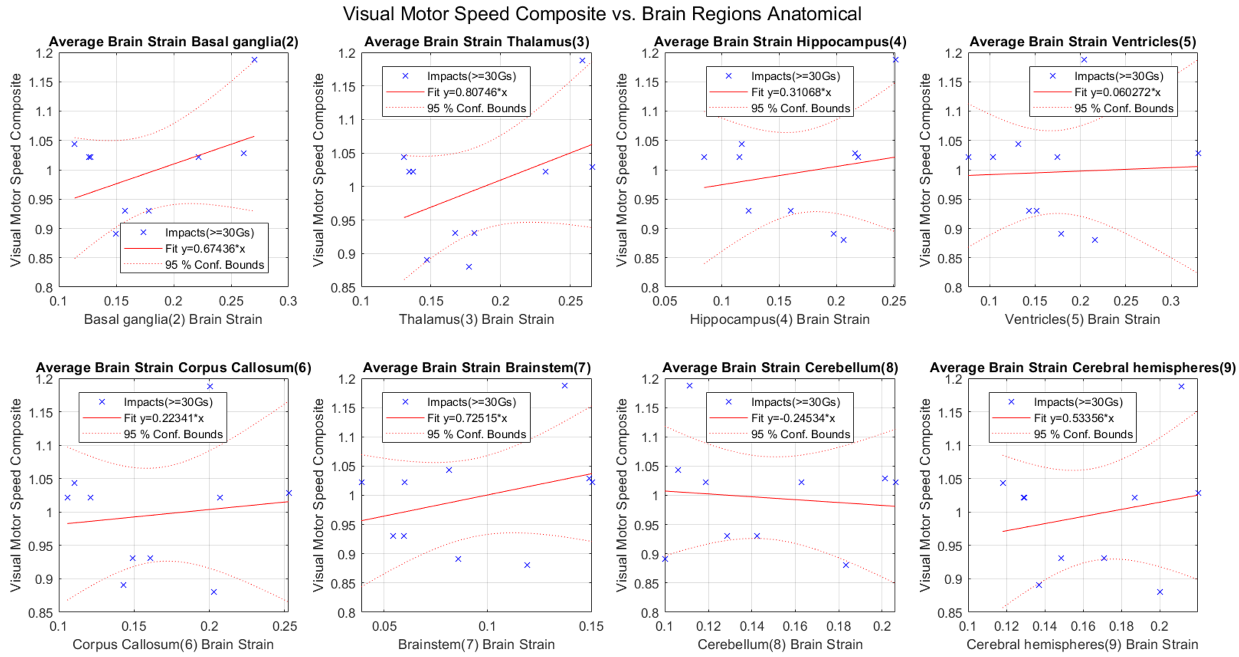


Figure 70: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Average MPS95

		Visual Motor Speed Composite
1	Basal ganglia(2)	0.6744
2	Thalamus(3)	0.8075
3	Hippocampus(4)	0.3107
4	Ventricles(5)	0.0603
5	Corpus Callosum(6)	0.2234
6	Brainstem(7)	0.7252
7	Cerebellum(8)	-0.2453
8	Cerebral hemispheres(9)	0.5336

Table 51: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Average MPS95 – Slopes

Figure 71 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed vs. Functional Brain Regions using Average MPS95 as the strain parameter, no brain regions have a negative slope indicating no possible correlation.

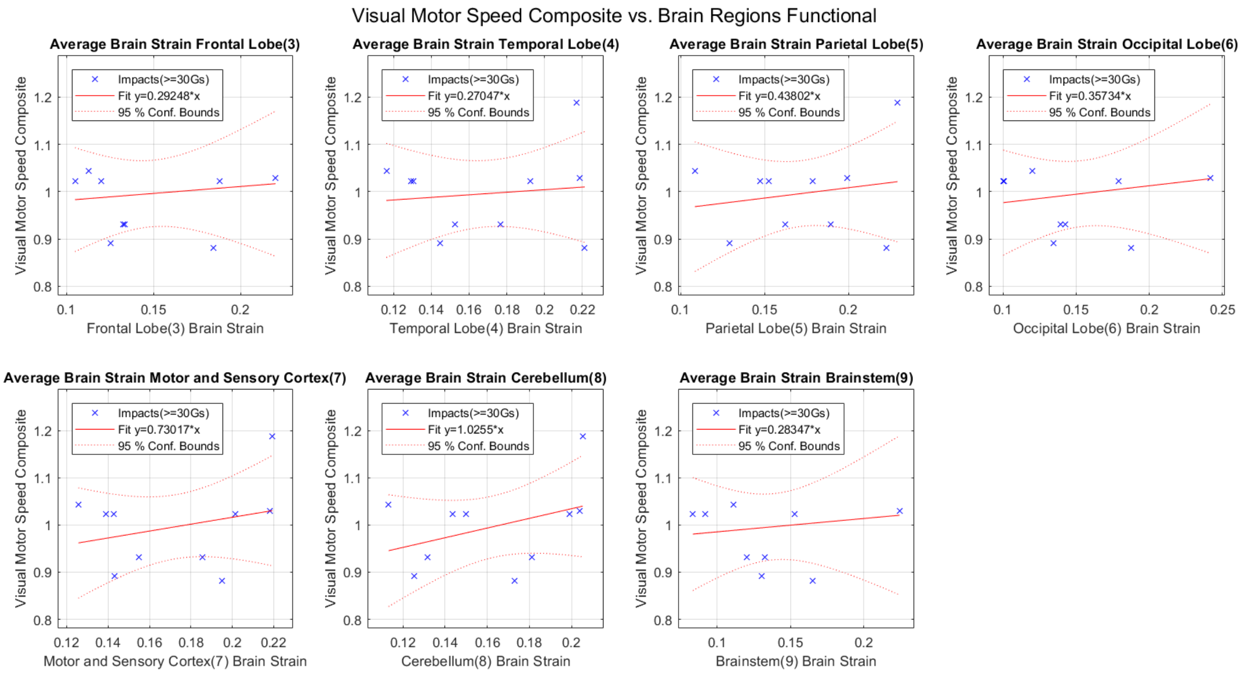


Figure 71: Visual Motor Speed Composite vs. Brain Regions (Functional) – Average MPS95

		Visual Motor Speed Composite
1	Frontal Lobe(3)	0.2925
2	Temporal Lobe(4)	0.2705
3	Parietal Lobe(5)	0.4380
4	Occipital Lobe(6)	0.3573
5	Motor and Sensory Cortex(7)	0.7302
6	Cerebellum(8)	1.0255
7	Brainstem(9)	0.2835

Table 52: Visual Motor Speed Composite vs. Brain Regions (Functional) – Average MPS95 – Slopes

Figure 72 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; one brain region has a negative slope indicating possible correlation, one brain region has a negative slope indicating possible correlation, Cerebellum.

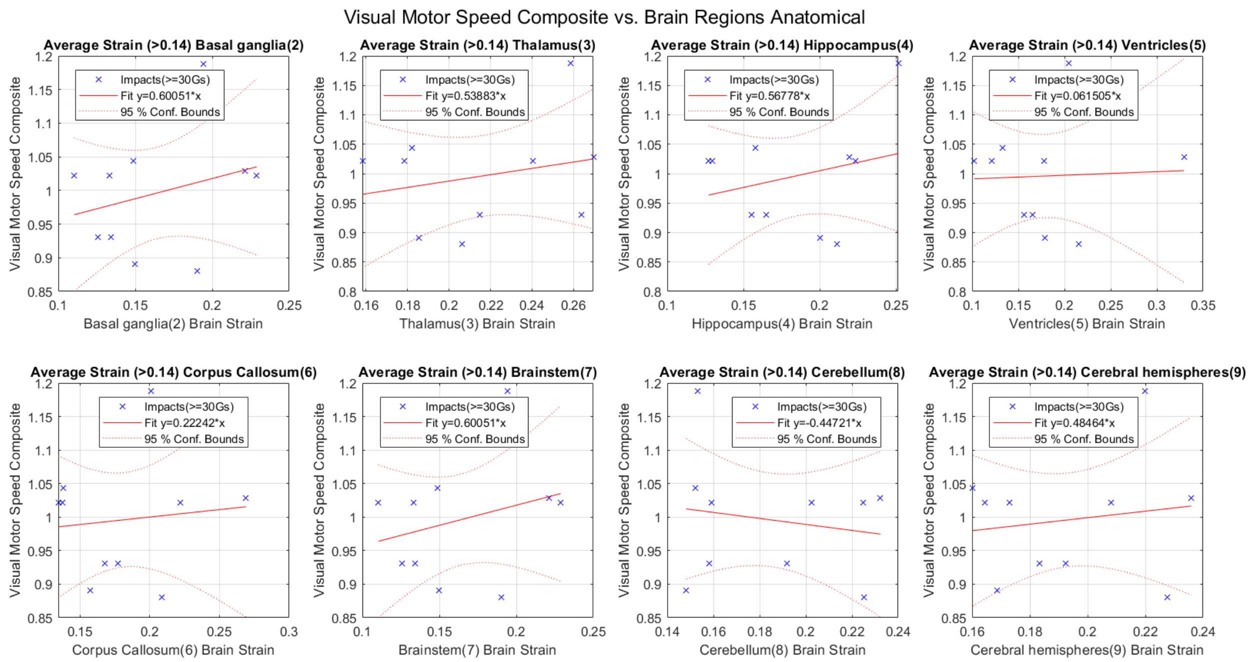


Figure 72: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Visual Motor Speed Composite
1	Basal ganglia(2)	0.6005
2	Thalamus(3)	0.5388
3	Hippocampus(4)	0.5678
4	Ventricles(5)	0.0615
5	Corpus Callosum(6)	0.2224
6	Brainstem(7)	0.6005
7	Cerebellum(8)	-0.4472
8	Cerebral hemispheres(9)	0.4846

Table 53: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 73 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; two brain regions have a negative slope indicating possible correlation, Motor and Sensory Cortex and Temporal Lobe.

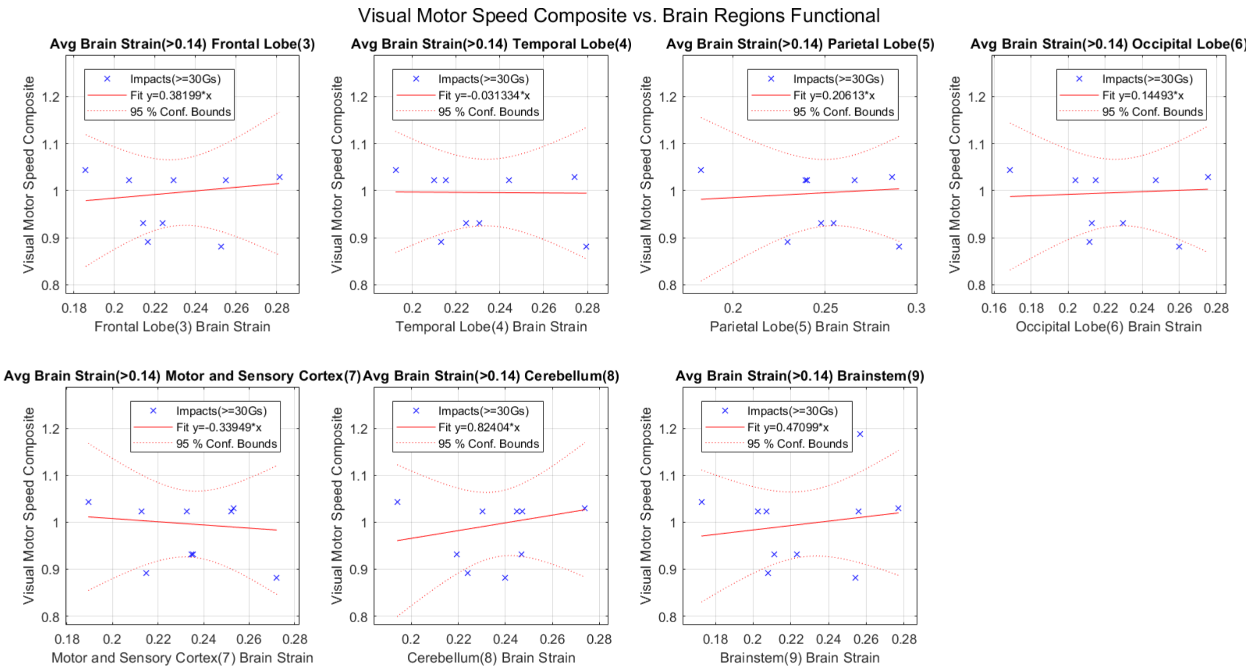


Figure 73: Visual Motor Speed Composite vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Visual Motor Speed Composite
1	Frontal Lobe(3)	0.3820
2	Temporal Lobe(4)	-0.0313
3	Parietal Lobe(5)	0.2061
4	Occipital Lobe(6)	0.1449
5	Motor and Sensory Cortex(7)	-0.3395
6	Cerebellum(8)	0.8240
7	Brainstem(9)	0.4710

Table 54: Visual Motor Speed Composite vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 74 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; one brain region has a negative slope indicating possible correlation: Cerebellum.

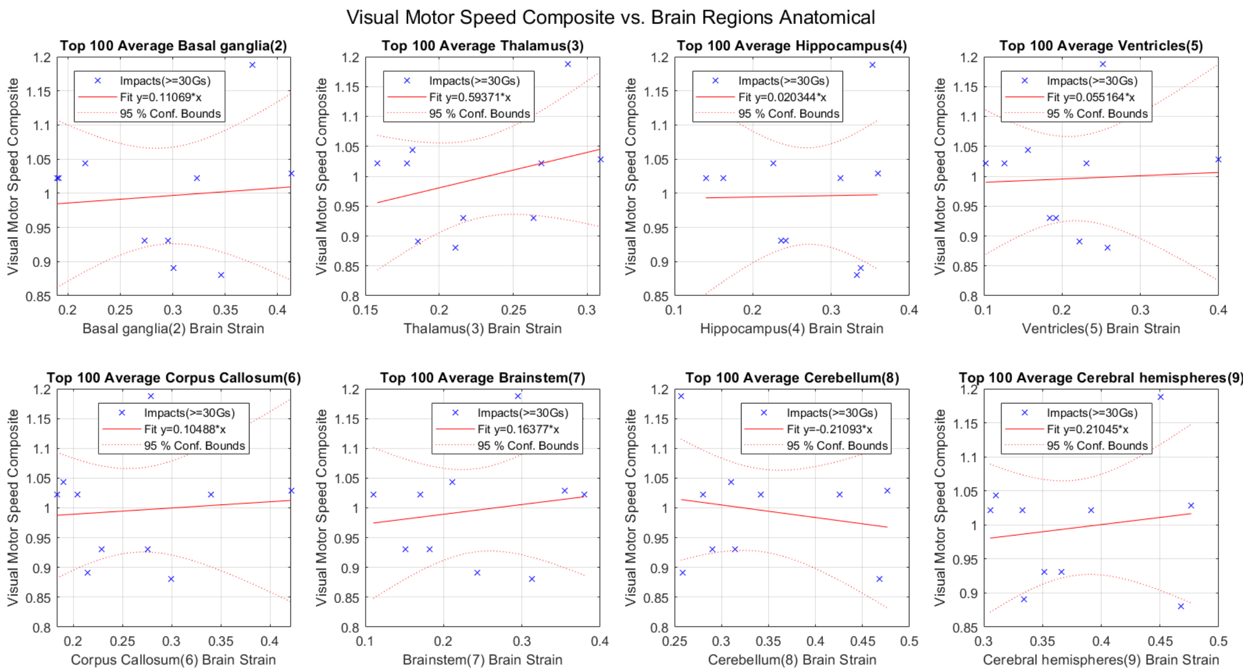


Figure 74: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Visual Motor Speed Composite
1	Basal ganglia(2)	0.1107
2	Thalamus(3)	0.5937
3	Hippocampus(4)	0.0203
4	Ventricles(5)	0.0552
5	Corpus Callosum(6)	0.1049
6	Brainstem(7)	0.1638
7	Cerebellum(8)	-0.2109
8	Cerebral hemispheres(9)	0.2104

Table 55: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 75 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, one brain region has a negative slope indicating possible correlation: Temporal Lobe.

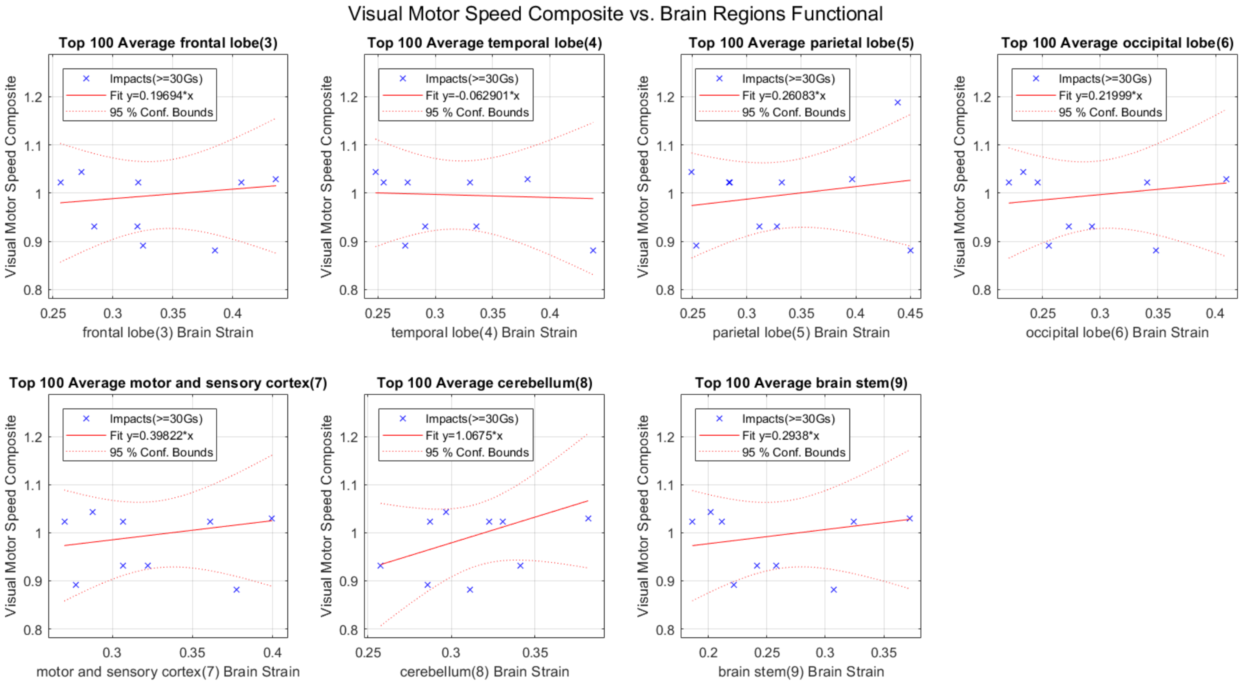


Figure 75: Visual Motor Speed Composite vs. Brain Regions (Functional) – Top 100 Strain Average

		Visual Motor Speed Composite
1	frontal lobe(3)	0.1969
2	temporal lobe(4)	-0.0629
3	parietal lobe(5)	0.2608
4	occipital lobe(6)	0.2200
5	motor and sensory cortex(7)	0.3982
6	cerebellum(8)	1.0675
7	brain stem(9)	0.2938

Table 56: Visual Motor Speed Composite vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 76 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, three brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, and Cerebellum.

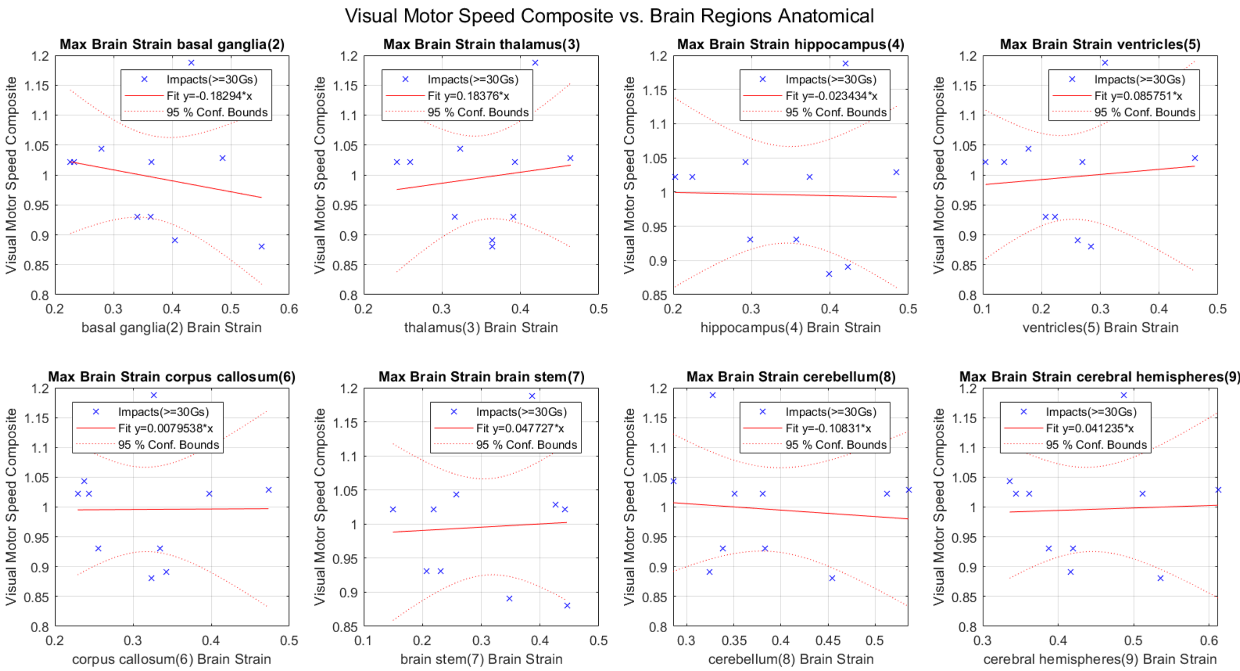


Figure 76: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Visual Motor Speed Composite
1	basal ganglia(2)	-0.1829
2	thalamus(3)	0.1838
3	hippocampus(4)	-0.0234
4	ventricles(5)	0.0858
5	corpus callosum(6)	0.0080
6	brain stem(7)	0.0477
7	cerebellum(8)	-0.1083
8	cerebral hemispheres(9)	0.0412

Table 57: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 77 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Functional Brain Regions using Max Strain Value as the strain parameter, two brain regions have a negative slope indicating possible correlation: Frontal Lobe and Temporal Lobe.

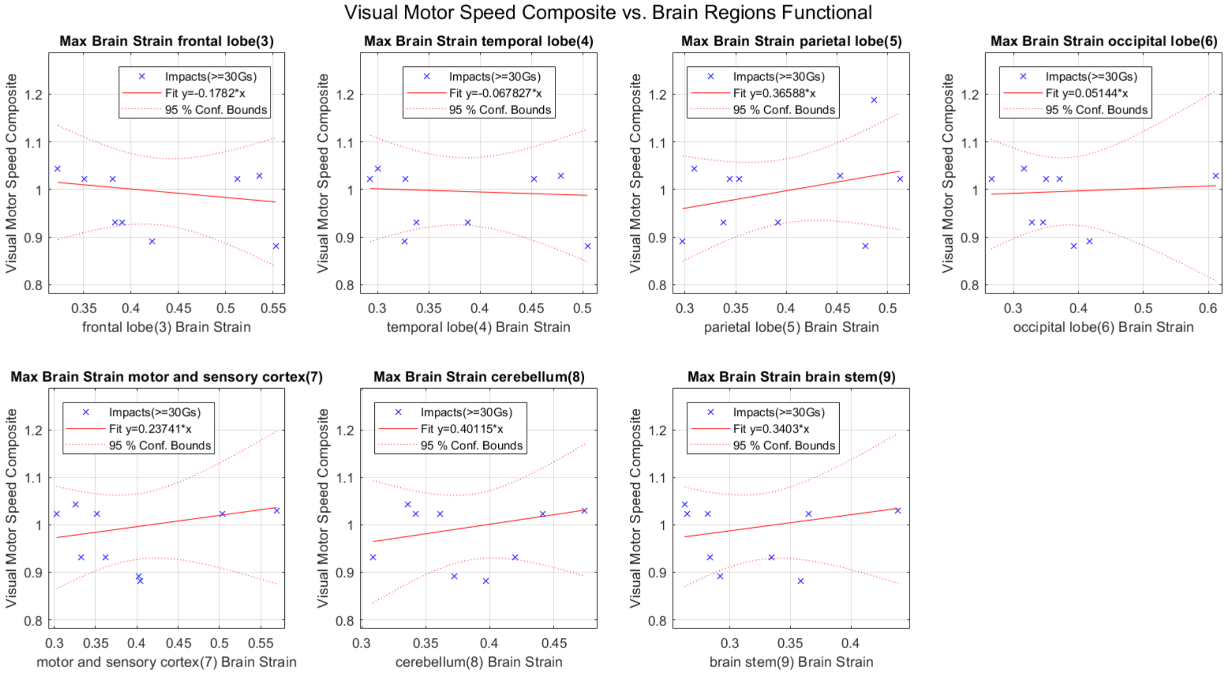


Figure 77: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Visual Motor Speed Composite
1	frontal lobe(3)	-0.1782
2	temporal lobe(4)	-0.0678
3	parietal lobe(5)	0.3659
4	occipital lobe(6)	0.0514
5	motor and sensory cortex(7)	0.2374
6	cerebellum(8)	0.4012
7	brain stem(9)	0.3403

Table 58: Visual Motor Speed Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.7. *Reaction Time Percentage*

Figure 78 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Percentage vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, two brain regions have a negative slope indicating possible correlation, Cerebellum and Ventricles.

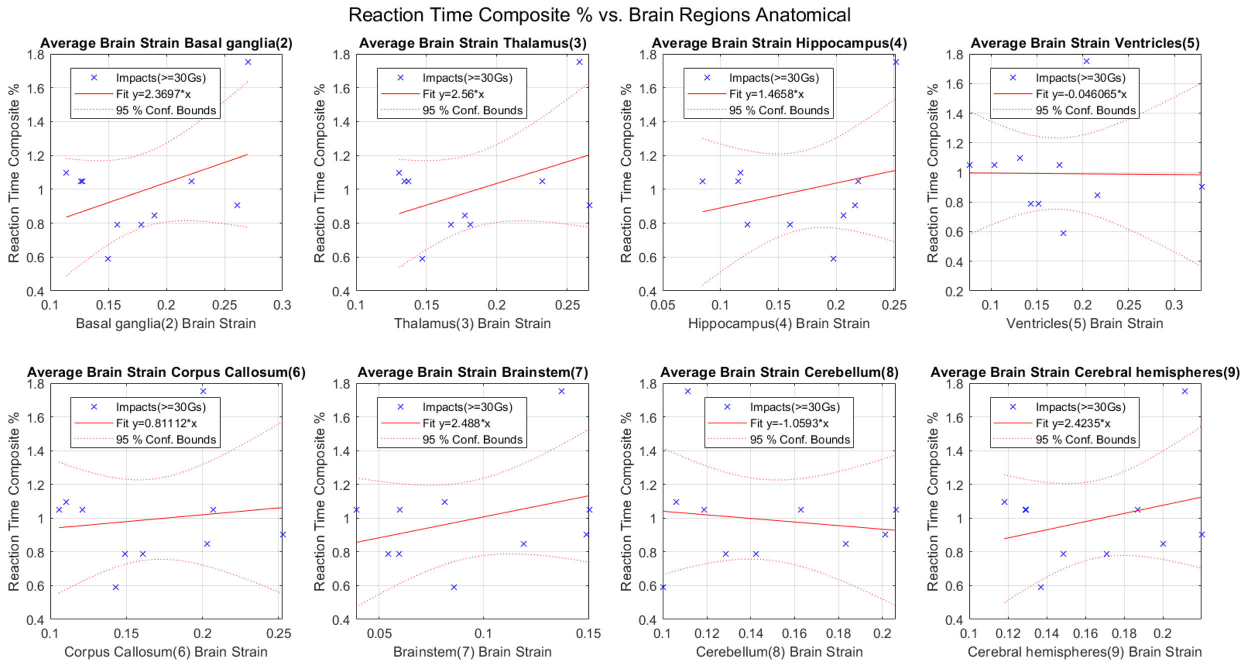


Figure 78: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95

		Reaction Time Composite %
1	Basal ganglia(2)	2.3697
2	Thalamus(3)	2.5600
3	Hippocampus(4)	1.4658
4	Ventricles(5)	-0.0461
5	Corpus Callosum(6)	0.8111
6	Brainstem(7)	2.4880
7	Cerebellum(8)	-1.0593
8	Cerebral hemispheres(9)	2.4235

Table 59: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Average MPS95- Slopes

Figure 79 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Percentage vs. Functional Brain Regions using Average MPS95 as the strain parameter, no brain regions have a negative slope indicating no possible correlation.

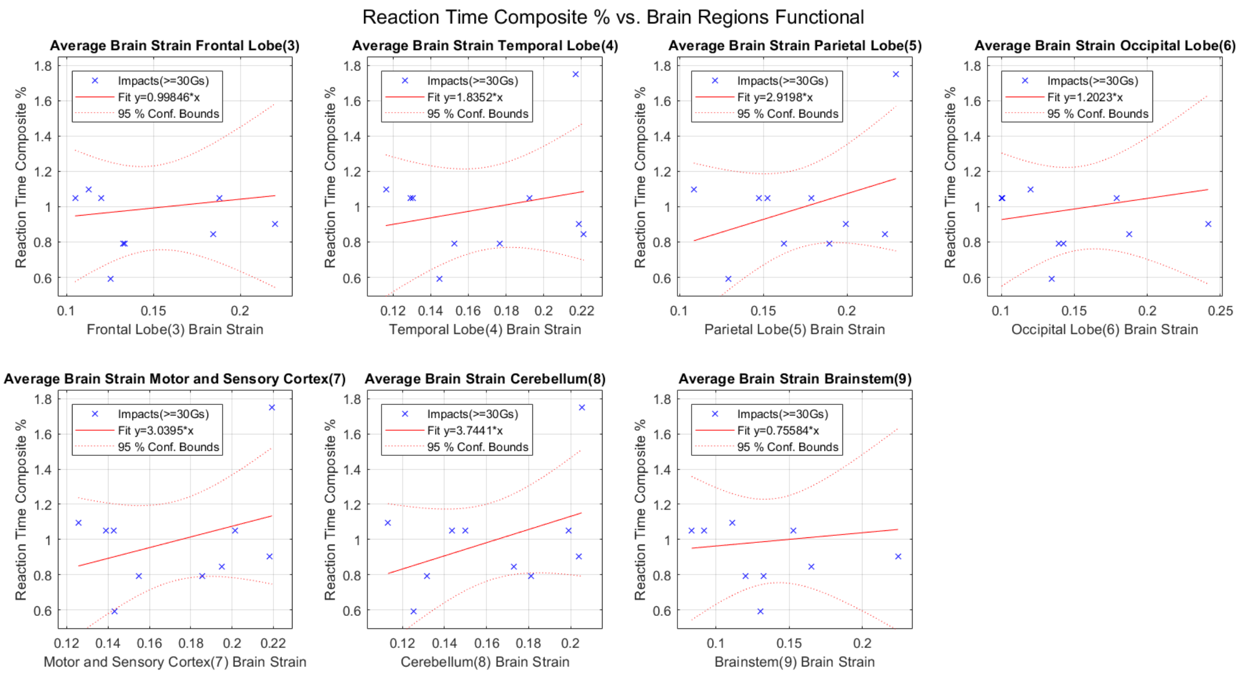


Figure 79: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Average MPS95

		Reaction Time Composite %
1	Frontal Lobe(3)	0.9985
2	Temporal Lobe(4)	1.8352
3	Parietal Lobe(5)	2.9198
4	Occipital Lobe(6)	1.2023
5	Motor and Sensory Cortex(7)	3.0395
6	Cerebellum(8)	3.7441
7	Brainstem(9)	0.7558

Table 60: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Average MPS95 - Slopes

Figure 80 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; seven brain regions have a negative slope indicating possible correlation, two brain regions has a negative slope indicating possible correlation, Cerebellum and Ventricles.

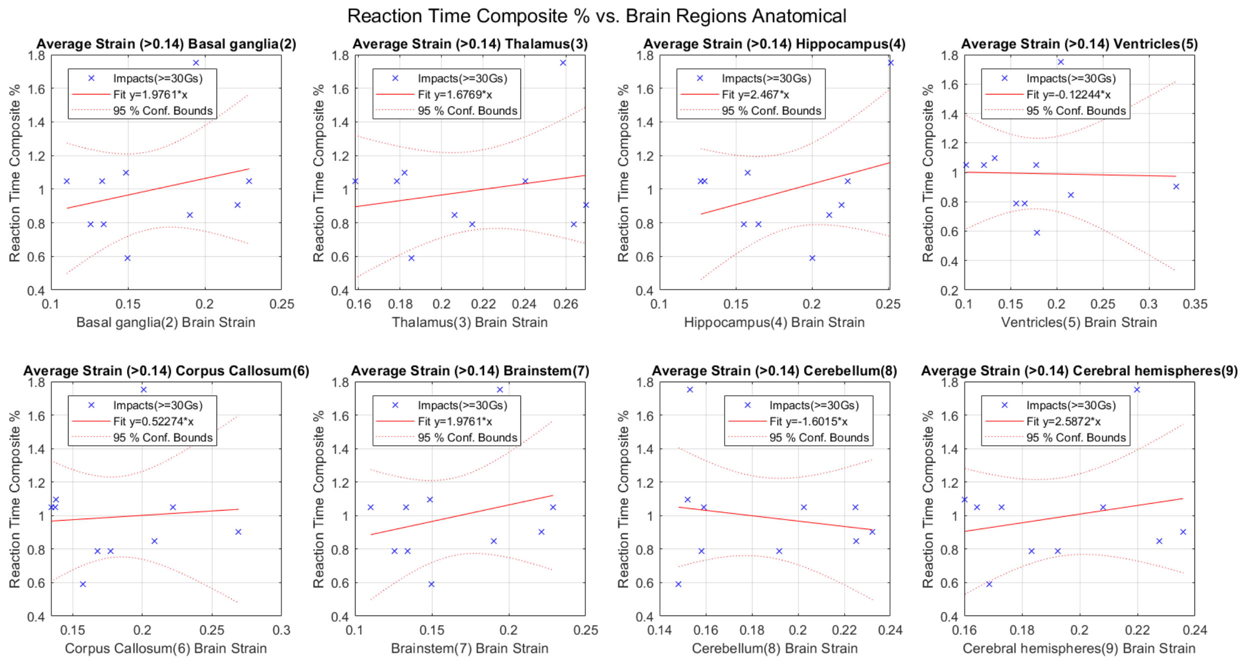


Figure 80: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Reaction Time Composite %
1	**Basal ganglia(2)**	1.9761
2	**Thalamus(3)**	1.6769
3	**Hippocampus(4)**	2.4670
4	**Ventricles(5)**	-0.1224
5	**Corpus Callosum(6)**	0.5227
6	**Brainstem(7)**	1.9761
7	**Cerebellum(8)**	-1.6015
8	**Cerebral hemispheres(9)**	2.5872

Table 61: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 81 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

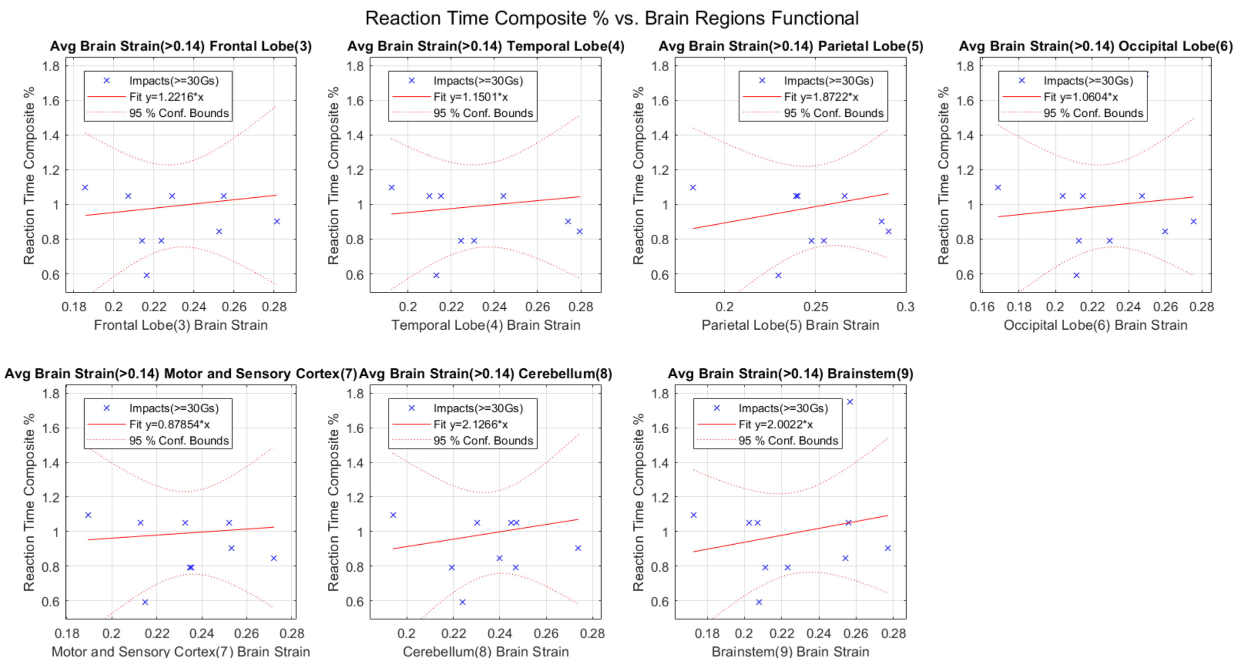


Figure 81: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Reaction Time Composite %
1	Frontal Lobe(3)	1.2216
2	Temporal Lobe(4)	1.1501
3	Parietal Lobe(5)	1.8722
4	Occipital Lobe(6)	1.0604
5	Motor and Sensory Cortex(7)	0.8785
6	Cerebellum(8)	2.1266
7	Brainstem(9)	2.0022

Table 62: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 82 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; two brain regions have a negative slope indicating possible correlation: Ventricles and Cerebellum.

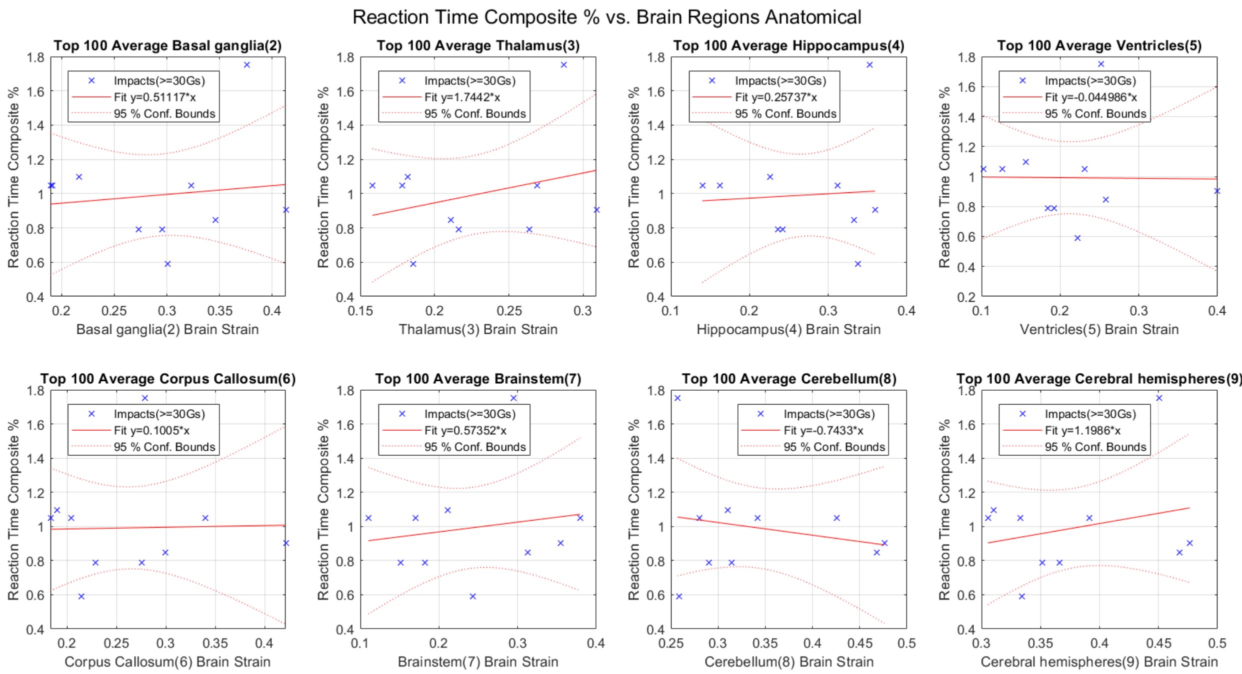


Figure 82: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Reaction Time Composite %
1	Basal ganglia(2)	0.5112
2	Thalamus(3)	1.7442
3	Hippocampus(4)	0.2574
4	Ventricles(5)	-0.0450
5	Corpus Callosum(6)	0.1005
6	Brainstem(7)	0.5735
7	Cerebellum(8)	-0.7433
8	Cerebral hemispheres(9)	1.1986

Table 63: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 83 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, no brain regions have a negative slope indicating possible correlation.

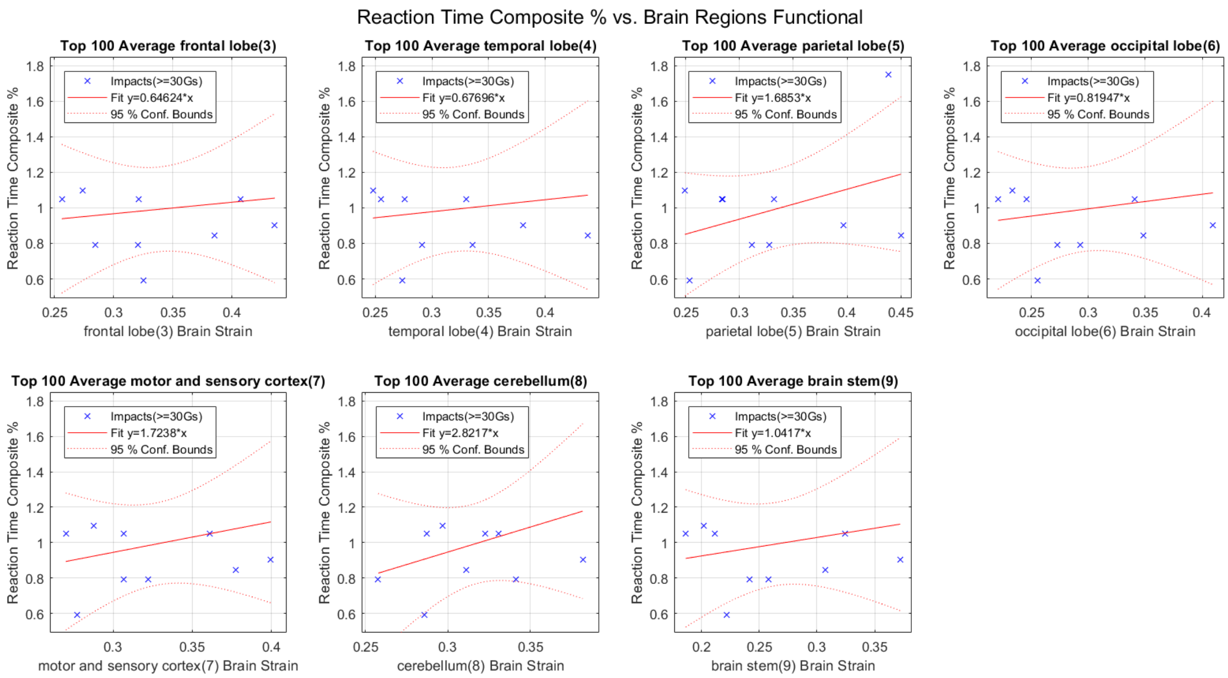


Figure 83: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average

		Reaction Time Composite %
1	frontal lobe(3)	0.6462
2	temporal lobe(4)	0.6770
3	parietal lobe(5)	1.6853
4	occipital lobe(6)	0.8195
5	motor and sensory cortex(7)	1.7238
6	cerebellum(8)	2.8217
7	brain stem(9)	1.0417

Table 64: Reaction Time Composite Percentage vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 84 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, four brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, Corpus Collosum, and Cerebellum.

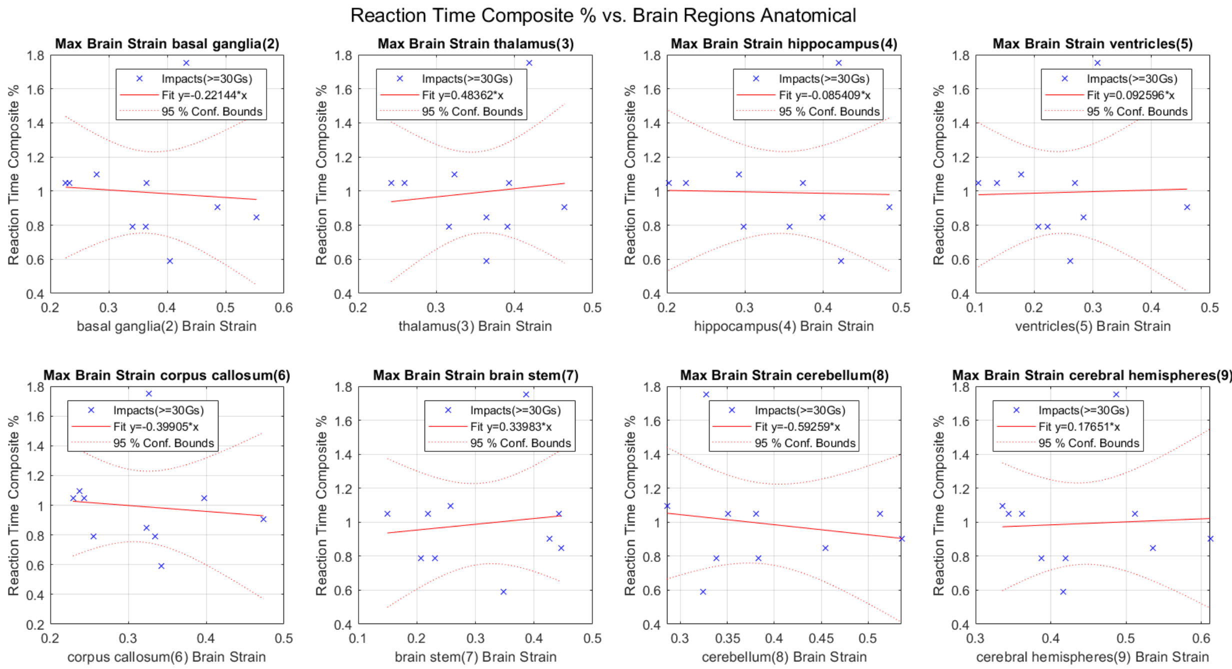


Figure 84: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Reaction Time Composite %
1	basal ganglia(2)	-0.2214
2	thalamus(3)	0.4836
3	hippocampus(4)	-0.0854
4	ventricles(5)	0.0926
5	corpus callosum(6)	-0.3991
6	brain stem(7)	0.3398
7	cerebellum(8)	-0.5926
8	cerebral hemispheres(9)	0.1765

Table 65: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 85 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite Percentage vs. Functional Brain Regions using Max Strain Value as the strain parameter, two brain regions have a negative slope indicating possible correlation: Frontal Lobe and Occipital Lobe.

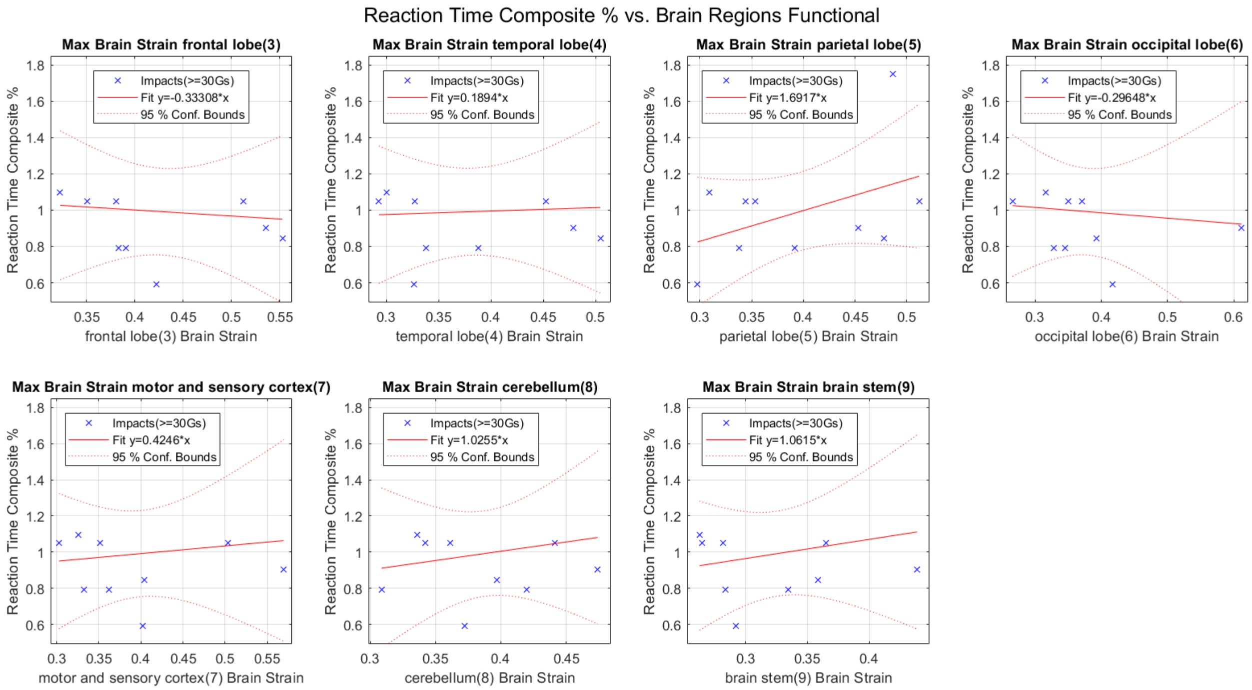


Figure 85: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Reaction Time Composite %
1	frontal lobe(3)	-0.3331
2	temporal lobe(4)	0.1894
3	parietal lobe(5)	1.6917
4	occipital lobe(6)	-0.2965
5	motor and sensory cortex(7)	0.4246
6	cerebellum(8)	1.0255
7	brain stem(9)	1.0615

Table 66: Reaction Time Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.8. *Reaction Time*

Figure 86 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, four brain regions have a negative slope indicating possible correlation, Hippocampus, Ventricles, Brainstem, and Cerebellum.

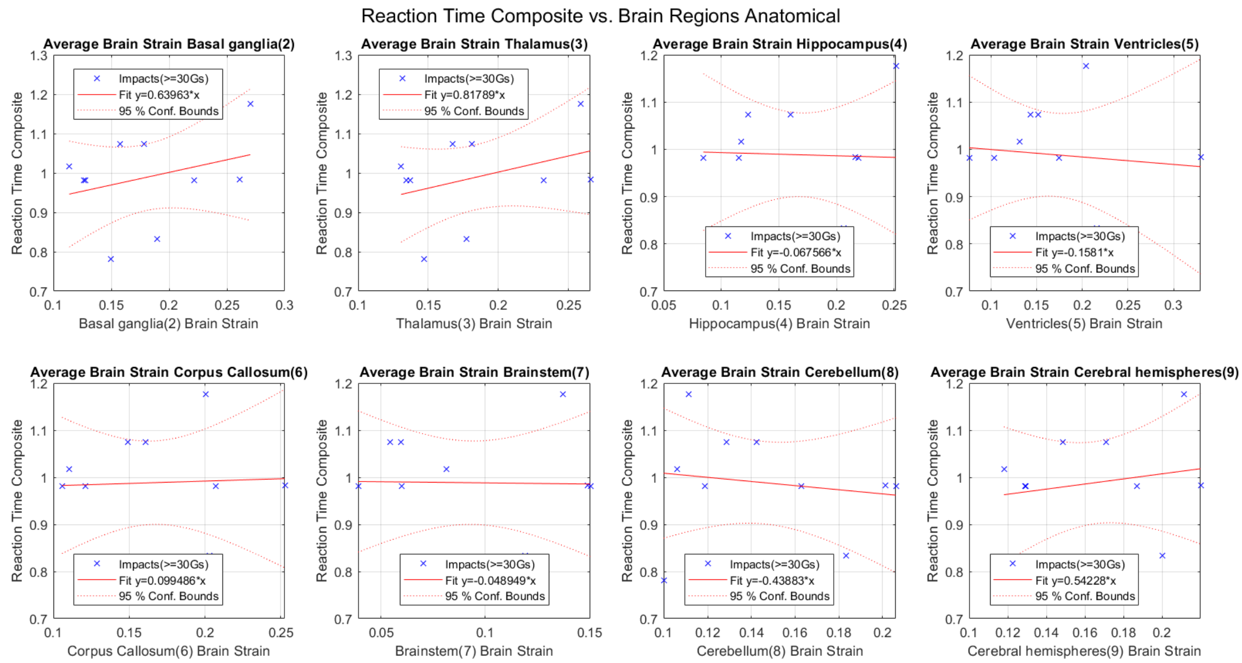


Figure 86: Reaction Time Composite vs. Brain Regions (Anatomical) – Average MPS95

		Reaction Time Composite
1	Basal ganglia(2)	0.6396
2	Thalamus(3)	0.8179
3	Hippocampus(4)	-0.0676
4	Ventricles(5)	-0.1581
5	Corpus Callosum(6)	0.0995
6	Brainstem(7)	-0.0489
7	Cerebellum(8)	-0.4388
8	Cerebral hemispheres(9)	0.5423

Table 67: Reaction Time Composite vs. Brain Regions (Anatomical) – Average MPS95 – Slopes

Figure 87 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time vs. Functional Brain Regions using Average MPS95 as the strain parameter, one brain region has a negative slope indicating possible correlation, Frontal Lobe.

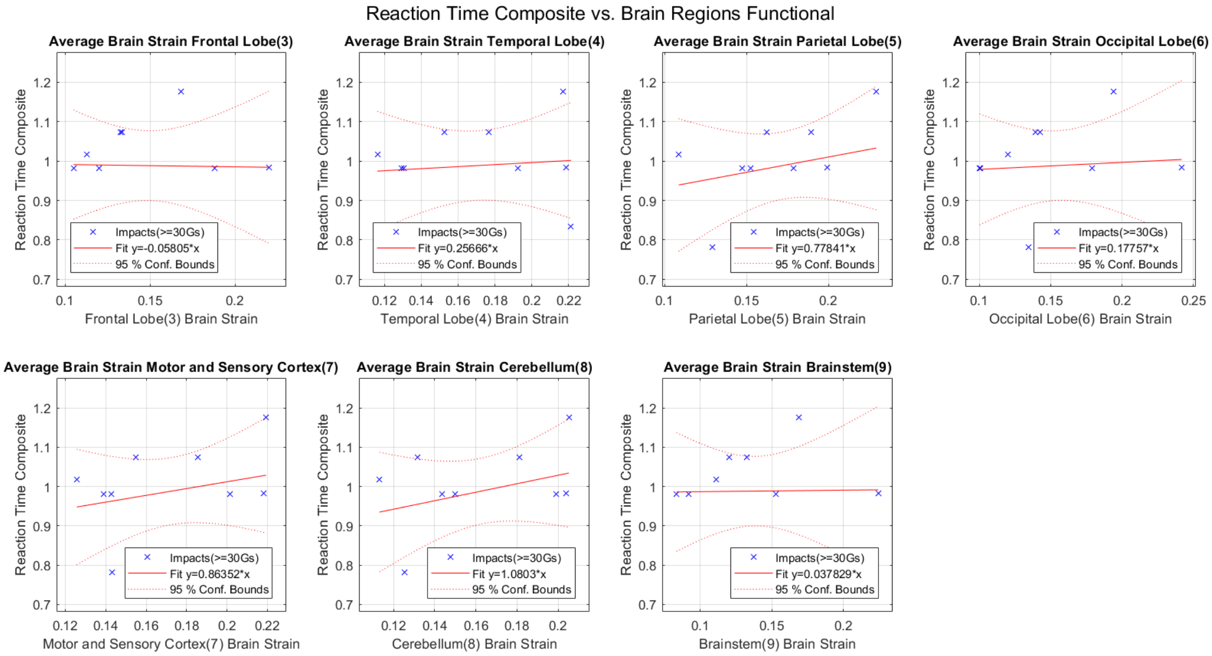


Figure 87: Reaction Time Composite vs. Brain Regions (Functional) – Average MPS95

		Reaction Time Composite
1	**Frontal Lobe(3)**	-0.0580
2	**Temporal Lobe(4)**	0.2567
3	**Parietal Lobe(5)**	0.7784
4	**Occipital Lobe(6)**	0.1776
5	**Motor and Sensory Cortex(7)**	0.8635
6	**Cerebellum(8)**	1.0803
7	**Brainstem(9)**	0.0378

Table 68: Reaction Time Composite vs. Brain Regions (Functional) – Average MPS95 – Slopes

Figure 88 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter, four brain regions has a negative indicating possible correlation, Basal Ganglia, Cerebellum, Brainstem and Ventricles.

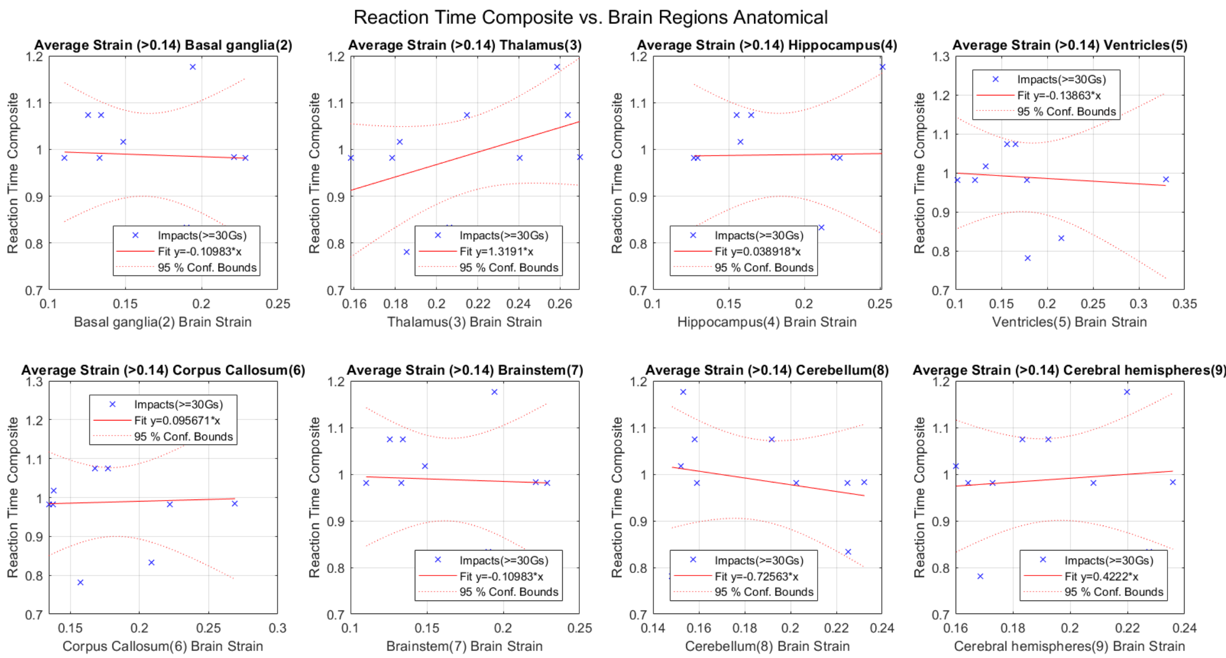


Figure 88: Reaction Time Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Reaction Time Composite
1	**Basal ganglia(2)**	-0.1098
2	**Thalamus(3)**	1.3191
3	**Hippocampus(4)**	0.0389
4	**Ventricles(5)**	-0.1386
5	**Corpus Callosum(6)**	0.0957
6	**Brainstem(7)**	-0.1098
7	**Cerebellum(8)**	-0.7256
8	**Cerebral hemispheres(9)**	0.4222

Table 69: Reaction Time Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 89 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; four brain regions have a negative slope indicating possible correlation, Frontal Lobe, Motor and Sensory Cortex, Occipital Lobe, and Temporal Lobe.

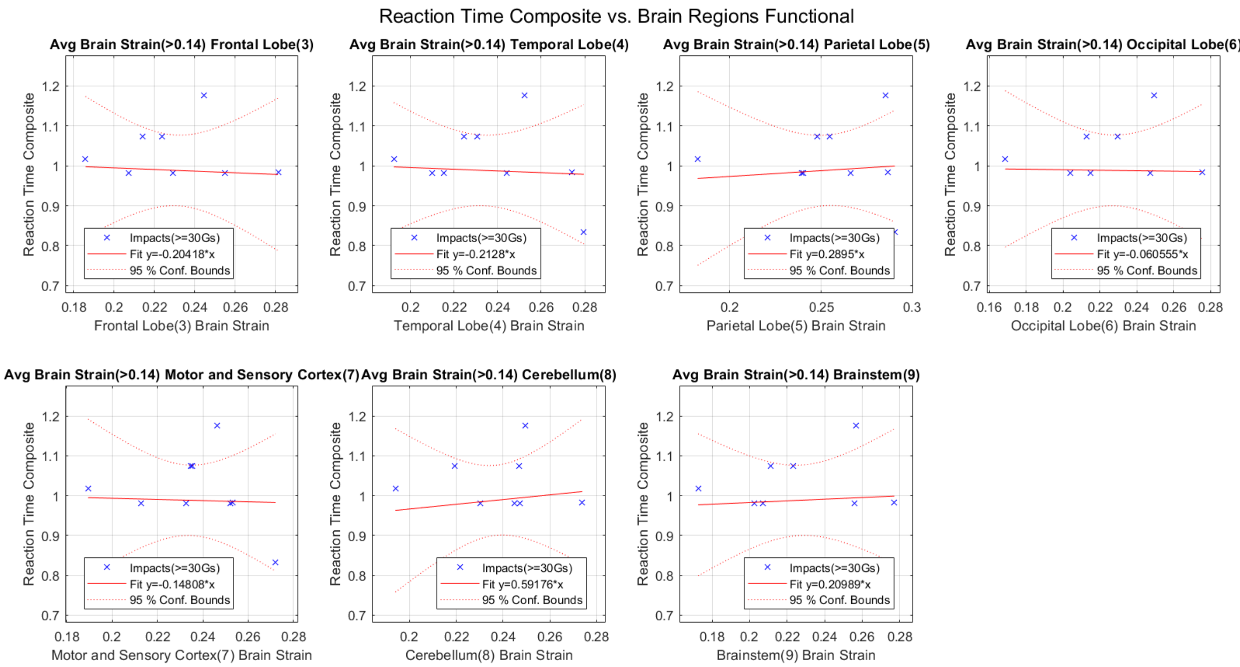


Figure 89: Reaction Time Composite vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Reaction Time Composite
1	Frontal Lobe(3)	-0.2042
2	Temporal Lobe(4)	-0.2128
3	Parietal Lobe(5)	0.2895
4	Occipital Lobe(6)	-0.0606
5	Motor and Sensory Cortex(7)	-0.1481
6	Cerebellum(8)	0.5918
7	Brainstem(9)	0.2099

Table 70: Reaction Time Composite vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

Figure 90 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter; four brain regions have a negative slope indicating possible correlation: Hippocampus, Ventricles, Brainstem, and Cerebellum.

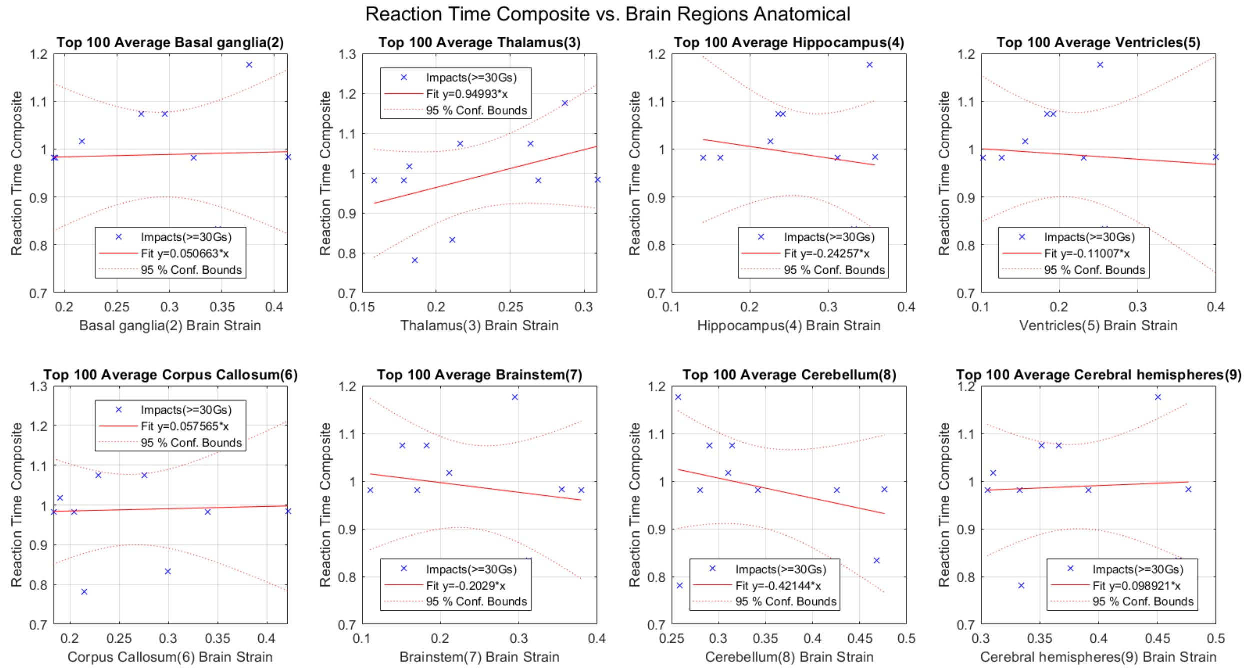


Figure 90: Reaction Time Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average

		Reaction Time Composite
1	Basal ganglia(2)	0.0507
2	Thalamus(3)	0.9499
3	Hippocampus(4)	-0.2426
4	Ventricles(5)	-0.1101
5	Corpus Callosum(6)	0.0576
6	Brainstem(7)	-0.2029
7	Cerebellum(8)	-0.4214
8	Cerebral hemispheres(9)	0.0989

Table 71: Reaction Time Composite vs. Brain Regions (Anatomical) – Top 100 Strain Average – Slopes

Figure 91 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, two brain regions have a negative slope indicating possible correlation: Frontal Lobe and Temporal Lobe.

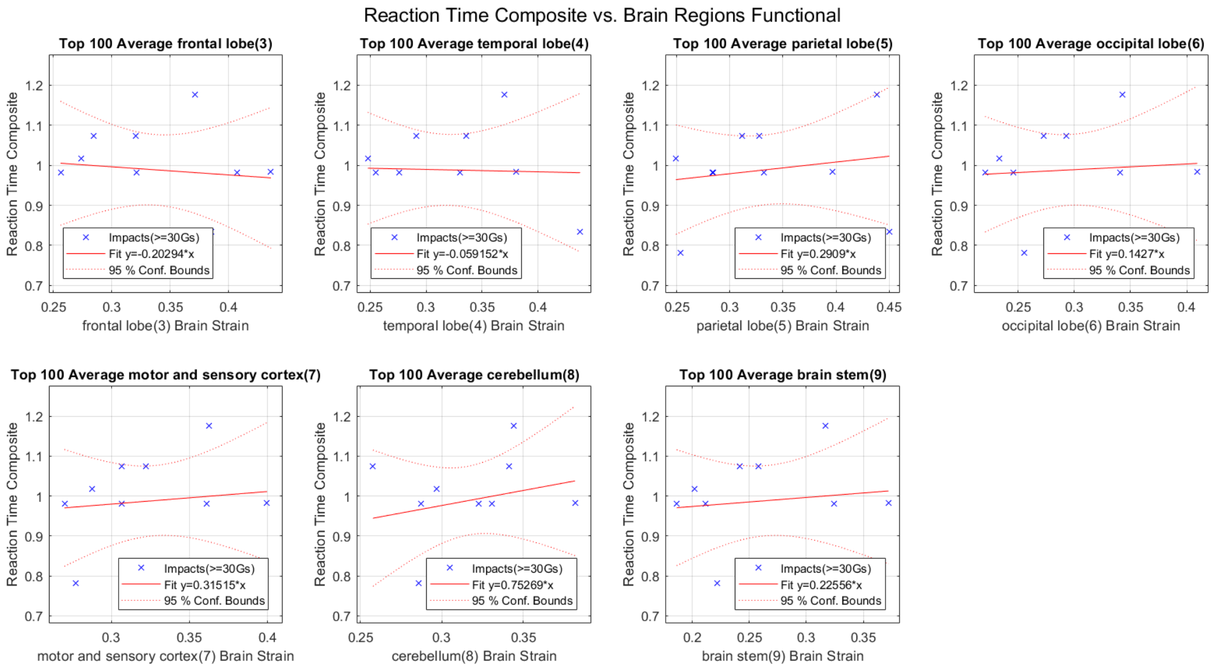


Figure 91: Reaction Time Composite vs. Brain Regions (Functional) – Top 100 Strain Average

		Reaction Time Composite
1	frontal lobe(3)	-0.2029
2	temporal lobe(4)	-0.0592
3	parietal lobe(5)	0.2909
4	occipital lobe(6)	0.1427
5	motor and sensory cortex(7)	0.3152
6	cerebellum(8)	0.7527
7	brain stem(9)	0.2256

Table 72: Reaction Time Composite vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 92 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, seven brain regions have a negative slope indicating possible correlation: Basal Ganglia, Hippocampus, Ventricles, Corpus Collosum, Brainstem, Cerebellum, and Cerebral Hemispheres.

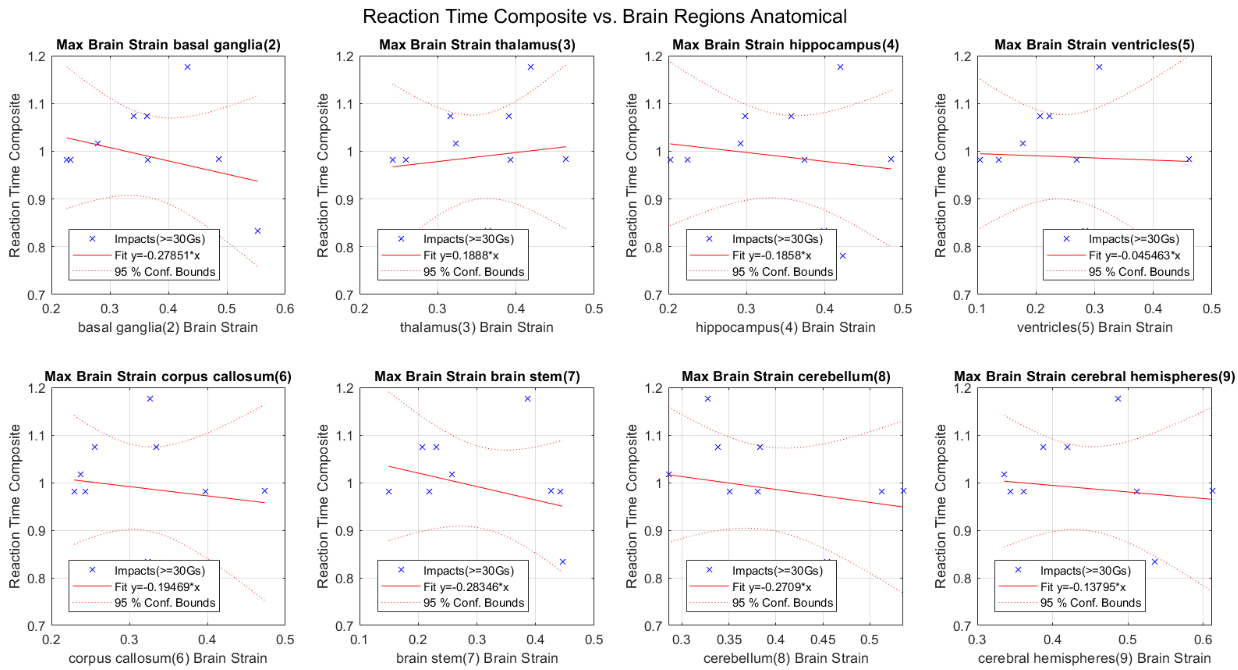


Figure 92: Reaction Time Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Reaction Time Composite
1	basal ganglia(2)	-0.2785
2	thalamus(3)	0.1888
3	hippocampus(4)	-0.1858
4	ventricles(5)	-0.0455
5	corpus callosum(6)	-0.1947
6	brain stem(7)	-0.2835
7	cerebellum(8)	-0.2709
8	cerebral hemispheres(9)	-0.1380

Table 73: Reaction Time Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 93 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Composite vs. Functional Brain Regions using Max Strain Value as the strain parameter, four brain regions have a negative slope indicating possible correlation: Frontal Lobe, Temporal Lobe, Occipital Lobe, and Motor and Sensory Cortex

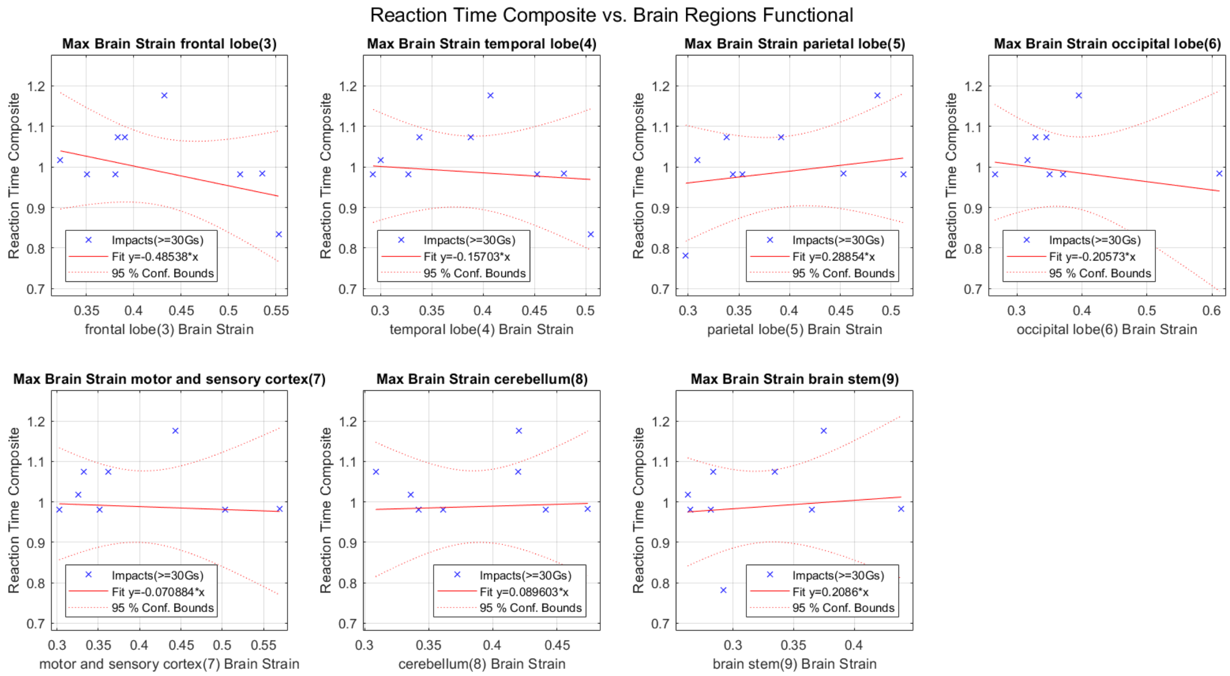


Figure 93: Reaction Time Composite vs. Brain Regions (Anatomical) – Max Strain Value

		Reaction Time Composite
1	frontal lobe(3)	-0.4854
2	temporal lobe(4)	-0.1570
3	parietal lobe(5)	0.2885
4	occipital lobe(6)	-0.2057
5	motor and sensory cortex(7)	-0.0709
6	cerebellum(8)	0.0896
7	brain stem(9)	0.2086

Table 74: Reaction Time Composite vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

4.1.9. *Impulse Control*

Figure 94 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Impulse Control vs. Anatomical Brain Regions using Average MPS95 as the strain parameter, all brain regions have a negative slope indicating possible correlation: Basal Ganglia, Thalamus, Hippocampus, Ventricles, Corpus Callosum, Brainstem, Cerebellum, Cerebral Hemispheres.

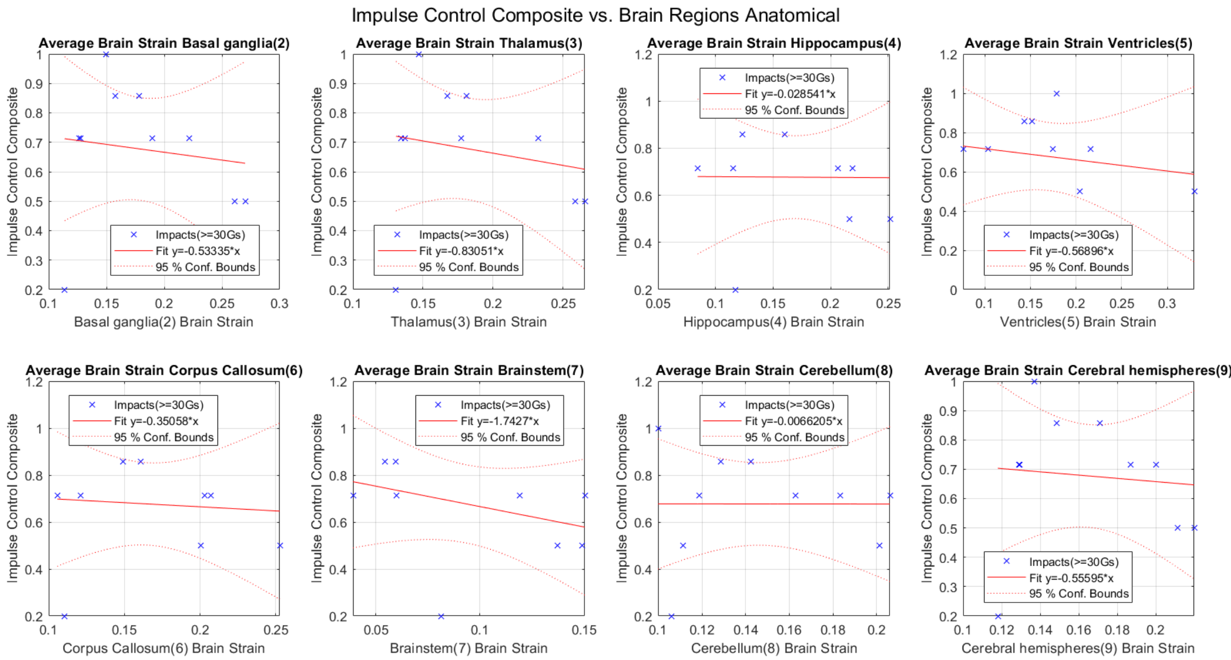


Figure 94: Impulse Control Composite vs. Brain Regions (Anatomical) – Average MPS95

		Impulse Control Composite
1	Basal ganglia(2)	-0.5333
2	Thalamus(3)	-0.8305
3	Hippocampus(4)	-0.0285
4	Ventricles(5)	-0.5690
5	Corpus Callosum(6)	-0.3506
6	Brainstem(7)	-1.7427
7	Cerebellum(8)	-0.0066
8	Cerebral hemispheres(9)	-0.5560

Table 75: Impulse Control Composite vs. Brain Regions (Anatomical) – Average MPS95 – Slopes

Figure 95 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Reaction Time Percentage vs. Functional Brain Regions using MPS95 > 0.14 as the strain parameter, six brain regions have a positive slope indicating possible correlation: Frontal Lobe, Temporal Lobe, Occipital Lobe, Motor and Sensory Cortex, Cerebellum, Brainstem.

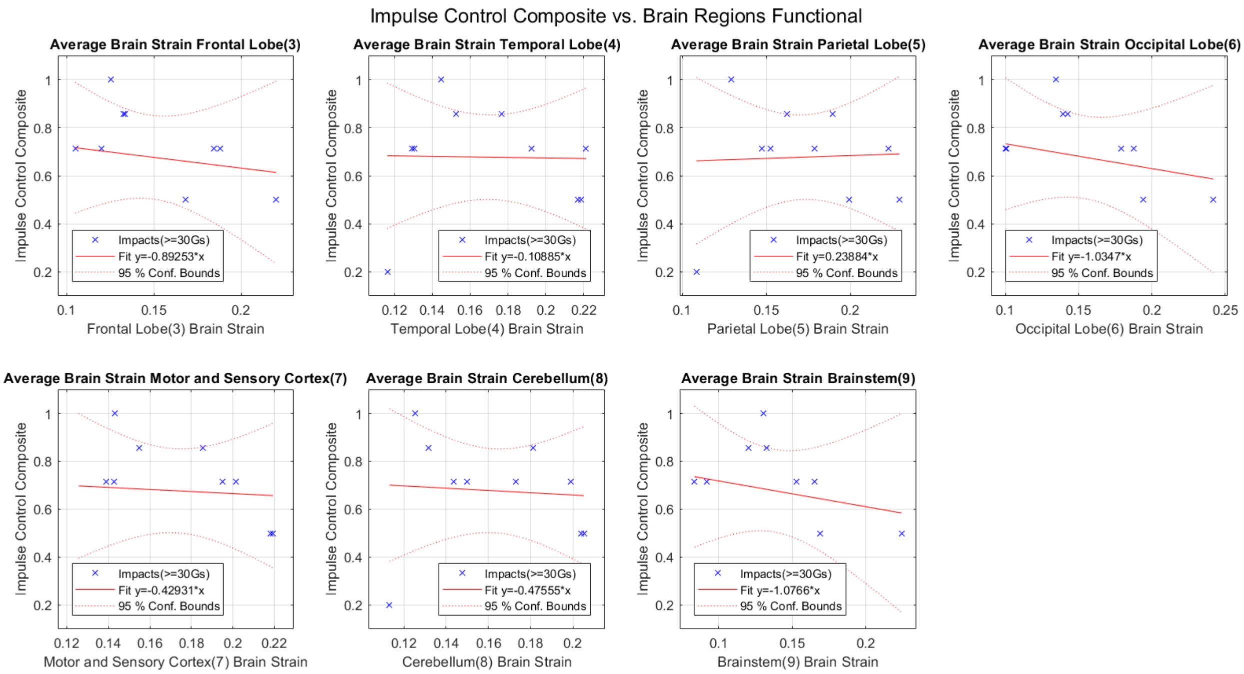


Figure 95: Impulse Control Composite vs. Brain Regions (Functional) – Average MPS95

		Impulse Control Composite
1	Frontal Lobe(3)	-0.8925
2	Temporal Lobe(4)	-0.1089
3	Parietal Lobe(5)	0.2388
4	Occipital Lobe(6)	-1.0347
5	Motor and Sensory Cortex(7)	-0.4293
6	Cerebellum(8)	-0.4756
7	Brainstem(9)	-1.0766

Table 76: Impulse Control Composite vs. Brain Regions (Functional) – Average MPS95 – Slopes

Figure 96 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Impulse Control Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; seven brain regions have a negative slope indicating possible correlation, seven brain regions has a negative slope indicating possible correlation, Basal Ganglia, Thalamus, Hippocampus, Ventricles, Corpus Collosum, Brainstem, and Cerebral Hemispheres.

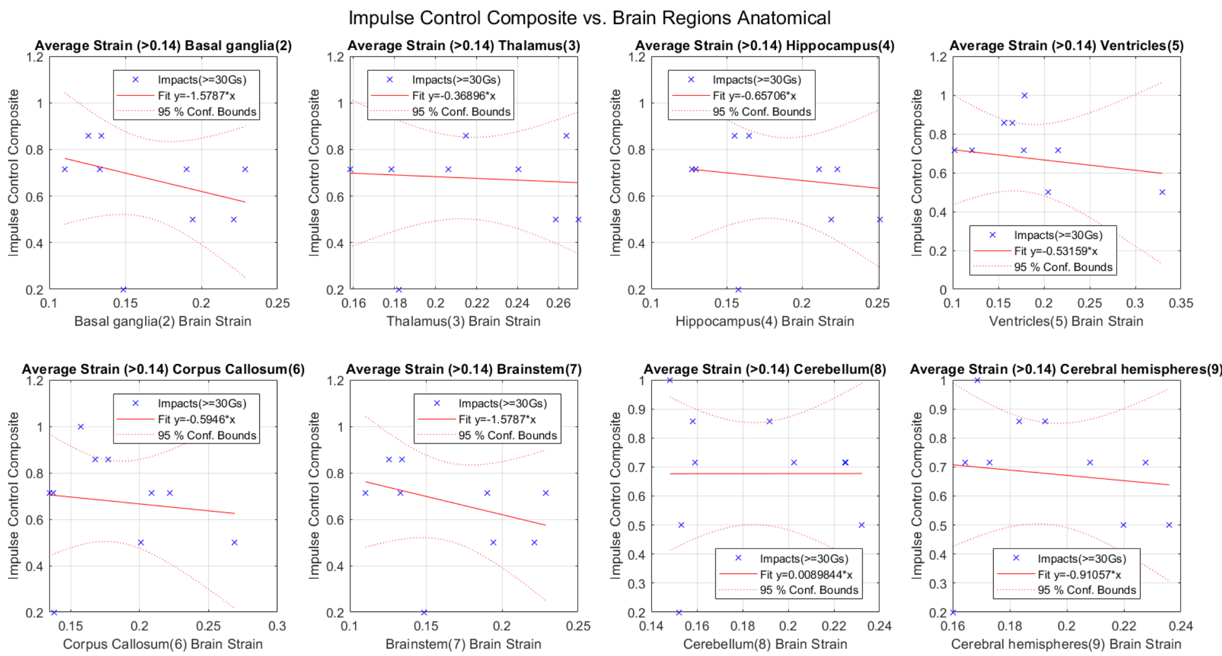


Figure 96: Impulse Control Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Impulse Control Composite
1	Basal ganglia(2)	-1.5787
2	Thalamus(3)	-0.3690
3	Hippocampus(4)	-0.6571
4	Ventricles(5)	-0.5316
5	Corpus Callosum(6)	-0.5946
6	Brainstem(7)	-1.5787
7	Cerebellum(8)	0.0090
8	Cerebral hemispheres(9)	-0.9106

Table 77: Impulse Control Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 97 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Impulse Control Composite vs. Anatomical Brain Regions using MPS95 > 0.14 as the strain parameter; no brain regions have a negative slope indicating no possible correlation.

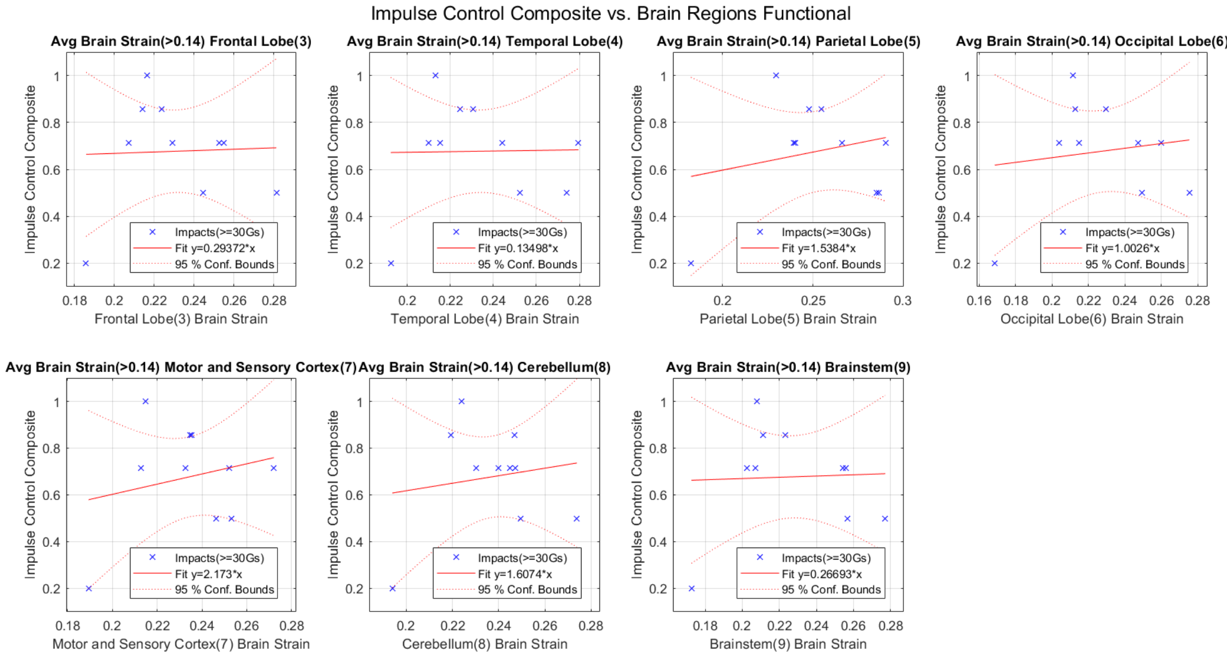


Figure 97: Impulse Control Composite vs. Brain Regions (Functional) – Average (MPS95>0.14)

		Impulse Control Composite
1	Frontal Lobe(3)	0.2937
2	Temporal Lobe(4)	0.1350
3	Parietal Lobe(5)	1.5384
4	Occipital Lobe(6)	1.0026
5	Motor and Sensory Cortex(7)	2.1730
6	Cerebellum(8)	1.6074
7	Brainstem(9)	0.2669

Table 78: Impulse Control Composite vs. Brain Regions (Functional) – Average (MPS95>0.14) – Slopes

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Figure 98 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Impulse Control vs. Anatomical Brain Regions using Top 100 Strain Average as the strain parameter, all brain regions have a negative slope indicating possible correlation: Basal Ganglia, Thalamus, Hippocampus, Ventricles, Corpus Callosum, Brainstem, Cerebellum, Cerebral Hemispheres.

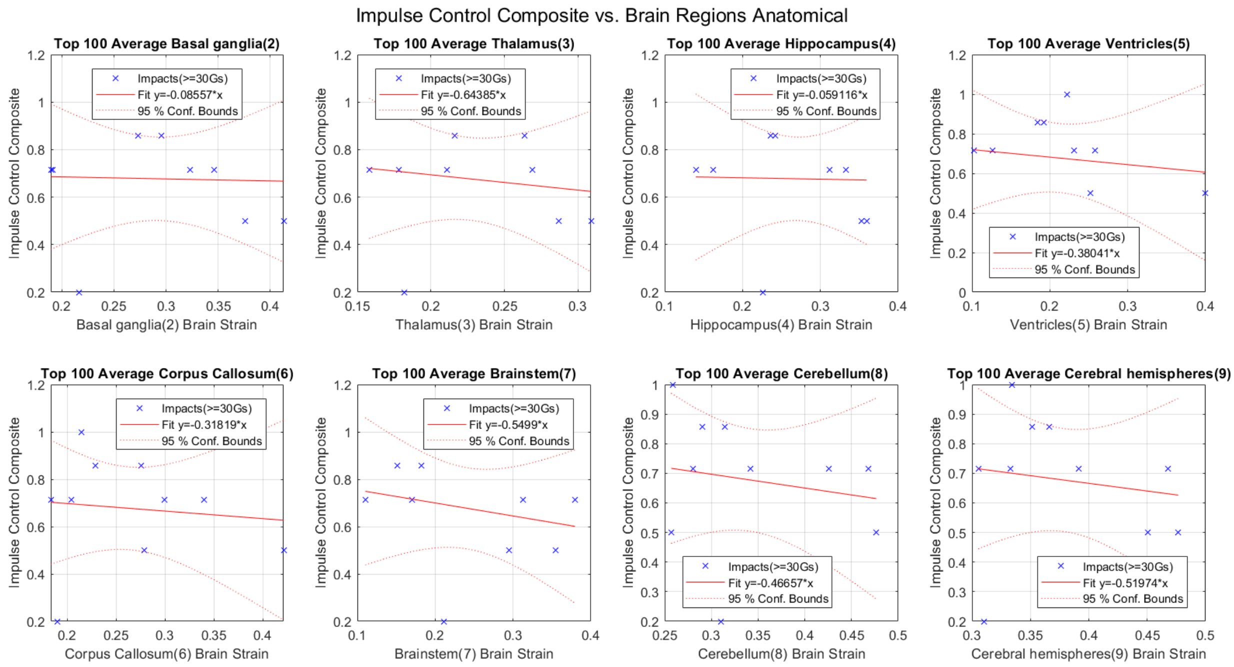

Figure 98: Impulse Control Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14)

		Impulse Control Composite
1	Basal ganglia(2)	-0.0856
2	Thalamus(3)	-0.6439
3	Hippocampus(4)	-0.0591
4	Ventricles(5)	-0.3804
5	Corpus Callosum(6)	-0.3182
6	Brainstem(7)	-0.5499
7	Cerebellum(8)	-0.4666
8	Cerebral hemispheres(9)	-0.5197

Table 79: Impulse Control Composite vs. Brain Regions (Anatomical) – Average (MPS95>0.14) – Slopes

Figure 99 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Motor Speed Composite vs. Functional Brain Regions using Top 100 Strain Average as the strain parameter, seven brain regions have a negative slope indicating possible correlation: Frontal Lobe, Temporal Lobe, Parietal Lobe, Occipital Lobe, Motor and Sensory Cortex, Cerebellum, Brainstem.

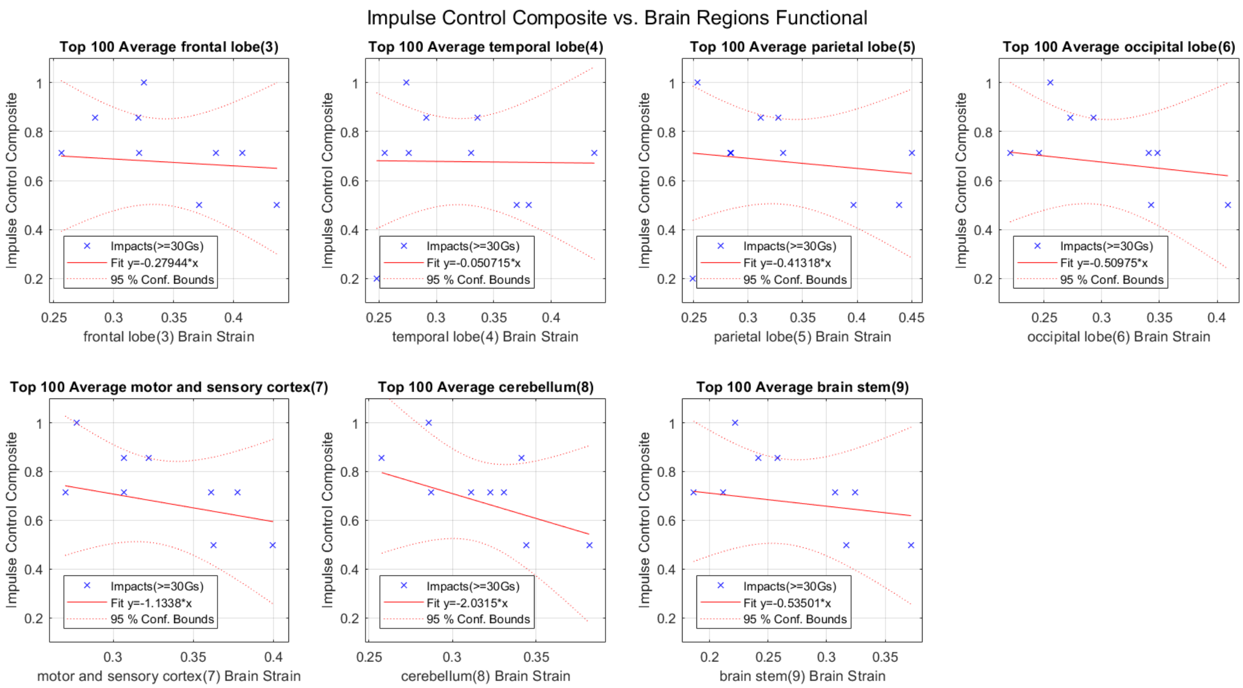

Figure 99: Impulse Control Composite vs. Brain Regions (Functional) – Top 100 Strain Average

		Impulse Control Composite
1	frontal lobe(3)	-0.2794
2	temporal lobe(4)	-0.0507
3	parietal lobe(5)	-0.4132
4	occipital lobe(6)	-0.5097
5	motor and sensory cortex(7)	-1.1338
6	cerebellum(8)	-2.0315
7	brain stem(9)	-0.5350

Table 80: Impulse Control Composite vs. Brain Regions (Functional) – Top 100 Strain Average – Slopes

Figure 100 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Visual Memory Composite Percentage vs. Anatomical Brain Regions using Max Strain Value as the strain parameter, five brain regions have a negative slope indicating possible correlation: Thalamus, Hippocampus, Ventricles, Brainstem, and Cerebral Hemispheres.

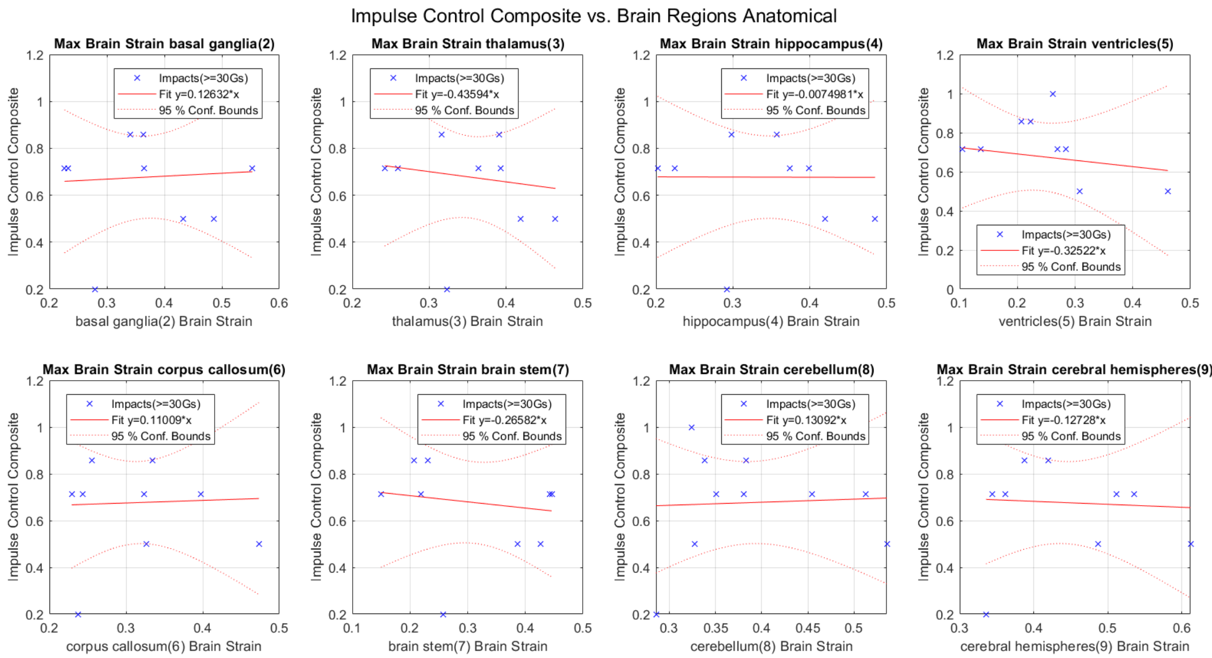

Figure 100: Impulse Control Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value

		Impulse Control Composite
1	basal ganglia(2)	0.1263
2	thalamus(3)	-0.4359
3	hippocampus(4)	-0.0075
4	ventricles(5)	-0.3252
5	corpus callosum(6)	0.1101
6	brain stem(7)	-0.2658
7	cerebellum(8)	0.1309
8	cerebral hemispheres(9)	-0.1273

Table 81: Impulse Control Composite Percentage vs. Brain Regions (Anatomical) – Max Strain Value – Slopes

Figure 101 displays linear regression plots fit to the nine impact data points (x-Brain Strain, Y-Composite Ratio) for Impulse Control Composite vs. Functional Brain Regions using Max Strain Value as the strain parameter, seven brain regions have a negative slope indicating possible correlation: Temporal Lobe, Parietal Lobe, Occipital Lobe, Motor and Sensory Cortex, Cerebellum, and Brainstem.

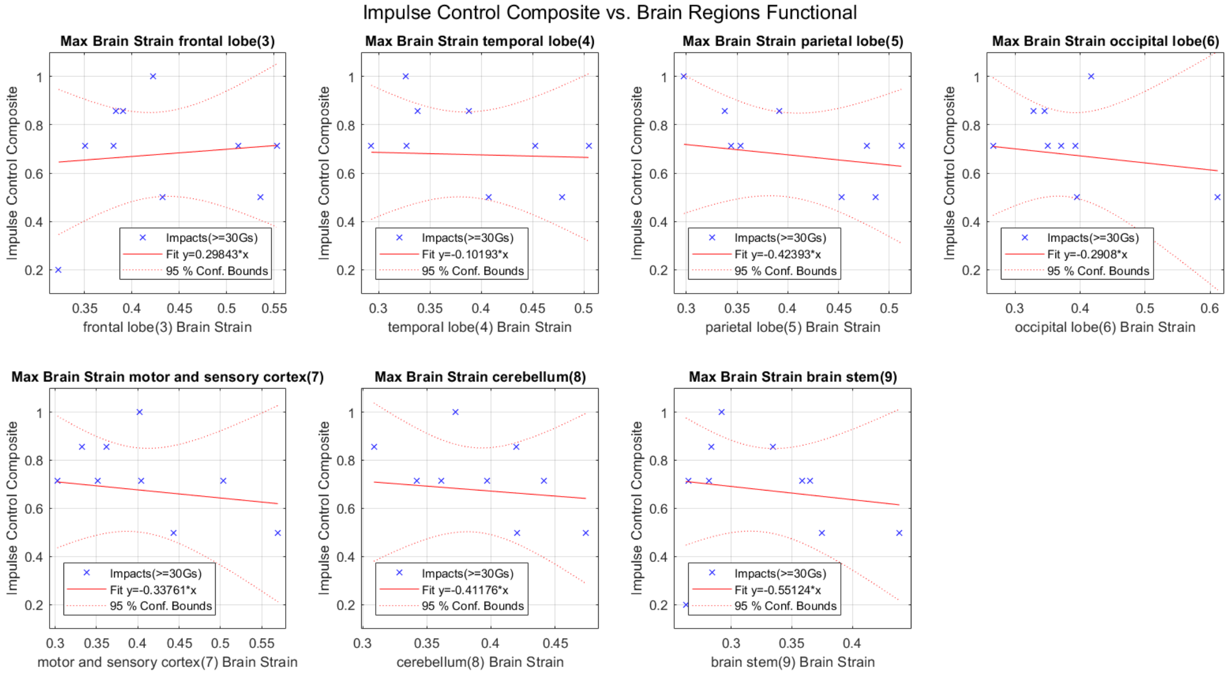

Figure 101: Impulse Control Composite vs. Brain Regions (Functional) – Max Strain Value

		Impulse Control Composite
1	frontal lobe(3)	0.2984
2	temporal lobe(4)	-0.1019
3	parietal lobe(5)	-0.4239
4	occipital lobe(6)	-0.2908
5	motor and sensory cortex(7)	-0.3376
6	cerebellum(8)	-0.4118
7	brain stem(9)	-0.5512

Table 82: Impulse Control Composite vs. Brain Regions (Functional) – Max Strain Value – Slopes

4.2. Forecasted Cognitive Results for Brain Regions

Seen in Table 1 and Table 2, all brain regions have composite scores that should be expected to see dysfunction when strain is applied to that region. The following tables show the composite scores that should appear based on brain strain form iMGs. This data will be analyzed using the same four strain data parameters from the linger regression slope data, MPS95 average, MPS95 average>0.14, top 100 elements average, and maximum strain element. These tables will show if the iMGs' data produces the same composites scores with dysfunction as research has proven. The slopes of the linear regression models will be listened in column two in ascending order (negative to positive). Any Composite variable that should show dysfunction by the brain strain values will be highlighted in green, any composite variable that that should show dysfunction by brain strain values but had a positive slope will be highlighted in orange and will be considered insignificant, and any composite variable that was not expected to have dysfunction will be white.

4.2.1. *Basil Ganglia*

Table 82 presents anticipated composite results linked to potential damage to the basal ganglia (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 20%, Average MPS95>0.14 parameter predicted 40%, Average Top 100 MPS95 parameter predicted 20%, and Maximum element MPS95 parameter predicted 60% of the composite parameters.

Basal Ganglia					
Average MPS95 (Functional Regions)			Average MPS95 > 0.14 (Anatomical Regions)		
	Basal_Ganglia_Expected	Basal_Ganglia_Slope		Basal_Ganglia_Expected	Basal_Ganglia_Slope
1	'Reaction Time Composite %'	'Impulse Control Composite'	1	'Reaction Time Composite %'	'Impulse Control Composite'
2	'Visual Motor Speed Composite %	'Memory Composite (Verbal)'	2	'Visual Motor Speed Composite %'	'Memory Composite (Verbal) %'
3	'Impulse Control Composite'	'Visual Motor Speed Composite'	3	'Impulse Control Composite'	'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Reaction Time Composite'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Memory Composite (Verbal) %'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Regions)			Max MPS95 (Anatomical Regions)		
	Basal_Ganglia_Expected	Basal_Ganglia_Slope		Basal_Ganglia_Expected	Basal_Ganglia_Slope
1	'Reaction Time Composite %'	'Impulse Control Composite'	1	'Reaction Time Composite %'	'Memory Composite (Verbal) %'
2	'Visual Motor Speed Composite %	'Memory Composite (Visual)'	2	'Visual Motor Speed Composite %'	'Reaction Time Composite'
3	'Impulse Control Composite'	'Reaction Time Composite'	3	'Impulse Control Composite'	'Reaction Time Composite %'
		'Memory Composite (Verbal)'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Visual)'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal)'
		'Reaction Time Composite %'			'Impulse Control Composite'
		'Memory Composite (Visual) %'			'Visual Motor Speed Composite %'
		'Visual Motor Speed Composite %'			'Memory Composite (Visual) %'

Table 82: Expected Brain Composite Scores Basal Ganglia for All Strain Variables

4.2.2. *Thalamus*

Table 83 presents anticipated composite results linked to potential damage to the Thalamus (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 0%, Average MPS95>0.14 parameter predicted 0%, Average Top 100 MPS95 parameter predicted 0%, and Maximum element MPS95 parameter predicted 50% of the composite parameters.

Thalamus

Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Thalamus_Expected	Thalamus_Slope		Thalamus_Expected	Thalamus_Slope
1	'Memory Composite (Verbal)'	'Impulse Control Composite'	1	'Memory Composite (Verbal)'	'Impulse Control Composite'
2	'Memory Composite (Visual)'	'Memory Composite (Verbal)'	2	'Memory Composite (Visual)'	'Memory Composite (Verbal)'
3	''	'Memory Composite (Visual)'	3	''	'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Visual)'
		'Reaction Time Composite'			'Reaction Time Composite'
		'Memory Composite (Verbal) %'			'Memory Composite (Visual) %'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Verbal) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Thalamus_Expected	Thalamus_Slope		Thalamus_Expected	Thalamus_Slope
1	'Memory Composite (Verbal)'	'Impulse Control Composite'	1	'Memory Composite (Verbal)'	'Memory Composite (Visual) %'
2	'Memory Composite (Visual)'	'Memory Composite (Verbal)'	2	'Memory Composite (Visual)'	'Impulse Control Composite'
3	''	'Memory Composite (Visual)'	3	''	'Memory Composite (Visual)'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Reaction Time Composite'
		'Reaction Time Composite %'			'Memory Composite (Verbal) %'
		'Memory Composite (Verbal) %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 83: Expected Brain Composite Scores Thalamus for All Strain Variables

4.2.3. *Hippocampus*

Table 84 presents anticipated composite results linked to potential damage to the Hippocampus (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 0%, Average MPS95>0.14 parameter predicted 16.67%, Average Top 100 MPS95 parameter predicted 66.67%, and Maximum element MPS95 parameter predicted 83.33% of the composite parameters.

Hippocampus					
Average MPS95 (Anatomical Region)			**Average MPS95 > 0.14 (Anatomical Region)**		
	Hippocampus_Expected	Hippocampus_Slope		Hippocampus_Expected	Hippocampus_Slope
1	'Memory Composite (Verbal)'	'Reaction Time Composite'	1	'Memory Composite (Verbal)'	'Impulse Control Composite'
2	'Visual Motor Speed Composite'	'Impulse Control Composite'	2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'
3	'Memory Composite (Visual)'	'Memory Composite (Visual)'	3	'Memory Composite (Visual)'	'Memory Composite (Verbal)'
		'Memory Composite (Verbal) %'			'Reaction Time Composite'
		'Memory Composite (Verbal)'			'Memory Composite (Visual)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Region)			**Max MPS95 (Anatomical Region)**		
	Hippocampus_Expected	Hippocampus_Slope		Hippocampus_Expected	Hippocampus_Slope
1	'Memory Composite (Verbal)'	'Memory Composite (Verbal) %'	1	'Memory Composite (Verbal)'	'Memory Composite (Visual) %'
2	'Visual Motor Speed Composite'	'Memory Composite (Visual)'	2	'Visual Motor Speed Composite'	'Memory Composite (Visual)'
3	'Memory Composite (Visual)'	'Reaction Time Composite'	3	'Memory Composite (Visual)'	'Memory Composite (Verbal) %'
		'Memory Composite (Visual) %'			'Reaction Time Composite'
		'Impulse Control Composite'			'Reaction Time Composite %'
		'Memory Composite (Verbal)'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal)'
		'Reaction Time Composite %'			'Impulse Control Composite'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 84:Expected Brain Composite Scores Hippocampus for All Strain Variables

4.2.4. *Ventricles*

Table 85 presents anticipated composite results linked to potential damage to the Ventricles (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 100%, Average MPS95>0.14 parameter predicted 100%, Average Top 100 MPS95 parameter predicted 100%, and Maximum element MPS95 parameter predicted 80% of the composite parameters.

Ventricles					
Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Ventricles_Expected	Ventricles_Slope		Ventricles_Expected	Ventricles_Slope
1	'Impulse Control Composite'	'Memory Composite (Visual) %'	1	'Impulse Control Composite'	'Impulse Control Composite'
2	'Reaction Time Composite'	'Impulse Control Composite'	2	'Reaction Time Composite'	'Memory Composite (Visual) %'
3	'Memory Composite (Visual)'	'Memory Composite (Verbal) %'	3	'Memory Composite (Visual)'	'Memory Composite (Verbal) %'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Reaction Time Composite'			'Reaction Time Composite'
		'Memory Composite (Verbal)'			'Memory Composite (Verbal)'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Ventricles_Expected	Ventricles_Slope		Ventricles_Expected	Ventricles_Slope
1	'Impulse Control Composite'	'Memory Composite (Visual) %'	1	'Impulse Control Composite'	'Memory Composite (Visual) %'
2	'Reaction Time Composite'	'Impulse Control Composite'	2	'Reaction Time Composite'	'Impulse Control Composite'
3	'Memory Composite (Visual)'	'Memory Composite (Visual)'	3	'Memory Composite (Visual)'	'Memory Composite (Visual)'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal) %'
		'Reaction Time Composite'			'Reaction Time Composite'
		'Reaction Time Composite %'			'Memory Composite (Verbal)'
		'Memory Composite (Verbal)'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 85: Expected Brain Composite Scores Ventricles for All Strain Variables

4.2.5. *Corpus Collosum*

Table 86 presents anticipated composite results linked to potential damage to the Corpus Collosum (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 20%, Average MPS95>0.14 parameter predicted 20%, Average Top 100 MPS95 parameter predicted 20%, and Maximum element MPS95 parameter predicted 40% of the composite parameters.

Corpus Collosum					
Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Corpus_Collosum_Expected	Corpus_Collosum_Slope		Corpus_Collosum_Expected	Corpus_Collosum_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Impulse Control Composite'
2	'Visual Motor Speed Composi	'Reaction Time Composite'	2	'Visual Motor Speed Composit	'Reaction Time Composite'
3	'Impulse Control Composite'	'Memory Composite (Verbal)'	3	'Impulse Control Composite'	'Memory Composite (Verbal)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Corpus_Collosum_Expected	Corpus_Collosum_Slope		Corpus_Collosum_Expected	Corpus_Collosum_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Memory Composite (Visual) %'
2	'Visual Motor Speed Composi	'Reaction Time Composite'	2	'Visual Motor Speed Composit	'Memory Composite (Visual)'
3	'Impulse Control Composite'	'Memory Composite (Verbal)'	3	'Impulse Control Composite'	'Reaction Time Composite %'
		'Reaction Time Composite %'			'Reaction Time Composite'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual)'			'Memory Composite (Verbal)'
		'Memory Composite (Verbal) %'			'Impulse Control Composite'
		'Memory Composite (Visual) %'			'Memory Composite (Verbal) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 86: Expected Brain Composite Scores Corpus Collosum for All Strain Variables

4.2.6. *Brainstem*

Table 87 and Table 88 presents anticipated composite results linked to potential damage to the Brainstem (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. The brainstem is a region of the anatomical and functional regions; therefore, two tables are presented for each. As mentioned in Chapter 3.5.3, the anatomical and functional regions are broken down by different element IDs in the FE model, therefore, will produce slightly different results. For the composite parameters anticipated to be observed, the predictive performance varied across the different anatomical strain parameters.

Anatomical prediction for the brainstem is as follows: Average MPS95 parameter predicted 60%, Average MPS95>0.14 parameter predicted 40%, Average Top 100 MPS95 parameter predicted 40%, and Maximum element MPS95 parameter predicted 40% of the composite parameters. Functional prediction for the brainstem is as follows: Average MPS95 parameter predicted 20%, Average MPS95>0.14 parameter predicted 20%, Average Top 100 MPS95 parameter predicted 20%, and Maximum element MPS95 parameter predicted 20% of the composite parameters.

Brainstem (Anatomical)					
Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Brainstem_Expected	Brainstem_Slope		Brainstem_Expected	Brainstem_Slope
1	'Reaction Time Composite'	'Impulse Control Composite'	1	'Reaction Time Composite'	'Impulse Control Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'
3	'Impulse Control Composite'	'Memory Composite (Verbal)'	3	'Impulse Control Composite'	'Memory Composite (Verbal)'
		'Memory Composite (Visual)'			'Reaction Time Composite'
		'Reaction Time Composite'			'Memory Composite (Visual)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Brainstem_Expected	Brainstem_Slope		Brainstem_Expected	Brainstem_Slope
1	'Reaction Time Composite'	'Memory Composite (Verbal) %'	1	'Reaction Time Composite'	'Memory Composite (Verbal) %'
2	'Visual Motor Speed Composite'	'Impulse Control Composite'	2	'Visual Motor Speed Composite'	'Reaction Time Composite'
3	'Impulse Control Composite'	'Reaction Time Composite'	3	'Impulse Control Composite'	'Impulse Control Composite'
		'Memory Composite (Verbal)'			'Memory Composite (Verbal)'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 87: Expected Brain Composite Scores Brainstem for All Strain Variables (Anatomical)

Brainstem (Functional)					
Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Brainstem_Expected	Brainstem_Slope		Brainstem_Expected	Brainstem_Slope
1	'Reaction Time Composite'	'Impulse Control Composite'	1	'Reaction Time Composite'	'Reaction Time Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	2	'Visual Motor Speed Composite'	'Impulse Control Composite'
3	'Impulse Control Composite'	'Memory Composite (Visual)'	3	'Impulse Control Composite'	'Memory Composite (Verbal)'
		'Memory Composite (Verbal)'			'Visual Motor Speed Composite'
		'Reaction Time Composite'			'Memory Composite (Visual)'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Brainstem_Expected	Brainstem_Slope		Brainstem_Expected	Brainstem_Slope
1	'Reaction Time Composite'	'Impulse Control Composite'	1	'Reaction Time Composite'	'Impulse Control Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'	2	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'
3	'Impulse Control Composite'	'Reaction Time Composite'	3	'Impulse Control Composite'	'Reaction Time Composite'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Verbal) %'			'Memory Composite (Visual)'
		'Memory Composite (Visual)'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 88: Expected Brain Composite Scores Brainstem for All Strain Variables (Functional)

4.2.7. *Cerebellum*

Table 89 and Table 90 presents anticipated composite results linked to potential damage to the Cerebellum (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. The cerebellum is a region of the anatomical and functional regions; therefore, two tables are presented for each. As mentioned in Chapter 3.5.3, the anatomical and functional regions are broken down by different element IDs in the FE model, therefore, will produce slightly different results. For the composite parameters anticipated to be observed, the predictive performance varied across the different anatomical strain parameters.

Anatomical prediction for the cerebellum is as follows: Average MPS95 parameter predicted 100%, Average MPS95>0.14 parameter predicted 33.33%, Average Top 100 MPS95 parameter predicted 100%, and Maximum element MPS95 parameter predicted 100% of the composite parameters. Functional prediction for the cerebellum is as follows: Average MPS95 parameter predicted 100%, Average MPS95>0.14 parameter predicted 66.67%, Average Top 100 MPS95 parameter predicted 100%, and Maximum element MPS95 parameter predicted 66.67% of the composite parameters.

Cerebellum (Anatomical)					
Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Cerebellum_Expected	Cerebellum_Slope		Cerebellum_Expected	Cerebellum_Slope
1	'Reaction Time Composite'	'Visual Motor Speed Composite %'	1	'Reaction Time Composite'	'Visual Motor Speed Composite %'
2	'Impulse Control Composite'	'Reaction Time Composite %'	2	'Impulse Control Composite'	'Reaction Time Composite %'
3	''	'Reaction Time Composite'	3	''	'Memory Composite (Verbal) %'
		'Memory Composite (Verbal) %'			'Reaction Time Composite'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Impulse Control Composite'			'Memory Composite (Verbal)'
		'Memory Composite (Verbal)'			'Impulse Control Composite'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Cerebellum_Expected	Cerebellum_Slope		Cerebellum_Expected	Cerebellum_Slope
1	'Reaction Time Composite'	'Visual Motor Speed Composite %'	1	'Reaction Time Composite'	'Visual Motor Speed Composite %'
2	'Impulse Control Composite'	'Memory Composite (Verbal) %'	2	'Impulse Control Composite'	'Reaction Time Composite %'
3	''	'Reaction Time Composite %'	3	''	'Reaction Time Composite'
		'Impulse Control Composite'			'Visual Motor Speed Composite'
		'Reaction Time Composite'			'Memory Composite (Verbal) %'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal)'
		'Memory Composite (Verbal)'			'Impulse Control Composite'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'

Table 89: Expected Brain Composite Scores Cerebellum for All Strain Variables (Anatomical)

Cerebellum (Functional)					
Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Cerebellum_Expected	Cerebellum_Slope		Cerebellum_Expected	Cerebellum_Slope
1	'Reaction Time Composite'	'Impulse Control Composite'	1	'Reaction Time Composite'	'Reaction Time Composite'
2	'Impulse Control Composite'	'Memory Composite (Verbal)'	2	'Impulse Control Composite'	'Visual Motor Speed Composite'
3	[]	'Visual Motor Speed Composite'	3	[]	'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Memory Composite (Visual)'
		'Memory Composite (Visual)'			Impulse Control Composite'
		'Memory Composite (Verbal) %'			'Reaction Time Composite %'
		'Reaction Time Composite %'			'Memory Composite (Visual) %'
		'Memory Composite (Visual) %'			'Memory Composite (Verbal) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Cerebellum_Expected	Cerebellum_Slope		Cerebellum_Expected	Cerebellum_Slope
1	'Reaction Time Composite'	'Impulse Control Composite'	1	'Reaction Time Composite'	'Impulse Control Composite'
2	'Impulse Control Composite'	'Memory Composite (Verbal)'	2	'Impulse Control Composite'	'Reaction Time Composite'
3	[]	'Reaction Time Composite'	3	[]	'Memory Composite (Verbal)'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Memory Composite (Verbal) %'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 90: Expected Brain Composite Scores Cerebellum for All Strain Variables (Functional)

4.2.8. *Cerebral Hemispheres*

Table 91 presents anticipated composite results linked to potential damage to the Cerebral Hemispheres (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 100%, Average MPS95>0.14 parameter predicted 0%, Average Top 100 MPS95 parameter predicted 0%, and Maximum element MPS95 parameter predicted 16.67% of the composite parameters.

Cerebral Hemispheres					
Average MPS95 (Anatomical Region)			Average MPS95 > 0.14 (Anatomical Region)		
	Cerebral_Hemispheres_Expected	Cerebral_Hemispheres_Slope		Cerebral_Hemispheres_Expected	Cerebral_Hemispheres_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Impulse Control Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'	2	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'
3	'Reaction Time Composite'	'Reaction Time Composite'	3	'Reaction Time Composite'	'Reaction Time Composite'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Anatomical Region)			Max MPS95 (Anatomical Region)		
	Cerebral_Hemispheres_Expected	Cerebral_Hemispheres_Slope		Cerebral_Hemispheres_Expected	Cerebral_Hemispheres_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Reaction Time Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	2	'Visual Motor Speed Composite'	'Impulse Control Composite'
3	'Reaction Time Composite'	'Memory Composite (Verbal)'	3	'Reaction Time Composite'	'Memory Composite (Verbal) %'
		'Reaction Time Composite'			'Memory Composite (Verbal)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 91: Expected Brain Composite Scores Cerebral Hemispheres for All Strain Variables

4.2.9. *Frontal Lobe*

Table 92 presents anticipated composite results linked to potential damage to the Frontal Lobe (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 33.33%, Average MPS95>0.14 parameter predicted 16.67%, Average Top 100 MPS95 parameter predicted 33.33%, and Maximum element MPS95 parameter predicted 100% of the composite parameters.

Frontal Lobe					
Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Frontal_Lobe_Expected	Frontal_Lobe_Slope		Frontal_Lobe_Expected	Frontal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Impulse Control Composite'	1	'Visual Motor Speed Composite'	'Reaction Time Composite'
2	'Memory Composite (Verbal)'	'Memory Composite (Verbal) %'	2	'Memory Composite (Verbal)'	'Impulse Control Composite'
3	'Reaction Time Composite'	'Reaction Time Composite'	3	'Reaction Time Composite'	'Memory Composite (Verbal)'
		'Memory Composite (Verbal)'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Visual)'
		'Memory Composite (Visual)'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Frontal_Lobe_Expected	Frontal_Lobe_Slope		Frontal_Lobe_Expected	Frontal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Impulse Control Composite'	1	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'
2	'Memory Composite (Verbal)'	'Reaction Time Composite'	2	'Memory Composite (Verbal)'	'Reaction Time Composite'
3	'Reaction Time Composite'	'Memory Composite (Verbal) %'	3	'Reaction Time Composite'	'Visual Motor Speed Composite %'
		'Memory Composite (Verbal)'			'Reaction Time Composite %'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Visual)'			'Memory Composite (Verbal)'
		'Reaction Time Composite %'			'Memory Composite (Visual)'
		'Memory Composite (Visual) %'			'Impulse Control Composite'
		'Visual Motor Speed Composite %'			'Memory Composite (Visual) %'

Table 92: Expected Brain Composite Scores Frontal Lobe for All Strain Variables

4.2.10. *Temporal Lobe*

Table 93 presents anticipated composite results linked to potential damage to the Temporal Lobe (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 0%, Average MPS95>0.14 parameter predicted 16.67%, Average Top 100 MPS95 parameter predicted 50%, and Maximum element MPS95 parameter predicted 50% of the composite parameters.

Temporal Lobe					
Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Temporal_Lobe_Expected	Temporal_Lobe_Slope		Temporal_Lobe_Expected	Frontal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Impulse Control Composite'	1	'Visual Motor Speed Composite'	'Reaction Time Composite'
2	'Memory Composite (Verbal)'	'Memory Composite (Verbal)'	2	'Memory Composite (Verbal)'	'Impulse Control Composite'
3	'Reaction Time Composite'	'Reaction Time Composite'	3	'Reaction Time Composite'	'Memory Composite (Verbal)'
		'Visual Motor Speed Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Verbal) %'			'Memory Composite (Visual)'
		'Memory Composite (Visual)'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Temporal_Lobe_Expected	Temporal_Lobe_Slope		Temporal_Lobe_Expected	Temporal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	1	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'
2	'Memory Composite (Verbal)'	'Visual Motor Speed Composite'	2	'Memory Composite (Verbal)'	'Reaction Time Composite'
3	'Reaction Time Composite'	'Reaction Time Composite'	3	'Reaction Time Composite'	'Impulse Control Composite'
		'Impulse Control Composite'			'Visual Motor Speed Composite'
		'Memory Composite (Verbal)'			'Memory Composite (Verbal)'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Memory Composite (Visual)'			'Visual Motor Speed Composite %'
		'Visual Motor Speed Composite %'			'Memory Composite (Visual)'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'

Table 93: Expected Brain Composite Scores Temporal Lobe for All Strain Variables

4.2.11. *Parietal Lobe*

Table 94 presents anticipated composite results linked to potential damage to the Parietal Lobe (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 0%, Average MPS95>0.14 parameter predicted 0%, Average Top 100 MPS95 parameter predicted 33.33%, and Maximum element MPS95 parameter predicted 66.67% of the composite parameters.

Parietal Lobe					
Average MPS95 (Functional Region)			**Average MPS95 > 0.14 (Functional Region)**		
	Parietal_Lobe_Expected	Parietal_Lobe_Slope		Parietal_Lobe_Expected	Parietal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Impulse Control Composite'	1	'Visual Motor Speed Composite'	'Visual Motor Speed Composite'
2	'Impulse Control Composite'	'Visual Motor Speed Composite'	2	'Impulse Control Composite'	'Reaction Time Composite'
3	'Reaction Time Composite'	'Memory Composite (Verbal)'	3	'Reaction Time Composite'	'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Impulse Control Composite'
		'Memory Composite (Verbal) %'			'Reaction Time Composite %'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Reaction Time Composite %'			'Memory Composite (Verbal) %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'
Top 100 Average MPS95 (Functional Region)			**Max MPS95 (Functional Region)**		
	Parietal_Lobe_Expected	Parietal_Lobe_Slope		Parietal_Lobe_Expected	Parietal_Lobe_Slope
1	'Visual Motor Speed Composite'	'Impulse Control Composite'	1	'Visual Motor Speed Composite'	'Impulse Control Composite'
2	'Impulse Control Composite'	'Memory Composite (Verbal)'	2	'Impulse Control Composite'	'Memory Composite (Verbal)'
3	'Reaction Time Composite'	'Visual Motor Speed Composite'	3	'Reaction Time Composite'	'Reaction Time Composite'
		'Memory Composite (Verbal) %'			'Visual Motor Speed Composite'
		'Reaction Time Composite'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual)'			'Memory Composite (Visual)'
		'Reaction Time Composite %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'
		'Memory Composite (Visual) %'			'Memory Composite (Visual) %'

Table 94: Expected Brain Composite Scores Parietal Lobe for All Strain Variables

4.2.12. *Occipital Lobe*

Table 95 presents anticipated composite results linked to potential damage to the Occipital Lobe (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 20%, Average MPS95>0.14 parameter predicted 0%, Average Top 100 MPS95 parameter predicted 20%, and Maximum element MPS95 parameter predicted 60% of the composite parameters.

Occipital Lobe					
Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Occipital_Lobe_Expected	Occipital_Lobe_Slope		Occipital_Lobe_Expected	Occipital_Lobe_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Reaction Time Composite'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	2	'Visual Motor Speed Composite'	'Visual Motor Speed Composite'
3	'Impulse Control Composite'	'Memory Composite (Verbal)'	3	'Impulse Control Composite'	'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Impulse Control Composite'
		'Memory Composite (Visual)'			'Reaction Time Composite %'
		'Visual Motor Speed Composite'			'Memory Composite (Visual)'
		'Reaction Time Composite %'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual) %'			'Visual Motor Speed Composite %'
		'Visual Motor Speed Composite %'			'Memory Composite (Visual) %'
Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Occipital_Lobe_Expected	Occipital_Lobe_Slope		Occipital_Lobe_Expected	Occipital_Lobe_Slope
1	'Memory Composite (Visual)'	'Impulse Control Composite'	1	'Memory Composite (Visual)'	'Memory Composite (Visual) %'
2	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'	2	'Visual Motor Speed Composite'	'Memory Composite (Visual)'
3	'Impulse Control Composite'	'Reaction Time Composite'	3	'Impulse Control Composite'	'Reaction Time Composite %'
		'Visual Motor Speed Composite'			'Impulse Control Composite'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal) %'
		'Memory Composite (Visual)'			'Reaction Time Composite'
		'Reaction Time Composite %'			'Memory Composite (Verbal)'
		'Memory Composite (Visual) %'			'Visual Motor Speed Composite'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 95: Expected Brain Composite Scores Occipital Lobe for All Strain Variables

4.2.13. *Motor and Sensory Cortex*

Table 96 presents anticipated composite results linked to potential damage to the Motor and Sensory Cortex (column one) alongside ascending slope values derived from linear regression models for each composite variable based on four distinct strain parameters. For the composite parameters anticipated to be observed, the predictive performance varied across the different strain parameters: Average MPS95 parameter predicted 0%, Average MPS95>0.14 parameter predicted 33.33%, Average Top 100 MPS95 parameter predicted 0%, and Maximum element MPS95 parameter predicted 16.67% of the composite parameters.

Motor and Sensory Cortex

Average MPS95 (Functional Region)			Average MPS95 > 0.14 (Functional Region)		
	Motor_Sensory_Cortex_Expected	Motor_Sensory_Cortex_Slope		Motor_Sensory_Cortex_Expected	Motor_Sensory_Cortex_Slope
1	'Memory Composite (Verbal)'	'Impulse Control Composite'	1	'Memory Composite (Verbal)'	'Visual Motor Speed Composite'
2	'Reaction Time Composite'	'Memory Composite (Verbal)'	2	'Reaction Time Composite'	'Reaction Time Composite'
3	'Visual Motor Speed Composite'	'Visual Motor Speed Composite'	3	'Visual Motor Speed Composite'	'Memory Composite (Verbal)'
		'Reaction Time Composite'			'Visual Motor Speed Composite %'
		'Memory Composite (Visual)'			'Reaction Time Composite %'
		'Memory Composite (Verbal) %'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Impulse Control Composite'
		'Memory Composite (Visual) %'			'Memory Composite (Visual)'
		'Visual Motor Speed Composite %'			'Memory Composite (Visual) %'

Top 100 Average MPS95 (Functional Region)			Max MPS95 (Functional Region)		
	Motor_Sensory_Cortex_Expected	Motor_Sensory_Cortex_Slope		Motor_Sensory_Cortex_Expected	Motor_Sensory_Cortex_Slope
1	'Memory Composite (Verbal)'	'Impulse Control Composite'	1	'Memory Composite (Verbal)'	'Memory Composite (Visual) %'
2	'Reaction Time Composite'	'Memory Composite (Verbal)'	2	'Reaction Time Composite'	'Impulse Control Composite'
3	'Visual Motor Speed Composite'	'Memory Composite (Verbal) %'	3	'Visual Motor Speed Composite'	'Memory Composite (Visual)'
		'Reaction Time Composite'			'Reaction Time Composite'
		'Visual Motor Speed Composite'			'Memory Composite (Verbal)'
		'Memory Composite (Visual)'			'Memory Composite (Verbal) %'
		'Reaction Time Composite %'			'Visual Motor Speed Composite'
		'Memory Composite (Visual) %'			'Reaction Time Composite %'
		'Visual Motor Speed Composite %'			'Visual Motor Speed Composite %'

Table 96: Expected Brain Composite Scores Motor and Sensory Cortex for All Strain Variables

4.3. Prediction Results

Prediction values were computed for each brain region and strain variable to assess their predictive capabilities regarding expected composite scores. This evaluation involves determining the extent to which a brain region, based on the strain variable, accurately predicts the anticipated composite scores outlined in column one of the tables in Section 4.2. The prediction percentage quantifies the percentage of composite scores observed to have a negative correlation, as depicted in column two of Section 4.2. This metric provides insight into the proportion of composite scores predicted by linear regression slopes. PdV determines if the predicted composite scores are amongst the highest slope values. If a brain region has a high PP value but a low PdV, the brain region has predicted cognitive parameters expected but there are other parameters that slopes prove to be more substantially related.

Prediciton Results (PP) (Percetage)	Average MPS95	Average MPS95 > 0.14	Average MPS95 Top 100	Maximum Element MPS95	Averages Brain Area
Anatomical Areas					
Basal Ganglia	20.00%	40.00%	20.00%	60.00%	35.00%
Thalamus	0.00%	0.00%	0.00%	50.00%	12.50%
Hippocampus	0.00%	16.67%	66.67%	83.33%	41.67%
Ventricles	100.00%	100.00%	100.00%	80.00%	95.00%
Corpus Collosum	20.00%	20.00%	20.00%	40.00%	25.00%
Brainstem	60.00%	40.00%	40.00%	40.00%	45.00%
Cerebellum	100.00%	66.67%	100.00%	66.67%	83.33%
Cerebral Hemispheres	100.00%	0.00%	0.00%	16.67%	29.17%
Average Strain Varible (Ana)	50.00%	35.42%	43.33%	54.58%	45.83%
Functional Areas					
Frontal Lobe	33.33%	16.67%	33.33%	100.00%	45.83%
Temporal Lobe	0.00%	16.67%	50.00%	50.00%	29.17%
Parietal Lobe	0.00%	0.00%	33.33%	16.67%	12.50%
Occipital Lobe	20.00%	0.00%	20.00%	60.00%	25.00%
Motor Sensory Cortex	0.00%	33.33%	0.00%	16.67%	12.50%
Cerebellum	33.33%	0.00%	33.33%	33.33%	25.00%
Brainstem	20.00%	20.00%	20.00%	20.00%	20.00%
Averages Strain Variable(Fun)	15.24%	12.38%	27.14%	42.38%	24.29%
Averages Strain Variable	33.78%	24.67%	35.78%	48.89%	

Figure 102: Prediction Percentage (PP)

Prediciton Values (PdV)				PdV = PP*Sum(ranked slopes)	
	Average MPS95	Average MPS95 > 0.14	Average MPS95 Top 100	Maximum Element MPS95	Averages Brain Area
Anatomical Areas					
Basal Ganglia	1.80	6.00	1.80	12.60	5.55
Thalamus	0.00	0.00	0.00	8.00	2.00
Hippocampus	0.00	1.33	18.00	25.83	11.29
Ventricles	31.00	33.00	33.00	16.80	28.45
Corpus Collosum	1.80	6.20	1.80	6.80	4.15
Brainstem	10.80	6.00	6.00	6.00	7.20
Cerebellum	19.00	9.33	18.00	10.00	14.08
Cerebral Hemispheres	23.00	0.00	0.00	1.50	6.13
Average Strain Varible	10.93	7.73	9.83	10.94	9.86
Functional Areas					
Frontal Lobe	5.00	1.50	3.00	39.00	12.13
Temporal Lobe	0.00	1.50	12.00	11.50	6.25
Parietal Lobe	0.00	0.00	4.67	1.50	1.54
Occipital Lobe	1.80	0.00	1.80	13.80	4.35
Motor Sensory Cortex	0.00	5.67	0.00	1.00	1.67
Cerebellum	3.00	0.00	3.00	3.00	2.25
Brainstem	1.80	1.80	1.80	1.80	1.80
Averages Strain Variable	1.66	1.50	3.75	10.23	4.28
Total Strain Averages	6.60	4.82	6.99	10.61	

Figure 103: Prediction Value (PdV)

CHAPTER 5: DISCUSSION

5.1. Participant Learning Factor

The cognitive function test, ImPACT, uses the same questions each time to evaluate the test taker's performance. Following the same format and pattern, retaking the ImPACT test multiple times in a season; presents an opportunity for players to learn and memorize testing processes and order. Thus, it is possible for a test taker to improve their scores simply by taking the test multiple times. Because the baseline test must be performed before post-impact tests there is no way to eliminate learning effects from the study. These learning effects were observed mostly in reaction time and visual motor speed during this study, especially in participants who undergo the test multiple times. Learning likely contributes to positive slopes in linear regression plots, particularly with player 3. This participant underwent the post-injury exam four times, affording ample opportunity to familiarize themselves with the test. Visual motor speed and reaction time analysis revealed substantial increases in composite scoring from baseline to the fourth post-impact test for player 3. Specifically, visual motor speed percentage exhibited a remarkable 153% increase, while visual motor speed composite showed a 15% increase. Similarly, reaction time percentage demonstrated a notable 93% increase, with reaction time composite indicating a 19% increase. Player 3 also experienced brain strain values exceeding 0.14 in brain regions associated with visual motor speed and reaction time throughout the season, eliminating the possibility of low strain in these particular brain areas and enhancing cognitive function. However, the study's design did not permit the elimination of this learning factor. ImPACT's unchanging order and presentation format encourage learning and pattern memorization when taken multiple times a season. One potential solution to address this issue in future studies could be to retest participants only once, after a 30G impact or at the end of the study period. This approach would mitigate the likelihood of participants becoming accustomed to or improving their performance on ImPACT test modules, and it would also provide a measure of the learning effect for participants who did not experience a severe head impact. However, implementing this solution would require a larger participant pool.

5.2. Correlation Brain Strain and Cognitive Function

This study aimed to determine if brain strain data collected from iMGs is correlated with cognitive function measured using ImPACT. Linear regression plots determined that only ten brain regions across the four strain parameters (Average MPS95, Average MPS95>0.14, Average Top 100, Maximum strain element) were able to predict a negative correlation between the regions of the brain affected by axonal strain and cognitive function at least 80% of the time. Of those eleven brain regions, only seven had a PdV value that indicated the predicted composite scores were among the highest correlated slopes. These seven cases only include four brain regions: ventricles, cerebellum, cerebral hemispheres, and frontal lobe. For the average MPS95, average MPS95>0.14, and top 100 average, the ventricles had a 100% accuracy for cognitive dysfunction forecasting as well as PdV values greater than 30, and for maximum element MPS95, the ventricles had 80% forecasting accuracy and a PdV value of 16.80.

Of the 15 possible brain regions, the ventricles and cerebellum had significantly higher correlated cognitive variables than any other brain region. The ventricles, on average, have a 66.79% more likelihood of predicting associated composite scores compared to all brain regions, and the cerebellum has a 61.14% more likelihood of predicting composite scores compared to all brain regions. The ventricles being among the top two brain regions that showed the most significant correlations and predictions was surprising. The ventricles had a 95% overall prediction score across the four strain parameters. Even though the ventricles themselves are not solely associated with cognitive function as a lobe would be, they serve as the cushion for the brain in addition to regulating the central nervous system. The cerebellum was expected to show heavy correlations as it is recognized as an associated center for higher cognitive function [54]. Something to be noted is the number of composite scores from ImPACT that were expected to be seen with damage to the cerebellum. Compared to the other brain regions, which had upwards of six expected cognitive variables, the cerebellum had only three. The prediction percentages will create a misconception of accuracy compared to the other brain regions, given that the cerebellum only had to predict three variables to have 100% accuracy. In comparison, the ventricles needed to predict five for 100% accuracy. Even though the cerebellum's prediction value was only 11.67% lower than the ventricles, the PdV number is 23% lower.

5.3. Strain Variables with Best Performance

In the early stages of research, it was hypothesized that the strain parameters would provide the most significant data in this order: (1) average MPS95>0.14, (2) average top 100 MPS95, (3) average MPS, (4) maximum element MPS95. Average MPS95>0.14 represents the whole brain area with only very low values of strain removed. Thus, this would give a better understanding of strain over the entire brain region without putting too much focus on high-strain elements. The average top 100 strain would focus primarily on high strain. However, taking the top 100 values still had enough elements to notice if there needed to be greater strain in a particular brain region. Average MPS95 was expected to give a low representation of strain in the brain regions because of the low-strain elements in an FE model. With ~77,000 elements in an FE model, if the majority of the brain areas did not show high strain, the average of a whole brain region would greatly diminish the strain shown by the MPS95 average. The maximum element MPS was considered an overestimate of strain since only one element of each brain region was evaluated in post-processing, skipping over all low strain values that occurred.

However, it was proved that the Maximum MPS95 had the greatest prediction capability with a PP value of 48.89%. The PP value of the Maximum MPS95 was 13.11% higher than the top 100 average (35.78%), 20.8% higher than the Average MPS95 (33.78%), and 24.22% higher than the average MPS95>0.14 (24.67%). It is believed that maximum MPS95 produces the greatest prediction capability because it focuses on damage rather than a holistic representation. Averaging in low-strain to high-strain values diminishes the effect of possible axonal damage done to the brain. Even though this does not represent the entire brain region, it emphasizes the elements with damage rather than focusing on elements with low damage. The other strain variables focus too much on what is not happening to the brain rather than what is; this provides reasoning for the results of the order of strain parameter PP values. The top 100 average would be the next highest strain parameter because it focuses on the brain the most. As for MPS95>0.14, which has the lowest prediction capabilities, removing lower strain values shifts the focus of the strain to higher values, but removing lower values reduces the data set's standard deviation. A data set with a lower range will create a lower probability of showing corrections [57]. The average MPS95 has a higher prediction percentage than MPS95>0.14 because considering all the extremely low strain values creates more variation in the data set.

Max MPS95 will overestimate strain over the entire region of the brain. Initially, there was concern regarding the potential for misinterpreting brain strain across various brain regions. This matter arose because many brain regions consist of over 5,000 elements. However, through the finite element analysis process, the strain experienced by a single element is represented by a hexahedron shape. A hexahedron is a 3D shape with six faces, ParaView uses a cube shaped hexahedron. A element of this nature has eight nodes connected to other elements, elements, and nodes. Strain is calculated for a single element by interpolating the displacement of nodes around the element. This interconnectedness implies that strain experienced by a single element will not underestimate strain around each element. Additionally, it is essential to recognize that mathematical models differ from experimental data spikes. Mathematical models utilize a combination of averages and arrays to estimate the values of elements, providing a more continuous representation of the system's behavior rather than discrete data points.

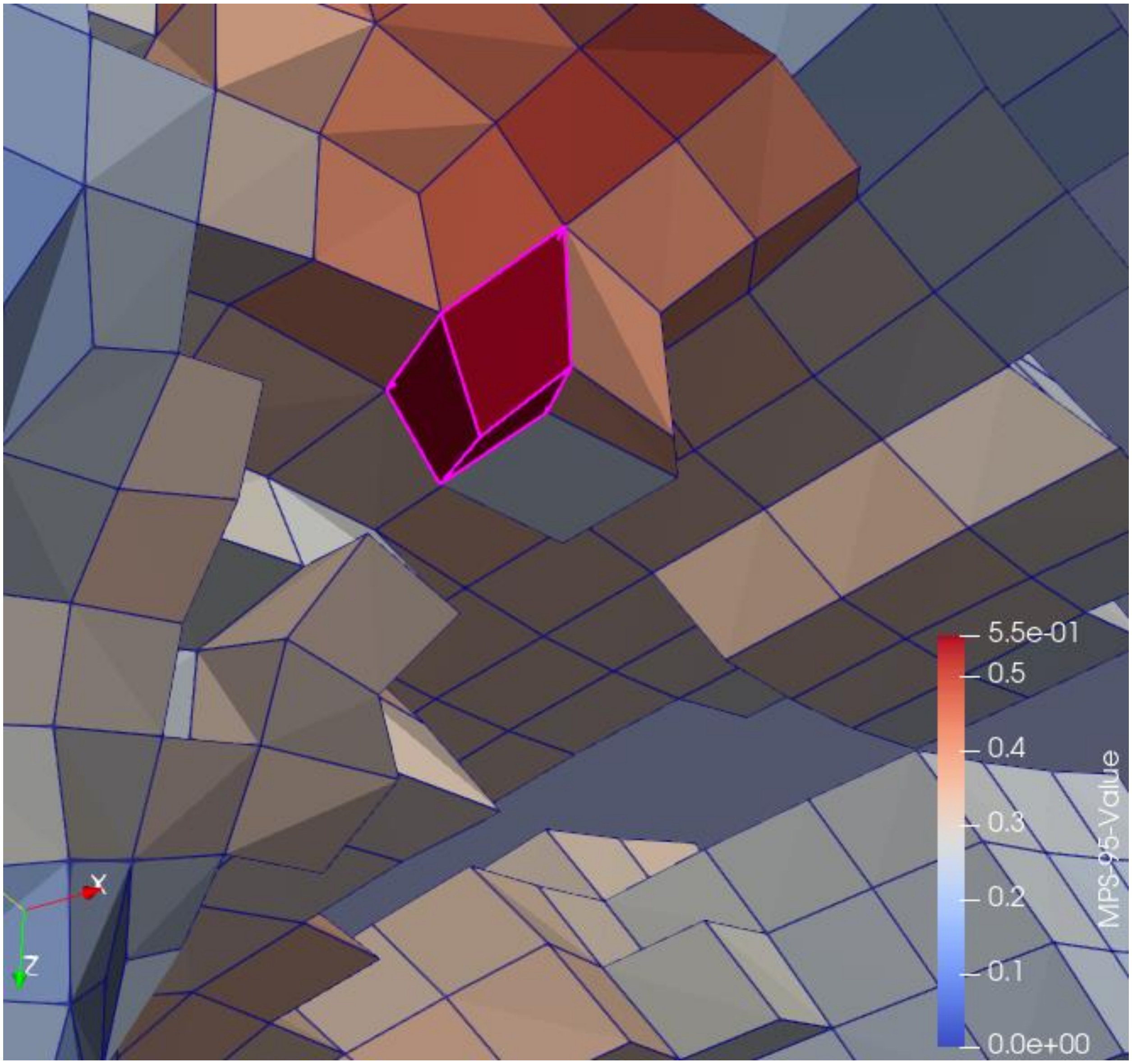

Figure 104: Hexahedron Element from ParaView

5.4. Functional vs Anatomical Brain regions

Between the functional regions and the anatomical brain regions, the functional regions were expected have a higher prediction percentage as well as prediction value in comparison to the anatomical regions. Functional regions focus more on regions of the brain that control function rather than anatomical location of the brain regions. For example, in the anatomical brain regions, the cerebral hemispheres are taken and analyzed as a whole, where in the functional brain regions, it is broken down into frontal, parietal, temporal, and occipital lobes. Thus, it was presumed that the functional brain regions would have a greater predictive power than anatomical brain regions. Looking at functional vs anatomical brain regions, functional regions were found to have a substantially lower prediction percentage and prediction variable (24.29% and 4.28) than the anatomical regions (45.83% and 9.86). Comparing the box and whisker plots for brain regions, the range of median strain from region to region is greater for anatomical brain regions than functional regions. With median values of strain in the box plots within a range of 0.05 for all functional brain regions, there is less variation in the independent variable (brain strain), thus causing the overall effect on the dependent variable (cognitive function) to decrease. The effect on the dependent variable decreasing causes the linear regression slope to flatten, making it more difficult for a plot to have a negative slope indicating cognitive dysfunction.

5.5. Mild Traumatic Brain Injury Detection

During the data collection period, no players in the study experienced a diagnosed TBI, although evidence to indicate the existence of mTBIs were relatively frequent. Unlike TBIs, which often manifest with observable physical, emotional, cognitive, and psychological symptoms, mTBIs may occur without obvious signs, making their detection challenging. MTBIs are small injures that can accumulate over time, where TBIs are often acute and noticeable. Nonetheless, mTBIs, while less severe, can still have enduring effects on brain health. Detecting and diagnosing mTBIs could significantly mitigate the long-term consequences of repetitive head impacts such as second impact syndrome, post concussive syndrome, and decreased risk of Chronic Traumatic Encephalopathy (CTE). Utilizing innovative methods and tools like iMGs and brain modeling, we discovered that despite the absence of high linear accelerations indicative of concussion likelihood (90Gs) [58], instances of brain strain impairing cognitive function were evident. Even impacts registering around 30Gs, which might not produce immediately noticeable symptoms, demonstrated the potential to influence cognitive function, as highlighted in the linear regression analyses presented in Chapter 4. The use of iMG-based brain modeling revealed that impacts as low as 30Gs could lead to cognitive dysfunction, signaling a possibility of mTBIs. Equipped with models and tools of this nature, trainers, coaches, and players could gain insight into the cumulative load placed on players brains throughout the season and their careers. This information could be used to protect players from possible long-term damage caused by multiple mTBIs. This knowledge could empower stakeholders to make informed decisions regarding player safety and well-being.

CHAPTER 6: CONCLUSION

Data collected at Western Carolina University during the 2023 Football season showed axonal brain strain in the ventricles and cerebellum were the best indicators of cognitive impairment. Of the four strain parameters maximum element MPS95 was more likely to predict cognitive dysfunction than the other strain parameters. In addition, impacts resulting in linear accelerations as low as 30Gs resulted in cognitive dysfunction in many of the post-impact cognitive tests. This value is well below the published value of 90Gs for TBIs. While the existence of mTBIs was not directly evaluated, the presence of cognitive dysfunction and the associated brain strain indicates that the possibility of an mTBI occurring is likely. This suggests that our research methods may be able to detect the existence of mild traumatic brain injury. Ultimately, these findings may provide coaches, trainers, and clinicians further knowledge to help mitigate TBIs/mTBIs in American football. Moreover, this study has contributed to the existing body of knowledge in brain strain and modeling by linking brain strain to cognitive function across 13 different brain regions.

Despite the achievements made, there are still areas for further exploration and investigation. Future research could delve deeper by expanding the quantity of participants. Including ten players in the study was a great starting point for acquiring initial findings, but this research has the potential for a much greater impact with more participants enrolled. Though many brain areas did not show as notable of findings as the ventricles and cerebellum; there are some brain areas with predictive qualities. The predictive capabilities of these brain areas could be further strengthened by future research and more participants. In addition, finding ways to alleviate learning effects associated with cognitive testing could improve the accuracy of post impact test results.

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