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Examining the Relationship Between White Matter Integrity, Cognitive Function, and Narrative Discourse in Military Personnel with Blast Traumatic Brain Injury

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Introduction

Blast Traumatic Brain Injuries (bTBI)

Among traumatic brain injury, blast injuries in particular are becoming increasingly common due to a multitude of factors. First, the number of troops serving in the military has increased in recent years due to military conflicts in Iraq and Afghanistan, resulting in a larger number of opportunities for combat related injury. Improvised explosive devices (IEDs), a common cause of injury in combat, are becoming more prevalent. Additionally, medical advances as well as more protective body armor are leading to a higher survival rate among soldiers who are victims of blast injuries (Magnuson, Leonessa, & Ling, 2012). This leads to soldiers who have returned home from war dealing with the repercussions of these often devastating injuries, many of which entail brain injuries. In fact, studies have found that between 47 and 53 percent of all IED-related injuries involve the head or neck (Taber, Warden, & Hurley, 2006), suggesting that large numbers of veterans may be suffering from traumatic brain injury (TBI) as a result of blast exposure. Additionally, the Defense and Veterans Brain Injury Center (DVBIC) reports that as many as 59 percent of an at-risk population of soldiers returning home and being seen at Walter Reed Medical Center suffered at least a mild traumatic brain injury (mTBI) while overseas (Taber, Warden, & Hurley, 2006).

Blast injuries secondary to explosions are multidimensional in nature and result in a series of potential opportunities for damage. Primary blast injuries refer to the effect of the wave-induced changes of atmospheric pressure that occur when an IED is detonated (Taber, Warden, & Hurley, 2006). This results in barotrauma, which occurs when energy is transferred between structures and leads to acceleration and deformation (Magnuson et al., 2012). Due to the presence of tissues that have different densities, there is distinct motion between the various tissues, leading to shearing and tearing. In addition, rotational-translational acceleration commonly occurs, which contributes to tissue shearing (Magnuson et al., 2012). This shearing, stretching, and tearing in the brain is known as diffuse axonal injury (DAI), and is one of the trademarks of closed head injuries (CHI), including blast injuries (Taber, Warden, & Hurley, 2006).

Injuries such as this are often difficult to visualize on traditional methods of imaging, such as CT scans and MRI. Through newer technology known as diffusion tensor imaging (DTI), these small lesions in white matter tracts are able to be visualized. As a result, we are able to show direct connections between areas of the brain, supporting the presence of functional connective networks, as well as detect subtle areas of damage to these white matter pathways. (Geva, Correia, & Warburton, 2011). Diffusion tensor imaging measures the amount of water diffusion in an area, and is highly sensitive to this microscopic motion (Geva et al., 2011). In healthy white matter tracts, bundles of axons restrict the movement of these molecules in a direction parallel to the direction of the axons. However, when damage has occurred, this movement is unrestricted and molecules are free to travel in various directions as opposed to a straight path along the axon. One specific measurement of interest related to this concept is called fractional anisotropy (FA), which refers to how similar diffusion is in all of the different directions. When movement is restricted as it is in healthy white matter tracts, the FA value approaches 1.0; in damaged tracts where movement is unrestricted, however, the value becomes lower and closer to 0 (Geva et al., 2011).

Hayes, Bigler, and Verfaellie (2016) conducted a review of the literature on white matter integrity in TBI in order to examine connectivity in TBI. Their findings overwhelmingly suggest that TBI is associated with decreased integrity of white matter pathways, leading them to define

TBI as a disorder of brain connectivity. Regardless of severity of injury, TBI is characterized by both acute and chronic white matter abnormalities involving loss of axonal integrity and myelination (Hayes et al., 2016). This damage leads to alterations in functional connectivity required for complex cognitive behaviors such as memory, executive functions, and language.

Regions of Interest

The **corpus callosum** is the largest collection of white matter fibers in the brain and may be particularly vulnerable to damage in those with TBI (Hayes et al., 2016). This C-shaped structure lies between the left and right cerebral hemispheres, allowing for interhemispheric communication. This structure is divided into four parts - the *splenium*, which is the most posterior portion of the corpus callosum, connects the occipital lobes; the *body*, also called the trunk, contains fibers that pass through the corona radiata and extend to the lateral surface of the hemispheres; the *genu*, which connects the medial and lateral surfaces of the frontal lobes; and the *rostrum*, which connects the orbital surfaces of the frontal lobes. Anatomically, the corpus callosum lies directly below the falx cerebri, a fold of the dura mater that extends into the longitudinal fissure dividing the two hemispheres of the brain. On either side of the structure, the cingulate gyrus runs adjacent to the body. Finally, the concave undersurface of the corpus callosum is attached to the fornix posteriorly. Given the large number of projections in this structure of the brain, a variety of cognitive deficits may result from TBI. Due to its connections with the frontal lobe as well as portions of the limbic system, executive functions and memory are two aspects of cognition which may be impaired as a result of TBI and consequent diffusion abnormalities in the corpus callosum.

Given the importance of the limbic system for memory, a number of limbic structures are of particular interest when looking at language abilities and narrative discourse in particular. The

fornix is also a C-shaped bundle of nerve fibers, lying directly inferior to the corpus callosum. The fibers of this structure originate in the hippocampus, and make up the crus of the fornix, composed of left and right portions. Moving anteriorly, these two projections come together at the midline and join to form the body. Given its connections with the hippocampus, the fornix is crucial for memory. Recent studies have shown that when damage occurs to the fornix, there are significant reductions in recall memory, indicating that this structure may be particularly important for recall of information versus recognition (Tsivilis et al., 2008).

Given its location and long shape, the **cingulum** is also particularly vulnerable to TBI. The cingulum makes up the white matter core of the cingulate gyrus, a portion of the cerebral cortex that lies immediately superior to the corpus callosum, running from the frontal lobe to the temporal lobe. The anterior portion of the cingulate gyrus is thought to be related to emotion (Bush, Luu, & Posner, 2000), while the posterior portion has several connections to the hippocampus and thus is implicated with memory function (Kozlovskiy, Vartanov, Nikonova, Pyasik, & Velichkovsky, 2012). A recent study has shown that damage to the left cingulum bundle in particular leads to decreased performance on delayed recall memory tasks (Wu et al., 2010), thus this region is of great interest when looking at discourse performance, which relies heavily on recall abilities.

The frontal lobe is responsible for a large number of executive functions, particularly in the area of the dorsolateral pre-frontal cortex. Several white matter tracts project to and throughout the frontal lobe and allow for communication, including the **anterior corona radiata** and the **uncinate fasciculus**. The corona radiata, of which the left and right portions are interconnected via the corpus callosum, originates in the internal capsule and extends throughout the cerebral hemispheres. The anterior portion in particular, given its location in the frontal lobe, is known to play a role in attentional control (Niogo et al., 2008). The uncinate fasciculus is a hook-shaped white matter bundle that links the limbic structures with the lower surfaces of the frontal lobe. Given its location between these two crucial regions, this region is of great interest when analyzing cognitive function and discourse. Finally, the **superior fronto-occipital fasciculus** is a long association tract that originates in the frontal lobe and travels posteriorly throughout the cortex, providing frontal regions with connections to numerous other parts of the brain. This white matter tract is thought to contribute to cognition (Schamahmann & Pandya, 2007), and given its extensive projections from the frontal lobe, it is of interest for its integration of both cognitive and language functions.

Communication Impairments Post-TBI

Following TBI, individuals may appear to have intact language skills. Although they may perform within normal limits on standardized language assessments, they commonly struggle with dimensions of pragmatics such as topic maintenance, providing appropriate amounts of information, achieving conversational synchrony, understanding humor, and adapting their conversational responses to the shared knowledge of their conversation partner (Rigon, Voss, Turkstra, Mutlu, & Duff, 2016). Language deficits are commonly thought to be due to damage in cortical areas within the left frontal and temporal lobes. However, given the number of diverse skills necessary for functional, effective communication, it follows that damage in other areas may also contribute to these deficits. Since TBI frequently results in diffuse axonal injury (i.e., widespread disruption in the white matter pathways that form connections between areas of the brain), lesions in a variety of brain areas, as well as these white matter tracts themselves, may lead to communication difficulties.

Deficits in communication are frequently apparent in discourse following TBI. Speakers with discourse impairments may be perceived by a listener as being off target, disorganized, or tangential (Coelho, 2007). In cases such as this, the impairment is not due to a linguistic deficit, but rather to cognitive impairments in areas such as memory and executive functions that are crucial to complex language formulation. Discourse may be measured through a story narrative, in which the speaker must retell a previously presented story. Analysis of the discourse is broken down into a variety of levels: microlinguistic measures refer to basic measures of productivity and grammatical complexity, such as T-units. Microstructure measures look at cohesion, and the speaker's ability to use cohesive ties to clearly refer to information within a sentence in their narrative. Macrostructural analyses include measures of coherence, which indicate thematic unity of a narrative, or the ability to relate meaning and content of an utterance to both the directly preceding utterance (local coherence), as well as the overall meaning of the story as a whole (global coherence) (Coelho, 2007). Finally, superstructural analysis refers to measurements such as story grammar, which relate to the organization of information throughout the story. By identifying the presence of key components of a story such as the initiating event, attempt, and direct consequence, as well as how often these elements are all present referred to as an episode, we are able to analyze the organization of the story as a whole. Measures that have been shown to be most sensitive for discriminating TBI and control participants are content and topic management. These deficits have the potential to disrupt conversational and narrative discourse, which can lead to decreased quality of life and difficulty with social reintegration, something that already may pose particular challenges for veterans post-deployment (Coelho, 2007).

Similar behavioral findings were noted in a study by Coelho and colleagues which examined discourse production following injury to the dorsolateral prefrontal cortex (DLPFC). The DLPFC, a functional region of the brain known for its involvement in executive functions, is a common area of damage in TBI. Due to the previously discussed importance of the frontal lobe in language function, damage to this area may lead to communication impairments. Previous studies have shown that adults with DLPFC lesions demonstrate difficulty with discourse, developing narratives that are disorganized, repetitious, and incomplete (Kaczmarek, 1984; Alexander, 2006). When presented with a storytelling task in the aforementioned study, individuals with damage to the DLPFC demonstrated a significant difference in measures of global coherence as well as completeness (Coelho et al., 2012). The difficulties indicate impairments associated with macrostructure, or the organization of longer units of language. Results of this study emphasize the role that memory plays in language, even when the retelling task was presented immediately following initial presentation.

In order to better characterize discourse production in individuals post-TBI, a 2011 study sought to develop a measure of "story goodness" (Lê, Coelho, Mozeiko, & Grafman, 2011). While story grammar is a common measure used in analyses of narratives, this description of organization alone has not proven to be a sufficient marker of a "good" story. For instance, an individual may produce an organized story in the sense that it includes the key elements of story grammar, however they may omit crucial components that are necessary to make the story complete. In order to combine these two factors, this measure of story goodness was created, in which organization (as determined by story grammar) and completeness (as determined by number of critical components included in the story) were examined together to quantify "story goodness" (Lê et al., 2011). Measures are plotted in a quadrant, with story grammar on one axis and story completeness on the other. It was found that these two elements were able to distinguish individuals with TBI from non-injured controls. The controls overwhelmingly clustered in quadrant 2 (indicating high organization and completeness) and the individuals with

TBI fell in the other three categories, indicating poor story grammar, poor completeness, or a combination of both. The two measures were moderately correlated, suggesting that a story can be strong in one area but lacking in the other (Lê et al., 2011). These results support the use of story goodness, which combines these two crucial measures, in differentiating TBI populations from non-injured, as well as to quantify performance on narrative tasks.

Examining the Relationship Between Communication Deficits Following TBI and DTI

While the majority of the literature has focused on establishing the relationship between TBI and communication impairments, Rigon and colleagues (2016) sought to determine the structural neural correlates of these deficits. In this study, forty-four individuals with chronic stage TBI, as well as their everyday communication partners, were surveyed on perceived communication problems; followed by DTI to assess white matter integrity. It was found that lower frontotemporal FA, indicative of damage to white matter tracts within and between these areas, was significantly correlated with communication difficulties as reported by partners. These findings highlight the importance of these connections for integrating a variety of skills that contribute to communication, including frontal lobe functions such as working memory, planning, and response inhibition (Rigon et al., 2016).

Present Study Aims

The present study aims to determine if narrative discourse and cognitive performance on measures of memory and executive functions can be predicted by white matter tract integrity in key pathways of the brain. Through the analysis of story goodness measures, cognitive measures, and DTI collected from military personnel who have suffered bTBI, we seek to examine the relationship between these factors. It is predicted that individuals who have disrupted white matter pathways, as evidenced by low FA values on DTI, will have decreased performance on cognitive tasks and narrative discourse.

Methods

Participants

Thirty-three military personnel diagnosed with TBI secondary to blast injury at Walter Reed National Military Medical Center in Bethesda, Maryland participated in this study. Twenty-four individuals were classified as having sustained mild injuries (classified as uncomplicated mTBI or equivocal mTBI) and 9 more severe injuries (complicated mTBI or moderate TBI). For the purposes of this study, uncomplicated mTBI is defined as loss of consciousness (LOC) lasting less than 30 minutes and/or post-traumatic amnesia (PTA) lasting less than 24 hours, combined with an absence of trauma-related intracranial abnormality. Those with equivocal mTBI have had alteration of consciousness not characterized by LOC or PTA. Complicated mTBI is defined as LOC lasting less than 30 minutes and/or PTA less than 24 hours, however with the presence of trauma-related intracranial abnormality. Finally, moderate TBI refers to injuries involving LOC 30 minutes to 24 hours and/or PTA 1-7 days with either the presence or absence of trauma-related intracranial abnormality.

Participants ranged in age from 19 to 50 with a mean age of 33, and included 31 males and 2 females. Levels of education ranged from 11 to 18 years, with a mean of 14.5 years.

Discourse Analysis Procedure

Participants were shown a wordless picture story - either Old McDonald had an Apartment House (Barrett, 1998) or Good Dog, Carl (Day, 1985). Stories were judged to be of comparable levels of complexity. Picture frames were presented on a computer screen. Upon completion, each participant was instructed to re-tell the story they had just watched. Each retelling was digitally recorded, and recordings were then transcribed verbatim. Transcriptions were segmented into T-units, which are defined as an independent clause plus any subordinate clauses associated with it (Hunt, 1970). T-units are thought to be superior to the sentence when analyzing language structure due to the fact that a sentence may be very long, however this may not capture the true complexity if it is merely a number of simple clauses tied together by conjunctions such as “and”. Thus, the T-unit aims to assess syntactic complexity through its more specific criteria.

Story grammar was assessed by calculating the number of T-units that contribute to episodic structure. Episodic structure consists of a purpose that drives the behavioral sequence (initiating event), an overt goal-directed behavior (attempt), and the attainment or non-attainment of the character’s goal (direct consequence) (Stein & Glein, 1979). In order for a complete episode to be counted, all three of these elements must be present. Through calculation of percentage of T-units in episodic structure, the ability of the participant to use story grammar as a framework for language is able to be inferred (Coelho et al., 2012).

Story completeness was determined by counting the number of critical components of the story that the participant included in their retell. Five components of each story were identified by at least 80% of participants in a normative group, indicating that they were crucial to the plot of the story. By reviewing retells for the presence or absence of these five components, a story completeness score was able to be generated, which captures how many of the critical elements (including characters and events) the participant identified and included in their story.

Finally, the Story Goodness Index (SGI; Le, Coelho, Mozeiko, & Grafman, 2011) was calculated by analyzing each participant’s completeness score along with their story grammar score. Those participants who included at least four of the five critical components, as well as had at least 60% of T-units in episodic structure were considered “good storytellers”. Those who did not meet this criteria in either category were considered “poor storytellers”. Of the thirty-three total participants, twenty-three were considered poor storytellers and ten were considered good storytellers.

Cognitive Measures

A battery of standardized tests was administered to all participants to obtain measures of cognitive functioning. The Wechsler Memory Scale, Fourth Edition (WMS-IV) was given in order to obtain index scores for Immediate Memory, Delayed Memory, Working Memory, and Visual Memory. Finally, subtests of the Delis-Kaplan Executive Function System (D-KEFS) provided an Executive Functioning Index score.

Diffusion Tensor Imaging

Each participant completed Diffusion Tensor Imaging (DTI) of the whole brain, on average, 28.1 months post-injury (SD=31.5). For DTI, fractional anisotropy (FA) was calculated across nineteen regions of interest (ROIs). The limbic system ROIs included (a) left and right segments of the cingulate gyrus, (b) left and right segments of the cingulum/hippocampus, and (c) left and right fornix/stria terminalis. The frontal ROIs include (a) left and right anterior corona radiata, (b) left and right superior fronto-occipital fasciculus, and (c) left and right uncinate fasciculus. Occipital ROIs include (a) left and right posterior corona radiata and (b) left and right posterior thalamic radiations. FA for the corpus callosum was also calculated, including the body, genu, and splenium.

Results

Does white matter integrity predict discourse performance?

A logistic regression was performed to determine whether discourse performance could be predicted using measures of white matter microstructural integrity (FA) obtained using DTI. Participants were grouped on the basis of whether their stories were classified as "good" or "poor" according to the SGI. Participants' stories were classified as "good" if they scored high on both content (story completeness) and organization (story grammar). Participants' stories were classified as "poor" if their SGI was low. The "good" storytellers all included four to five content units and had anywhere from 64 to 92 percent of T-units contributing to episodic structure. The "poor" storytellers ranged anywhere from one to five content units, and had 40 to 88 percent of T-units in episodic structure. White matter fiber tracts included in this analysis were those in which differences in FA scores were observed between participants classified in the "good" and "poor" story narrative groups. Results are summarized in Table 1. The logistic regression also provides information regarding how well participants can be categorized into "good" or "poor" based on their white matter integrity. These results are summarized in Table 2.

Limbic Structures

Several limbic areas were identified as areas of interest for differentiating the "good" and "poor" discourse groups: the left and right cingulum (including both the cingulate gyrus and the hippocampus) as well as the left and right fornix cres/stria terminalis. A logistic regression was run and the model accounted for 29 percent (Nagelkerke R^2) of the explained variance, but was not statistically significant ($\chi^2(6) = 7.78$, $p = .27$). Additionally, this model correctly classified 78.8 percent of participants (95.7 percent of "poor" participants and 40 percent of "good" participants).

Corpus Callosum

The corpus callosum was analyzed in three separate regions during DTI: the body, genu, and splenium. The logistic regression model included all three regions and accounted for approximately 9 percent of the explained variance (Nagelkerke R^2), but was not statistically significant ($\chi^2(3) = 2.14$, p =.54). This model correctly classified 66.07 percent of participants (91.3 percent of "poor" participants and 10 percent of "good" participants).

Occipital Region

Four occipital structures were identified as areas of interest: the left and right posterior corona radiata and the left and right posterior thalamic radiations. The logistic regression model obtained included all four regions, accounting for 3 percent of the explained variance (Nagelkerke R^2) but again was not statistically significant ($\chi^2(8) = 6.46$, p =.59). It correctly classified 69.7 percent of participants (100 percent of "poor" participants and 0 percent of "good" participants).

Frontal Region

Six areas in the frontal lobe were identified as areas of interest, including the left and right portions of the anterior corona radiata, superior fronto-occipital fasciculus, and uncinate fasciculus. The logistic regression model included all six regions and accounted for 14.5 percent of the explained variance (Nagelkerke R^2), but was not statistically significant ($\chi^2(6) = 3.57$, p =.74). It correctly classified 75.8 percent of participants (95.7 percent of "poor" participants and 30 percent of "good" participants).

Table 1: White matter integrity and cognitive measures as a predictor of discourse performance.

	Limbic Structures	Corpus Callosum	Occipital Region	Frontal Region	Cognitive Measures
χ^2	7.78	2.14	6.46	3.57	4.50
p-value	0.27	0.54	0.59	0.74	0.21
Variance Explained	29%	9%	3%	14.5%	18%

Note. Cognitive measures include measures of working memory, immediate memory, and executive function

Table 2: Participants correctly classified using DTI in a discriminant functional analysis

Participants	Limbic Structures	Corpus Callosum	Occipital Region	Frontal Region
"Poor" Storytellers	95.7%	91.3%	100%	95.7%
"Good" Storytellers	40%	10%	0%	30%

Do cognitive measures predict discourse performance?

A logistic regression was performed to determine whether discourse performance could be predicted using scores from three neuropsychological index scores: immediate memory, working memory, and executive function. These skills were chosen because previous research has suggested that they play key roles in discourse production (Chapman et al., 2006; Coelho, Lê, Mozeiko, Krueger, & Grafman, 2012; Lê et al., 2011; Mozeiko, Lê, Coelho, Grafman, & Krueger, 2011; Youse & Coelho, 2005). Components of memory chosen for analysis include immediate and working memory. Other measures of memory such as delayed and visual memory were obtained through testing but not entered into the regression model because they were found to be highly correlated, as shown in Table 3. The logistic regression model, which accounted for 18 percent of the explained variance (Nagelkerke R^2), was not statistically significant ($\chi^2(3) = 4.50$, $p = .21$), as shown in Table 1.

Table 3: Correlation between cognitive measures.

		Immediate Memory Index	Delayed Memory Index	Visual Memory Index	Working Memory Index
Immediate Memory Index	Pearson Correlation	1	.774**	.710**	.328
	Sig (2-tailed)		.000	.000	.063
	N	33	33	33	33
Delayed Memory Index	Pearson Correlation	.774**	1	.722**	.248
	Sig (2-tailed)	.000		.000	.164
	N	33	33	33	33
Visual Memory Index	Pearson Correlation	.710**	.722**	1	.355*
	Sig (2-tailed)	.000	.000		.043
	N	33	33	33	33
Working Memory Index	Pearson Correlation	.328	.248	.355*	1
	Sig (2-tailed)	.063	.164	.043	
	N	33	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Does white matter integrity predict cognitive performance?

The same three cognitive measures were chosen for analysis: working memory, immediate memory, and executive functioning. FA scores for areas of the limbic system were examined for working memory and immediate memory because they are known to be areas with heavy involvement with memory (Catani, Dell'Acqua, & De Schotten, 2014). DTI analysis of the frontal region was chosen to examine executive function because of its involvement with executive control (Reitan & Wolfson, 1994). Three models were compared for each neuropsychological assessment composite score. Model 1 looked only at group differences between participants with "poor" and "good" discourse. Model 2 examined group performance along with FA scores from select regions in the right hemisphere. Model 3 included previously mentioned points of interest and the left hemisphere, which is believed to contribute significantly to discourse.

Immediate Memory

Examining immediate memory, the first model, which examined group performance, was not successful in accounting for a significant portion of the variance. It accounted for only 2.3 percent of the explained variance (*F(1,31)=1.75 p=.20 adjusted* R^2*=.023*). Model 2 also did not account for a significant portion of the explained variance, 15.2 percent (*F(4,28)=2.44 p=.07 adjusted* R^2*=.152*). Model 3 was significant, accounting for 25.4 percent of the explained variance (*F(7,25)=2.55 p=.04 adjusted* R^2*=.254*) with FX-STL being the only region of significance (*β*= 224.87, *t*(33) = 2.28, *p* = .03). See Table 4.

Table 4: Discourse and DTI factors influencing immediate memory.

Variable	**Model 1 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**	**Model 2 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**	**Model 3 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**
Constant	109.96 .00		11.29 .78		11.50 .78	
Participant “Good” vs Poor	5.94 .20		9.76 .04*		9.43 .04*	
Model 1 Summary		.02 .20				
CGC-R			101.05 .29		-77.49 .61	
CGH-R			134.84 .10		111.19 .26	
FX/ST-R			-5.55 .95		-125.23 .22	
Model 2 Summary				.15 .07		
CGC-L					197.60 .18	
CGH-L					-92.39 .40	
FX/ST-L					224.89 .03*	
Model 3 Summary						.25 .04*

Note. Immediate memory measured via Logical Memory 1, CVLT Trials 1-5 Total, Visual Reproduction 1 of WMS-4
**. Significant at the 0.01 level.
*. Significant at the 0.05 level.

Working memory

When examining working memory, the first model, which examined group performance, did not account for a significant portion of the explained variance, 8.1 percent ($F(1,31)=3.81$ $p=.06$ *adjusted* $R^2=.081$). Model 2 also did not account for a significant portion of the explained variance, 17.8 percent ($F(4,28)=2.73$ $p=.05$ *adjusted* $R^2=.096$). Model 3 was significant, accounting for 28.2 percent of the explained variance ($F(7,25)=2.79$ $p=.03$ *adjusted* $R^2=.282$). Several neural areas were found to be significant predictors. See Table 5.

Table 5: Discourse and DTI factors influencing working memory.

Variable	**Model 1 Beta Sig**	**Adjusted $R^2\Delta$ Sig**	**Model 2 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**	**Model 3 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**
Constant	10.78 .00		-1.53 .88		-7.41 .49	
Participant "Good" vs Poor	2.22 .06		3.0 .02*		2.62 .03*	
Model 1 Summary		.08 .06				
CGC-R			20.62 .40		86.70 .03*	
CGH-R			44.91 .03*		55.07 .03*	
FX/ST-R			-31.28 .18		-52.73 .05	
Model 2 Summary				.18 .05		
CGC-L					-81.39 .04*	
CGH-L					1.09 0.97	
FX/ST-L					32.11 .21	
Model 3 Summary						.28 .03*

Note. Working memory measured via WAIS-IV Digit Span and WAIS-IV Letter Number Sequencing.
**. Significant at the 0.01 level.
*. Significant at the 0.05 level.

Executive Function

When examining executive function, the first model, which examined group performance, did not account for a significant portion of the explained variance, 2.3 percent

(*F(1,31)=1.76 p=.20 adjusted* R^2*=.023*). Model 2 accounted for significantly more of the explained variance, 22.9 percent (*F(4,28)=3.38 p=.02 adjusted* R^2*=.229*). Model 3 accounted for a larger portion of the explained variance, 44.3 percent (*F(7,25)=4.64 p=.00 adjusted* R^2*=.443*). ACR-L (β= 82.67, $t(33) = 3.31$, $p = .00$) and SFO-R (β= -47.76, $t(33) = -1.47$, $p = .01$) were the only two regions found to be significant predictors. See Table 6.

Table 6: Discourse and DTI factors influencing executive function.

Variable	**Model 1 Beta Sig**	**Adjusted $R^2\Delta$ Sig**	**Model 2 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**	**Model 3 Beta Sig**	**Adjusted $R^2\Delta$/ Sig**
Constant	10.52 .00		18.74 .03		25.90 .00	
Participant “Good” vs Poor	.99 .19		1.03 .14		1.60 .01**	
Model 1 Summary		.23 .19				
ACR-R			28.35 .03*		-42.34 .10	
SFO-R			-43.83 .01**		-47.76 .01**	
UNC-R			1.03 .91		-14.28 .15	
Model 2 Summary				.23 .02*		
ACR-L					82.67 .003**	
SFO-L					-14.24 .15	
UNC-L					3.88 .32	
Model 3 Summary						.44 .002**

Note. Delis-Kaplan Executive Function System Composite Score was used to examine executive function.
**. Significant at the 0.01 level.
*. Significant at the 0.05 level.

Discussion

The overall aim of this study was to examine the relationship between narrative discourse performance, white matter integrity, and cognitive measures. The first research question asked whether measures of DTI, specifically FA, could successfully predict narrative discourse ability.

Results indicated that discourse performance could not be predicted by white matter integrity in any of the brain regions examined in this study, which included limbic structures, the corpus callosum, and various pathways in the occipital and frontal regions. Although individuals with damage in certain cortical areas such as the dorsolateral prefrontal cortex show impaired discourse performance (Coelho et al., 2012), the white matter pathways we examined did not appear to show such predictive value. Given the network of brain regions that must work together in order for an individual to produce discourse, these findings were surprising, however they are consistent with previous work by Le and colleagues (2014). In that study, percent brain volume loss was similarly found not to predict narrative discourse performance. A related longitudinal study examining children with closed head injury found that neither site or extent of white matter injury were useful in predicting discourse production (Brookshire, Chapman, Song, & Levin, 2002). Thus, narrative performance may not be predicted by white matter integrity alone, but rather other factors likely must be taken into account in order to uncover a reliable predictor of this ability.

The second question asked if discourse performance could be predicted by cognitive measures associated with aspects of memory and executive functions. Once again, no cognitive measure was predictive of discourse performance. That is, a participant's performance on tasks of immediate memory, working memory, or executive functions did not predict their narrative discourse abilities. While these cognitive functions have been shown to be correlated with discourse performance (Coelho, Liles & Duffy, 1995; Lê, Coelho, Mozeiko, Krueger, & Grafman, 2012; Mozeiko et al., 2011; Youse & Coelho, 2005), they alone cannot predict performance. A possible explanation for this finding may be that the cognitive measures used in the present study were all index scores, which combine several individual subtests of a neuropsychological assessment in order to obtain a single score. Using these indices may result in less sensitivity to impairments in a single area, which may have a large impact on discourse production. Analyzing more individual, specific components of cognitive function in relation to discourse performance may produce more significant results in future research.

Another possible factor contributing to this study's findings in which no factors (neither DTI nor cognitive function) predicted discourse may be the categorical way in which storytellers were divided. While participants performed along a continuum in terms of their story grammar and completeness, their performance was looked at using SGI as a whole and they were simply classified as "good" or "poor" storytellers for the purposes of this study. This broad categorization, and the fact that averages among groups were used for analysis, may have led to insignificant results. For instance, there was a large amount of variation particularly among the "poor" group, and the stronger participants who performed on the higher end of the "poor" continuum may have counteracted those who performed very poorly. Adding more categories to account for these differences, or setting stricter criteria for placement into a group may lead to more significant findings related to prediction of narrative discourse.

Finally, the third question this study asked was whether white matter integrity in key regions of the brain could predict cognitive function. When analyzing white matter integrity of limbic structures in comparison with immediate memory performance, no models revealed significant correlations, indicating that participants' performance on immediate memory tasks could not be predicted by the integrity of white matter pathways of the limbic system. When analyzing white matter integrity of these same limbic structures in comparison with working memory, however, a significant amount of the variance could be explained. In model 3, which included both left and right portions of these structures, 28.2 percent of the variance in working memory performance could be explained by white matter integrity. Among these structures, both the left and right cingulate gyrus as well as the right hippocampus and the right fornix/stria terminalis were found to be significant. This indicated that these structures in particular are critical to working memory, which is not surprising given what is known about the limbic system, and suggests that when damage occurs to white matter pathways within both left and right areas, impairments in working memory may result.

In analysis of DTI of the frontal regions in comparison with measures of executive functions, significant relationships were also found. In model 2, which examined right structures only on top of group performance, 22.9 percent of the explained variance in executive function performance was accounted for by white matter integrity in frontal regions. The anterior corona radiata and the superior fronto-occipital fasciculus both made significant contributions. In model 3, which adds in DTI from structures on the left, there was a significant increase in portion of the variance explained, with 44 percent of executive function performance being attributed to white matter integrity in these regions. The left portion of the anterior corona radiata was found to be highly significant in this analysis. Given that the anterior portion of the corona radiata fans throughout the frontal lobe, it is not surprising that this structure makes a valuable contribution to executive functions. These findings align with previous research which has shown that FA in anterior corona radiata significantly correlates with measures of attentional control (Niogi et al., 2008), and that infarcts in this area have been found to lead to executive dysfunction (Vataja et al., 2003), further supporting the importance of the anterior corona radiata to executive functions, a group of cognitive skills crucial for language.

Another potential limitation of this study is the relatively small number of participants considering the number of analyses and comparisons that were made. A larger sample size in future studies would allow for stronger power and provide a greater likelihood that an effect may be found, as the limited number of participants may be an explanation for why no significant results were found. Additionally, the two groups in this study of “good” and “poor” storytellers were not of equal size, with a greater number of “poor” storytellers. While this is expected given that this is a brain injured population in which discourse deficits are common, our results found that the models were much better at categorizing the “poor” storytellers than they were the “good”, which may be partially explained by a smaller sample of “good” storytellers.

While normative values for DTI were obtained from non-brain injured (NBI) military personnel, and a limited number of story retells from non-injured populations are available, this study lacked a NBI control group across measures. Instead, the “good” and “bad” storytellers were only analyzed in comparison to one another, potentially limiting the findings. In future research, a NBI control group would allow for comparisons to be made between the injured and non-injured groups, and may reveal differences in the TBI population that would provide more information about the nature of DTI, discourse, and cognitive function in these individuals.

The findings of this study reinforce the difficulty of determining predictive relationships in TBI and discourse production. While it is known that a relationship exists between white matter integrity, cognitive function, and discourse production, uncovering specific factors between these variables continues to present a challenge. Due to the multidimensional nature of traumatic brain injury, as well as the many networks that contribute to discourse, it has proven to be difficult to pinpoint a specific pathway that can link the two. Thus, future research must take a multifaceted approach and incorporate an array of factors in order to gain further insight into the neurological basis of narrative discourse production, as well the relationship between discourse, cognitive function, and white matter integrity.

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