Evaluation of Visual Attention to Images by Adults with Traumatic Brain Injury

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF ARTS

Under the supervision of Jessica Brown

May 2017

Acknowledgements

First, I must express my profound appreciation for my advisor and mentor, Dr. Jessica Brown. I am eternally grateful for your guidance and support throughout this process and my entire graduate school journey. You continuously shared with me your knowledge while always pushing me to challenge myself. Your constant encouragement has provided me with the confidence and inspiration to be the best learner, teacher, and clinician that I can be. I am forever indebted to you for the time you invested in me.

To my committee members, Dr. Benjamin Munson and Dr. Peggy Nelson, I cannot thank you enough for your commitment to serving on my thesis defense panel. I am greatly appreciative of the time you invested in my education. Your expertise and insight is truly cherished.

To my parents—You taught me to be whatever I want to be. You have always encouraged me to challenge myself and do what makes me happy in life. You are my constant reminders of what it means to be caring, compassionate, and driven and I hope that I have made you proud. This accomplishment would not be possible without you. I am eternally grateful for your continuous guidance and support.

To Cole—thank you for providing me with endless support and encouragement throughout my graduate school journey. Thank you for the countless times you calmed me down and helped me remember the bigger picture awaiting at the end of this process. You have always pushed me to be the best version of myself and I am forever grateful for your love.

Dedication

To my parents for their endless support throughout my educational journey. I am forever indebted to you for your gracious sacrifices and unconditional love.

Abstract

The most common persistent symptoms following traumatic brain injury (TBI) include deficits in vision, cognition, and communication. The combination of cognitive-communication and visual impairments experienced by those with brain injury have detrimental effects on rehabilitation and recovery, affecting an individual's ability to interpret the physical and social world and even engage in basic self-care tasks. Considering the widespread effects of these deficits on an individual's daily life, healthcare professionals need information on implementation of visual supports in the rehabilitation process. Therefore, the purpose of this study was to determine how individuals with and without TBI exhibit differences in the decision-making process, organizational search, processing time, and accuracy when engaging in a visual processing task comparing explicit and implicit information conditions.

Participants included 15 adults with histories of mild to severe TBI and 15 age-, gender-, and education-matched controls. Participants completed a decision-making task where they matched picture to sentence for three conditions: (a) a condition targeting the main action, (b) a condition targeting a background detail, and (c) a condition targeting a physical or mental inference. The researchers utilized eye-tracking hardware and software to track participant eye movements and analyze various eye-movement metrics.

Results of this study demonstrated that participants with and without TBI demonstrated significantly more regressions to the sentence, a higher number of fixations, and longer average fixation duration for the inference condition. Furthermore, participants with TBI displayed significantly longer fixations for the inference condition

compared to controls, all of which suggest that the inference condition was more challenging or engaging than the explicit conditions. Additionally, all participants allocated nearly the same percentage of time fixating on the target image as they did to viewing all three foil images collectively. This information provides insight into how individuals with and without TBI make decisions.

Rehabilitation professionals need information regarding the use of visual supports for individuals with TBI. The knowledge gained from this research provides important information visual processing following TBI and the use of images in rehabilitation to support cognition and language comprehension.

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INTRODUCTION

Definition of TBI

Traumatic brain injury (TBI) is defined as a disruption in the normal function of the brain, or the presence of metabolic changes to brain tissue, caused by an external force (Centers for Disease Control and Prevention, 2016). Clinical signs indicating a disruption in brain function may include a period of decreased or lost consciousness; loss of memory for events directly before or after injury (i.e., retrograde and anterograde amnesia); neurologic deficits, including weakness, sensory loss, speech-language deficits, and visual disturbances; and a change in mental status at the time of injury, such as confusion or disorientation (Menon, Schwab, Wright, & Maas, 2010). Additionally, metabolic changes noted in response to brain injury often include an increase in activation of proteolytic enzymes, mitochondrial injury, and an increase in the release of excitatory neurotransmitters--resulting in an influx of sodium and calcium into cell bodies eventually causing cell death (Buki & Povlishock, 2006; Meythaler, Peduzzi, Eleftheriou, & Novack, 2001). Several events may create external forces substantial enough to cause these changes, including an object striking the head, abrupt acceleration and deceleration of the brain without direct contact to the skull, foreign objects penetrating the brain, and blast or explosion generated forces (Menon et al., 2010).

Approximately 2.5 million people endure a traumatic brain injury each year, resulting in emergency department visits, extended hospitalizations, or death (Centers for Disease Control and Prevention, 2016); however, these numbers are acquired through hospital administrative data and do not account for those many individuals who forego seeking medical attention. Consequently, the actual number of experienced brain injuries each year is likely much higher (Frieden, Houry, & Baldwin, 2015). From 2001-2010, children ages zero to four had the highest rates of TBI-related emergency department visits, followed by adolescents age 15-19, while adults age 65 and over experienced the highest rates of hospitalization and death related to TBI during this time (Faul, Xu, Wald, & Coronado, 2010). Falls, motor vehicle accidents, and being struck by an object are the most common causes of TBI. Falls disproportionately affect those in the youngest (i.e., 0-4) and oldest (i.e., over 65) age groups, while motor vehicle accidents most frequently affect those 20-24 years of age (Frieden, Houry, & Baldwin, 2015). Blast events were the leading cause of TBI for military personnel during the Iraq and Afghanistan wars, although it is unknown how many injuries caused by other external forces went undiagnosed (Chase, McMahon, & Winch, 2015).

An estimated 3.2 to 5.3 million Americans are currently living with long-term deficits or disabilities related to TBI (Centers for Disease Control and Prevention, 2015). These deficits experienced following TBI may be transient or chronic; however, many individuals incurring TBI require long-term medical care due to residual symptoms. Common residual symptoms include problems with vision; deficits in attention, memory, and processing; impulsivity, disinhibition, emotional lability, depression, and anxiety (Parikh, Koch, & Narayan, 2007). Many of these individuals require extended rehabilitation services for assistance with activities of daily living (ADLs).

Injury Severity and Evaluation of Cognitive Status

Researchers and medical professionals typically label initial injuries as either mild, moderate, or severe. Several additional classification systems exist, for instance, those that categorize injuries based on symptomology or pathologic anatomy (Saatman et al., 2008). However, it has been widely demonstrated that injury severity most accurately predicts patient outcomes when compared to other methods of classification (Cappa, Conger, & Conger, 2011). However, measures used to designate injury severity are not universally adopted (Perrin, et al., 2015). Several scales have been utilized in attempt to accurately assign initial injury severity.

One of these frequently used scales is the Glasgow Coma Scale (GCS), a measure of consciousness which scores a patient's best motor, verbal, and eye opening responses to stimulation (Teasdale & Jennette, 1974). GCS scores ranging from 13-15 are considered mild injuries, scores from 9-12 are considered moderate, and scores from 3-8 are severe (Sherer, Struchen, Yablon, Wang, & Nick, 2008; Williams, Levin, & Eisenberg, 1990). Another measure commonly used to assign initial injury severity is the Abbreviated Injury Scale (AIS), a system used to score injuries to every region of the body on a 6-point continuum (Gennarelli, 2006). Injuries considered minor are given a grade 1, while the most severe, life-threatening injuries are graded as a 6 (Timmons et al., 2011). Although these scales provide standardized measures of initial severity, there are limitations in their accuracy. One disadvantage in using GCS scores is the variability in the length of time post-injury when the score is obtained (McDonald, Togher, & Code, 2014). Additionally, it has been demonstrated that the subjectivity of the AIS yields low inter-rater reliability, potentially limiting its validity (Ringdal et al., 2013). For these reasons, researchers often look for information beyond standardized assessments of initial injury severity to assist in classifying an individual's cognition and recovery post-injury. Duration of loss of consciousness (LOC; Young, 2009) and length of post-traumatic amnesia (PTA; Perrin et al., 2015) are two of these other forms of information frequently investigated to gain a more comprehensive picture of injury severity and current physical/cognitive status.

Loss of consciousness refers to a state of unresponsiveness and absence of arousal of the brain during which an individual does not follow commands, produce spontaneous movements, or localize to external stimuli (Liversedge & Hirsch, 2010). A loss of consciousness may last anywhere from seconds to hours or days (National Institute of Neurological Disorders and Stroke, 2015) and occurs immediately following injury (Young, 2009). An injury is considered mild if lost consciousness lasts less than one hour, moderate for a duration between one and 24 hours, and severe if lost consciousness spans greater than 24 hours (Fortuny, Briggs, Newcombe, Ratcliff, & Thomas, 1980).

Posttraumatic amnesia is the condition of disorientation caused by a brain injury, including the loss of memory for events immediately before the injury (i.e., retrograde amnesia) and the inability to form new memories after the injury (i.e., anterograde amnesia; Perrin et al., 2015). Emergence from PTA is a slow and steady process rather than an abrupt change in awareness and memory (McDonald et al., 2014). PTA is considered terminated when a patient is fully oriented, aware, and able to continuously formulate and remember new information and events (Russell & Smith, 1961). Injuries are labeled mild if the length of PTA is less than 24 hours, moderate if PTA lasts 1 to 7 days, and severe if the length of PTA is greater than one week (Fortuny et al., 1980).

Mechanisms of Injury

Traumatic brain injury is characterized by two types of damage--that is, diffuse axonal injury (DAI) and focal cortical contusions (FCC; Cicerone, Levin, Malec, Stuss, & Whyte, 2006). DAI is the dominant mechanism of injury in roughly 50% of TBIs resulting in hospital admissions in the U.S. (Meythaler, et al., 2001). The primary characteristic of DAI is the presence of microscopic damage to neurons (Crooks, 1991) caused by shearing of axons and blood vessels throughout multiple brain structures (Cicerone et al., 2006). This damage occurs as a result of both rotational and longitudinal acceleration/deceleration forces sustained by the brain. Translational forces cause injury because different brain structures have various tissue consistencies. When rapid linear acceleration/deceleration of the head occurs, certain brain structures move slower than others, causing compressive forces that deform brain tissue (Andriessen, Jacobs, & Vos, 2010). Rotational acceleration occurs when nonlinear forces cause the brain to rotate within the skull (Rush, 2011), resulting in stretching and tearing of neuronal axons past their threshold of elasticity (Meythaler et al., 2001).

Objective measurements of injury forces often include Computed Tomography (CT; Parikh, Koch, & Narayan, 2007) and Magnetic Resonance Imaging (MRI; Menon et al., 2010), as they comprise the most sensitive modern imaging techniques to date. The microscopic nature of DAI, however, leaves it essentially invisible on conventional imaging (Andriessen et al., 2010). Thus, DAI is frequently diagnosed on autopsy following injuries resulting in death which reveals swollen and detached axons throughout the brain (Povlishock, 1992). More recently, equipment such as magnetic resonance spectroscopy has allowed for the detection of DAI in survivors of TBI through identification of metabolic changes to brain cells (van der Graaf, 2010).

Focal cortical contusions are caused by a direct blow to the head or strong inertial force causing the brain to strike against the inner surface of the skull (Cicerone et al., 2006). A direct blow to a focal region causes damage at the site of impact, called the coup. These powerful forces may cause the brain to rebound against the skull at the point directly opposite that of the initial impact, called the contrecoup (Drew & Drew, 2004). Focal lesions generally involve the superficial layers of the cortex while the deep white matter remains relatively unaffected (Gentry, Godersky, & Thompson, 1988). FCCs typically result in macroscopic lesions easily detectable on conventional imaging, such as hematomas and hemorrhages, and typically only affect limited regions of the brain (Andriessen et al., 2010).

Neural Correlates

Research has explored the brain regions implicated most frequently following both DAI and focal contusions. The microscopic damage to neuronal axons occurs throughout the entire brain in DAI, but disproportionately affects the deep white matter in the frontal lobe as well as many midline subcortical structures, including the corpus callosum and brainstem (Gentry et al., 1988; Smith, Meaney, & Shull, 2003). FCCs are more commonly seen in the lateral and anterior portions of the temporal lobe and the lateral or subfrontal portions of the frontal lobe, as these brain regions are housed in areas more closely confined by the skull (Cicerone et al., 2006). Additionally, the occipital is a common site for a contrecoup injury, considering the large number of focal injuries to the frontal lobe. Although these two types of injuries are described separately, it is common to find both focal and diffuse damage following a singular injury mechanism (Andriessen et al., 2010).

The brain regions most frequently affected in both DAI and focal brain injuries correspond to anatomical structures that mediate our vision, cognition, and communication, a few of the most severely impaired areas of functioning following TBI (Cicerone et al., 2000; Greenwald, Kapoor, & Singh, 2012; McDonald, 2013). For example, various portions of the frontal lobe control cognitive processes including sustained and selective attention, reasoning skills, and the ability to perceive and manipulate incoming information (Christoff et al., 2001; Stuss and Levine, 2002). Furthermore, aspects of the frontal, temporal, and occipital lobes manage pertinent cognitive-communication functions, such as understanding inferences, interpreting facial expressions and other visual information, and comprehending written texts (Ferstl & von Cramon, 2001; Haxby, Hoffman, & Gobbini, 2000; Jang et al., 2013). The remainder of this review will focus on the common visual, cognitive, and communication deficits frequently observed in TBI following damage to these brain regions.

Visual Deficits

Traumatic brain injury may result in residual impairments in many areas of functioning, including cognition, communication, and sensorimotor abilities (Greenwald et al., 2012). Visual deficits are a particularly common sensorimotor impairment found following TBI and can affect both visual acuity and visual perception. In fact, it has been demonstrated that roughly 50% of individuals with severe TBI experience some level of visual perceptual deficit six months post-injury (Kersel, Marsh, Havill, & Sleigh, 2001). Despite this, visual impairments are often overlooked when it comes to rehabilitation for those with TBI, as some believe that visual problems do not negatively affect patient outcomes (Kerkhoff, 2000). However, visual system impairments are a prevalent problem for individuals with TBI that often result in poor rehabilitation outcomes affecting independent mobility and daily living activities (Greenwald et al., 2012).

Visual System. Our sense of vision is constructed through a multitude of complex pathways involving all lobes of the cortex and portions of the brainstem and midbrain (Hulse & Dudley, 2010). Our ability to see is dependent upon the integrity of the internal structures of the eye, the optic fibers as they travel through the brain, and the occipital cortex (Kelts, 2010). The occipital pathway begins when light is initially focused as it enters the cornea (Hulse & Dudley, 2010). The light is then refocused by the lens and ciliary muscle onto the retina in the back of the eye (Kelts, 2010). Retinal photoreceptor cells begin to process and enhance the image, subsequently sending these signals to the optic nerve (Hulse & Dudley, 2010). The two optic nerves (i.e., one from each eye) then meet at the optic chiasm where roughly half of the nerve fibers cross contralaterally, resulting in the left visual field to be processed by the right side of the brain, and vice versa (Kelts, 2010). The nerve fibers then synapse in the lateral geniculate nucleus of the thalamus and continue through the optic radiation loops. The optic radiations terminate in the primary visual cortex of the occipital lobe (Hulse & Dudley, 2010).

The primary visual cortex is the location of initial visual processing (Hulse & Dudley, 2010). However, this area only provides a topographic map of visual signals, it does not allow for their interpretation. Purposeful identification, memory, and processing of visual information occurs in the visual association areas of the occipital cortex. Nerve fiber projections continue from the primary visual cortex through two main pathways: the dorsal pathway and the ventral pathway. The dorsal pathway, also called the "where" pathway, interprets motion and direction of movement, depth perception, and recognizes objects and faces. The ventral pathway, or the "what" pathway, processes complex shapes, colors, and the angles or orientation of objects (Kelts, 2010).

When the visual pathway is damaged, it greatly effects processing of environmental signals, interaction with our surroundings, and execution of daily living activities (Hulse & Dudley, 2010). Visual deficits may affect all aspects of life after injury including the rehabilitation process and safe return to independent living. Vision plays a prominent role in our balance and gait, as well as our ability to maintain attention on tasks. More specifically, our sense of vision is imperative in executing basic ADLs, such as driving, general ambulation in the home and the community, eating, dressing and grooming, and reading and writing (Greenwald et al., 2012).

Visual acuity deficits. Visual acuity deficits are a common residual symptom following severe TBI. The extensive nature of the visual pathway leaves it vulnerable to injury. Damage to almost any region of the brain can cause a visual deficit of some kind, whether related to visual acuity or processing of information in our visual field (Hulse & Dudley, 2010). Common visual acuity deficits observed in the TBI population include field cuts, blur, diplopia, sensitivity to light, color blindness, eyestrain, and impairments in oculomotor movements (Greenwald, et al., 2012; Kapoor & Ciuffreda, 2002). Visual acuity deficits are a major cause of disability within the community (Berryman, Rasavage, & Politzer, 2010), and are often a poor prognostic indicator in outcome studies (Kerkhoff, 2000).

Visual processing deficits. Poor visual acuity may result in the distortion or misrepresentation of visual information, effectively causing faulty visual processing (Hulse & Dudley, 2010). Possible visual processing deficits include difficulties with visuospatial attention (Halterman et al., 2006), visual feature integration (Beharelle, Tisserand, Stuss, McIntosh, & Levine, 2011), visual neglect (Berryman et al., 2010), visual memory (Aginsky & Tarr, 2000), visual-spatial relations and depth perception (Goodrich, Kirby, Cockeham, Ingalla, & Lew, 2007), visual recognition (Kerkhoff, 2000), and visual sequential memory (Hulse & Dudley, 2010). Impairments in visual processing may have a detrimental effect on our safety and engagement in activities of daily living (See Table 1). Deficiencies in visual recognition and memory may hinder our reading comprehension or ability to recognize familiar faces, while poor visual sequential memory may impede our spelling or ability to remember phone numbers or addresses (Hulse & Dudley, 2010). Furthermore, impaired visual-spatial relations, depth perception, and visual neglect may hamper our ability to locate or attend to objects in space, increasing the incidence of accidents (Kerkhoff, 2000).

Table 1. Functional symptoms following visual perceptual deficit.

Visual Perceptual Skill	Symptoms	Example Activity
Visual Discrimination	- Difficulty processing details - Confusing similar words or objects	Sorting laundry
Visual Memory	- Difficulty remembering people - Poor reading comprehension - Difficulty visualizing from memory	Remembering where an item was located in a room
Visual-Spatial Relations	- Confusion of left/right - Disorientation in space, getting lost - Poor organization	Telling time
Visual Sequential Memory	- Difficulty remembering words - Confusing sequence of tasks or directions - Difficulty remembering phone numbers or addresses	Following a recipe with correct ingredients
Visual Figure Ground	- Difficulty locating objects in a crowded environment - Overwhelmed in busy environment	Finding milk in the grocery store
Visual Closure	- Substituting words or numbers - Difficulty completing tasks	Filling out a check

Cognitive Deficits

Visual deficits following TBI often interact with and exacerbate the cognitive impairments frequently found in this population. Cognition is broadly defined as the brain's ability to encode, retrieve, analyze, and manipulate information to solve novel problems (Tromp & Mulder, 1991). Cognitive processes include, but are not limited to, attention, memory, reasoning, problem solving, processing, and judgment (Bargmann, 2015). Our ability to discriminate relevant from irrelevant stimuli, comprehend and retain information, analyze current circumstances, and apply knowledge appropriately to novel situations are all mediated by our cognition (Cicerone et al., 2000). Cognitive impairments are frequently the most evident and persistent residual symptoms in individuals with TBI (Cicerone et al., 2000), and are one of the leading causes of disability following injury (Castellanos, et al., 2010). A cognitive deficit may manifest as reduced productivity and speed of functioning, decreased independence during routine ADLs, or failure to adapt and solve novel problems (Cicerone et al., 2000). This occurs due to the widespread nature of DAI causing damage to multiple brain regions that control our ability to engage in these activities. Some of the most commonly impaired cognitive processes following TBI include attention, reasoning, problem solving, and information processing speed—which are each discussed below.

Attention. Attention is mediated by both bottom-up and top-down processes (Evans et al., 2011). Bottom-up processing refers to the tendency of certain stimulus features to attract attention regardless of our desire (Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013). The salience of stimulus item features is determined by their degree of difference from surrounding items. In visual attention, the most salient features that attract attention include color, motion, and figure complexity (Evans et al., 2011). Conversely, top-down processing refers to the voluntary direction of attention to certain objects, spaces, or features of an item (Pinto et al., 2013). Top-down processing is a combination of the ability to select and attend to certain features of a stimulus while inhibiting surrounding distracting information (Evans et al., 2011). Top-down processing is also known as sustained attention (Pinto et al., 2013) and is required when any task is novel or mentally taxing (McDonald et al., 2014).

The ability to direct attention to a single task and ignore distracting information in the environment is a frequent area of impairment found in individuals with TBI (Dockree et al., 2006; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), especially for those who have suffered severe injuries (van Zomeren & van den Burg, 1985). Attention deficits greatly interfere with an individual's ability to function safely and independently, as daily tasks including driving and pathfinding have high cognitive-demands. Such taxing activities require direction of selective focus, alternating cognitive resources to perform multiple tasks simultaneously, and guiding cognitive activity in a goal-oriented manner (Bonnelle et al., 2011). For individuals with TBI, attention deficits may manifest in several ways. Impairments in attention may result in serious motor vehicle accidents (Dockree et al., 2006). These individuals may have difficulty attending to multiple tasks simultaneously, alternating attention between separate, distinct tasks, or carrying out multi-step processes (McDonald et al., 2014). Furthermore, survivors of TBI frequently experience transient attentional lapses after just short periods of time, resulting in distractibility and task performance errors (Robertson et al., 1997). Impaired attention negatively affects the ability of these individuals to integrate and understand information from their environment.

Reasoning and Problem Solving. In addition to attentional deficits, individuals who have sustained TBIs often present with impairments in deductive reasoning and problem solving that impact their performance on daily activities (Goverover & Hinojosa, 2002). Deductive reasoning is defined as making logical decisions based on the integration of current knowledge (Wustenberg, Greiff, & Funke, 2012) and the ability to engage in deductive reasoning directs how individuals solve problems (Leighton & Sternberg, 2004). Deductive reasoning and problem solving are central cognitive processes and important components of intelligence (Johnson-Laird, 2010). Success with these skills is achieved when an individual evaluates information, formulates hypotheses, and generates logical conclusions (Goverover, 2004) as well as draws upon current knowledge and experiences to make informed decisions (Vas, Spence, & Chapman, 2014). These processes are important cognitive functions for maintaining independence as solving novel everyday problems requires logical reasoning to determine potential solutions (Raven, 2000).

Deductive reasoning and problem solving deficits may persist for many years after injury despite recovery to relatively normal levels of basic intelligence (Vas et al., 2014). The impaired ability to engage in successful problem solving after TBI may explain the drastic difference between an individual's high performance on traditional cognitive tests but difficulty completing complex, functional daily tasks (Vas et al., 2014). Individuals with TBI who exhibit reasoning and problem solving deficits frequently formulate disorganized plans to address problems (McDonald, 2014) demonstrating particular difficulty defining the problem and evaluating potential solutions (Hanten et al., 2011). Additionally, survivors of TBI are often unable to modify their actions in response to changing circumstances (Wustenberg, Greiff, & Funke, 2012). Furthermore, reasoning and problem solving deficits often interact with and exacerbate the Theory of Mind (ToM) deficits seen in this population. ToM refers to the ability to recognize social cues and use these cues to understand the emotional state and behaviors of others (Bibby & McDonald, 2005; Honan, McDonald, Gowland, Fisher, & Randall, 2015). These deficits frequently result in impaired social problem solving. A study by Moran et al. (2015) showed that adolescents with TBI were more likely to request adult intervention in negative social situations rather than approach the peer personally to work out the issue. These deficits have the potential to impact all areas of independent functioning for those with TBI as they are often unable to evaluate and process multiple facets of information, deduce logical solutions, and modify their behaviors to adjust to changing circumstances--all of which are required to solve problems encountered daily (Raven, 2000).

Processing Speed. An overarching contribution to cognitive deficits in individuals with TBI is processing speed impairments. Processing speed is the rate at which information stored in memory is retrieved, analyzed, integrated with new information, and manipulated to solve problems or make conclusions (Tromp & Mulder, 1991). Processing speed is dependent upon working memory, which is limited in the amount of information an individual can process at one time (McAllister et al., 2001); if this limit is exceeded, task performance rate decreases (Baddeley, 1986). This relationship between information load and performance rate may be used as a framework for understanding the difficulty individuals with TBI have executing complex tasks, as the demands of these tasks often exceed their cognitive resources (McDonald et al., 2014).

Slowed information processing has been consistently observed in individuals with TBI (e.g., Kennedy, Clement, & Curtiss, 2003; Madigan, DeLuca, Diamond, Tramontano, & Averill, 2000; Tromp & Mulder, 1991) and may negatively affect performance on several recreational and academic outcomes (Gorman, Barnes, Swank, & Prasa, 2016). Processing speed impairments may affect an individual's social participation, as research suggests that children who have suffered a severe TBI may have difficulty remaining engaged in rapidly progressing social situations (Shultz et al., 2016). Additionally, individuals with TBI who experience slower information processing demonstrate slower word decoding during reading activities, effectively reducing reading comprehension and fluency (Barnes, Dennis, & Wilkinson, 1999). Processing speed deficits may impede an individual's ability to participate in regular everyday activities, as their cognitive resources are taxed much faster by smaller amounts of incoming information.

Deficits Impacting Communication

Cognitive-communication skills are required to engage in appropriate discourse. Cognitive-communication is broadly defined as the ability to apply and adapt your cognitive, linguistic, and social skills to everyday communicative situations and contexts (Kimbarow, 2011). The term cognitive-communication was developed after numerous observations of communication difficulties exhibited by individuals with TBI. Individuals with TBI do not present with the traditional language deficits seen in people with aphasia (Angeleri et al., 2008), as word retrieval and syntactical abilities remain generally unaffected and performance on aphasia battery assessments remains within normal limits (McDonald, 1993). Despite spared language abilities, individuals with TBI still demonstrate extreme difficulty participating in conversational interactions because communication requires the perception and integration of information beyond literal meaning. Potentially, the cognitive-communication deficits exhibited by individuals with TBI stem from impaired processing of extralinguistic and paralinguistic information (Angeleri et al., 2008). Impaired recognition and integration of these extra facets of communication result in difficulty interpreting gestures, facial expressions, and tone to determine emotions, construct inferences, and find implicit meanings in both spoken and written modalities (Ferstl, Walther, Guthke, & Von Cramon, 2005; Green, Turner, & Thompson, 2004; Jackson & Moffat, 1987; Spell & Frank, 2000).

Reading. Reading comprehension is the process of simultaneously integrating novel information from text with previous knowledge (Solhberg, Griffiths, & Fickas, 2014). Although several models have been developed, the interactive activation (IA) model of reading comprehension focuses specifically on the negative impact of cognitive deficits on reading comprehension (Solhberg et al., 2014). According to this model, the two main processes of reading comprehension are word identification and text comprehension (Verhoeven & Perfetti, 2008). Word identification requires transforming the visual representation of the text into a semantic concept. Comprehension then is a continual process of identifying new words and adding this new information to the interpretation of the entire text. Text comprehension involves two layers of representation, the propositional layer and the situational layer. In the propositional layer, the basic premise of each sentence is understood and built upon by subsequent sentences. The situational layer is supplemental to the propositional layer by integrating prior knowledge to make inferences to construct the gist of the text (Verhoeven &

Perfetti, 2008). A combination of these processes is required for successful reading decoding and comprehension.

Many studies have documented the presence of reading deficits after severe TBI (Mathias, Bowden, Bigler, & Rosenfeld, 2007; Sohlberg et al., 2014). However, it has been demonstrated that basic word recognition and encoding at the propositional level remains relatively intact (Chapman et al., 2006; Gamino, Chapman, & Cook, 2009), while the ability to integrate pre-existing knowledge to form gist-based conclusions is more severely affected (Gamino et al., 2009). Reading deficits associated with severe TBI may have detrimental effects on independent functioning. Impaired reading comprehension hinders the academic and vocational success of adults with severe TBI and hampers their ability to participate in leisure reading (Harvey, Hux, Scott, & Snell, 2013). A study by Ewing-Cobbs, Fletcher, Levin, Iovino, & Miner (2010) demonstrated adolescent reading comprehension scores were significantly lower for those with severe TBI when compared to controls, and 79% of the severe group had either failed a grade level or acquired special education services by the 2-year follow-up.

Inferences. The reading deficits experienced by individuals with TBI are often worsened by their impaired ability to generate inferences. Making an inference requires looking past the literal meaning of a message and recognizing implicit content (Johnson & Turkstra, 2012). To make an inference, one must integrate information from multiple sources, including verbal and visual cues, the current physical context in which the conversation is taking place, and general background knowledge (McDonald & Saunders, 2005). The listener must understand the speaker's literal message, relate it to the context of conversation, and deduce the missing information that is not stated directly to formulate a conclusion (Johnson & Turkstra, 2012). Inference comprehension is an essential component of social communication and how we understand and use language in specific contexts.

Impairments in inference comprehension and social language have been repeatedly demonstrated in the TBI population (e.g., Angeleri et al., 2008; Brown, Hux, Knollman-Porter, & Wallace, 2015; Johnson & Turkstra, 2012). Individuals with TBI have been shown to exhibit impaired inference construction despite memory for specific details stated explicitly within a text (Gamino et al., 2009). Because of these deficits, members of the TBI population have difficulty interpreting basic social constructs encountered daily. These individuals have demonstrated impaired ability to understand sarcasm in conversation (McDonald, 2000). Inference comprehension deficits may also impair an individual's ability to interpret abstract meanings rooted in ambiguous commercial advertisements (Pearce, McDonald, & Coltheart, 1998) and decipher deeper meanings from various sources, such as paragraph-length stories (Ferstl et al., 2005), news, and lectures (Vas et al., 2014). Furthermore, these deficits may result in inappropriate social behaviors, including abrupt topic changes and prolonged perseveration on conversation topics (Johnson & Turkstra, 2012).

Emotional Perception and Theory of Mind. Impaired inference construction may translate into deficits in perceiving the emotions and intentions of others. Emotion perception is a vital skill contributing to understanding of conversations and the intentions of a communication partner. Nonverbal communication signals convey a large amount of information about an individual's emotional state. Such communication behaviors include facial expressions, gestures, body posture, and vocal intonation or prosody—all of these signals are imperative in conveying social information (Spell & Frank, 2000). In fact, it has been demonstrated that over half of conversational information is conveyed through nonverbal expression (Mehrabian & Ferris, 1967). Research shows that appropriate interpretation and utilization of nonverbal behaviors are strongly related to social competence and functioning (Feldman, Philippot, & Custrini, 1991).

Deficits in emotion perception are frequently seen in individuals with TBI when examining interpretation of facial expressions (Green, Turner, & Thompson, 2004; Croker & McDonald, 2009), body posture (Jackson & Moffat, 1987), and vocal prosody (Spell & Frank, 2000). Importantly, the perception and interpretation of these nonverbal signals largely contributes to our concept of Theory of Mind (ToM), an essential ability that allows us to interpret the thoughts, beliefs, and intentions of others (McDonald et al., 2014). Emotion perception and ToM deficits in the TBI population hinder social appropriateness and interpretation of events. People with ToM deficits are often unable to identify sources of conflict in interpersonal interactions (McDonald et al., 2014), appropriately interpret sarcastic remarks (Channon & Crawford, 2010), understand complex stories in which a main character is operating under a false pretense (Bibby & McDonald, 2005), or predict a depicted character's intentions (Havet-Thomassin, Etcharry-Bouyx, & Le Gall, 2006). Theory of Mind deficits also help to explain the difficulties exhibited by the TBI population in managing social interactions and maintaining social relationships (Bosco & Angeleri 2012).

Prior Research

The current study is follow-up of previous work done by Brown, Hux, Knollman-Porter, and Wallace (2015). The aims of the previous study were to determine whether individuals with TBI differed from individuals without TBI in their accuracy in matching a written sentence to the correct image from a field of four, comparing performance accuracy across three target categories: explicit vs. inferential information, main character vs. background detail, and physical vs. mental inferences. This study found that individuals with TBI had significantly lower accuracy scores than individuals without TBI when interpreting inferential and explicit information. However, interpretation of these findings was limited. As the authors suggested, the performance difficulties exhibited by the TBI population may represent deficits in integrating multiple facets of information or attending to and processing various components of the presented contextually-rich images. Without further evaluation, the cause of this disconnect is uncertain.

Therefore, the current study utilizes eye-tracking technology to provide insight into the decision-making process of individuals with TBI when interpreting information through the visual modality. Eye-tracking is a means of measuring attentional distribution (Blair, Watson, Walshe, & Maj, 2009); it is a method used to trace an individual's eye movements as to allow the researcher to evaluate where a person is looking, for how long they looked there, and the order in which their eyes moved to various locations (Poole & Ball, 2006). The area at which the individual is looking is assumed to indicate the thought at the forefront of their cognitive processes (Just & Carpenter, 1976). This assumption is the central component of the “eye-mind” theory, suggesting that analysis of eye movement patterns may provide an active account of where a person directs their attention (Poole & Ball, 2006). By measuring certain aspects of eye movements, we have the potential to gather information about what information is being encoded and the amount of processing devoted to specific areas (Poole & Ball, 2006). With this information, the researchers hope to formulate conclusions about what features of visual stimuli modify attention and information processing. This has the potential to provide insight into therapy approaches that are effective in enhancing visual information integration and improving comprehension of content presented visually.

Current Study’s Purpose

The visual system is arguably the most important sensory system needed to interpret the world around us. An estimated 35% of the brain is dedicated to vision and visual processing, with over one million neuronal axons constructing each optic nerve (Kelts, 2010). Roughly 80% of perception, cognition, and learning is mediated by the visual system (Hulse & Dudley, 2010) and it has been demonstrated that at least 50% of patients with severe TBI have a visual deficit of some kind (Kersel et al., 2001). Furthermore, cognitive and communication impairments are often the most persistent symptoms experienced during recovery from TBI (Cicerone et al., 2000). The combination of visual, cognitive, and communication deficits found in the TBI population have detrimental effects on rehabilitation and recovery, affecting an individual's ability to interpret the physical and social world. Visual deficits often heighten the effects of cognitive impairments such as memory, attention, and processing, as they further hinder the ability to maintain attention on tasks or remember information presented through the visual modality. Visual deficits also impede reading ability, causing individuals to read at a slower pace, misread texts, or lose their place in the middle of a paragraph (Greenwald et al., 2012). Furthermore, this combination of cognitive and visual impairments interferes with engagement in basic self-care tasks including walking, grooming, shopping, and cooking (Goodrich et al., 2007) as well as appropriately engaging in social interactions and interpreting implicit information (Johnson & Turkstra, 2012; McDonald, 2000).

Considering the widespread effects of these deficits on an individual's daily life, healthcare professionals need information on therapeutic techniques and supports that will serve to improve the integration and comprehension of information presented through the visual modality. Therefore, the specific research objectives of this study were:

1. To determine whether adults with and without TBI differ in the decision-making process when analyzing and interpreting main character/action, background, and inferential information from given photographic stimuli. We hypothesized that individuals with TBI would exhibit differences in the overall decision making process when analyzing images given the attention, reasoning and problem solving deficits associated with the TBI population.;

2. To determine whether adults with and without TBI differ in the organization of visual search when analyzing and interpreting main character/action, background, and inferential information from given photographic stimuli. We hypothesized that individuals with TBI would display disorganized visual processing patterns when analyzing images given the frequency of visual acuity, visual processing, and attention deficits observed in the TBI population.;
3. To determine whether adults with and without TBI differ in the amount of processing time utilized when analyzing and interpreting main character/action, background, and inferential information from given photographic stimuli. We hypothesized that adults with TBI would require increased processing time to complete the experiment than controls given the attention, reasoning, and processing speed deficits frequently observed in TBI.;
4. To determine whether adults with and without TBI differ in their accuracy in correctly identifying main character/action, background, or inferential information from given photographic stimuli. We hypothesized adults with TBI would exhibit significantly lower accuracy scores overall than their peers when identifying explicit and inferential information from images given the various cognitive and communicative processing deficits exhibited in the TBI population.;
5. To determine whether adults with TBI achieve higher accuracy scores when identifying explicit information than when identifying inferential information from given photographic stimuli. We hypothesized adults with TBI would attain higher accuracy scores when identifying explicit information than inferential

information from images given the inferencing, emotion processing, and Theory of Mind deficits commonly observed in individuals with TBI.

METHOD

Participants

Study participants included 15 adults with histories of TBI, 14 with severe TBI and one with mild TBI, and 15 healthy controls. All participants were Native speakers of American English and self-reported no history of developmental deficits or cognitive impairments. Participants also completed two vision screenings to ensure adequate visual acuity to complete the task. These screenings are described in detail within the procedures. Participants passed both vision screenings to continue to the experimental task.

Participants with Traumatic Brain Injury. The six male and nine female participants with TBI were between 44 and 65 years of age ($M = 53.33$, $SD = 6.79$) with an average of 15.6 years of education (range: 12 – 18, $SD = 1.72$; See Table 2). Participants provided information indicating details of their brain injury, therapy history, current living arrangements, employment status, and any visual impairments resulting from their accident. A total of 10 participants with TBI reported impairments in visual acuity or visual processing resulting from their brain injury. Participants also completed a brain injury symptom checklist indicating any chronic personality alterations, intellectual, psychological, physiological, or neurological impairments resulting from their injury. Participants reported an average of 19.80 symptoms (range: 4 – 40, $SD = 8.31$). All participants self-reported histories of mild or severe TBI. For purposes of this study, mild TBI was defined as an injury resulting in lost consciousness for less than one hour and length of post-traumatic amnesia less than 24 hours; severe TBI was defined as a loss of consciousness for longer than 24-hours and length of PTA greater than one week (Fortuny et al., 1980).

Table 2. Demographic information for participants with TBI.

ID	Age (years)	Education (years)	Time post-onset (years)	Number of Reported Symptoms
TBI1	44	18	6	12
TBI2	65	16	10	17
TBI3	47	16	29	27
TBI4	53	16	28	30
TBI5	52	14	15	19
TBI6	48	14	9	20
TBI7	49	16	6	17
TBI8	54	16	10	40
TBI9	50	18	30	4
TBI10	61	16	29	20
TBI11	56	14	2	24
TBI12	44	18	1	17
TBI13	53	12	1	19
TBI14	59	14	2	18
TBI15	65	16	45	13

Participants with TBI completed multiple standardized assessments as a means of describing current cognitive-linguistic abilities. First, participants completed the *Cognitive Linguistic Quick Test* (CLQT; Helm-Estabrooks, 2001), an assessment measuring attention, memory, executive function, language, and visuospatial skills through completion of ten tasks (e.g., confrontation naming, clock drawing, story retell, design memory). The *CLQT* includes data for both the normative populations as well as adults who have experienced a brain injury. Participants required approximately 40 minutes to complete the assessment and achieved composite severity scores ranging from

3.2 to 4.0 (*M* = 3.85, *SD* = 0.26; See Table 3). The *CLQT* was not used to determine study inclusion.

Participants also completed the *Western Aphasia Battery-Revised* (*WAB-R*; Kertesz, 2006) to confirm the presence, type, and severity of their language deficits. The test measures expressive and receptive language abilities on 10 subtests targeting spontaneous speech, auditory verbal comprehension, repetition, and naming and word finding. The assessment includes data for both the normative population as well as adults with have experienced stroke or brain injury. Participants required approximately 30 minutes to complete the assessment and achieved an average aphasia quotient score of 99.03 (range: 97.2 – 100, *SD* = 0.84; See Table 3). The *WAB-R* was not used to determine study inclusion.

Finally, participants completed the Comprehension of Written Sentences subtest of the *Comprehensive Aphasia Test* (*CAT*; Swinburn, Porter, & Howard, 2004). This subtest served as a reading screening to ensure adequate reading comprehension skills to complete the experimental task and required participants to match 16 written sentences to a field of four pictures. The assessment includes data for both the normative population as well as adults with have experienced stroke. Participants completed the entire subtest, although were only required to correctly answer nine out of the first 10 to proceed to the experimental task. Participants required approximately five minutes to complete the subtest and achieved an average score of 31.20 of 32 (range: 28 – 32, *SD* = 1.26; See Table 3).

Table 3. Assessment scores for participants with TBI.

ID	WAB	CAT – Written Sentences Subtest	CLQT – Composite Score	CLQT – Attention	CLQT – Memory	CLQT – Executive Function	CLQT – Language	CLQT – Visuospatial Skills
TBI1	99.5	32	4	211	185	36	37	101
TBI2	100	32	4	193	161	35	33	98
TBI3	97.2	32	4	208	173	37	35	102
TBI4	100	32	4	212	185	37	37	102
TBI5	98.2	28	3.4	154	152	24	29	80
TBI6	98	30	4	185	155	29	32	90
TBI7	100	30	4	197	172	34	34	98
TBI8	98.3	30	4	202	161	31	33	94
TBI9	98.8	32	4	206	167	37	34	102
TBI10	99.6	32	4	196	178	31	35	95
TBI11	99.6	32	3.6	185	174	23	36	77
TBI12	99.6	32	4	210	182	32	34	100
TBI13	98.6	30	3.8	179	167	37	34	102
TBI14	98.9	32	3.2	196	109	30	24	91
TBI15	99.2	32	3.8	198	145	35	32	96

Participants without Traumatic Brain Injury. The six male and nine female participants without TBI were between 42 and 65 years of age (M = 51.53, SD = 7.15) with an average of 15.73 years of education (range: 12 – 20, SD = 2.37). Completion of an independent samples t-test confirmed that participant groups did not vary on age, $t(28)=0.707$, $p=0.485$, or education, $t(28) = -0.176$, $p = 0.862$. Participants without TBI completed an eight-question neurological history form to ensure no history of a brain injury or any developmental language or cognitive impairments. Participants also completed the *Mini Mental State Exam* (*MMSE*; Folstein, Folstein, & McHugh, 1975) evaluating cognitive functioning through completion of 11 tasks (e.g. orientation to time and place, remote memory, and sentence construction). Participants achieved an average score of 29.8 (range: 29 – 30, SD = 0.41); a passing score of 25 out of 30 or greater indicated eligibility to proceed to the experimental task.

Table 4. Demographic information and scores for participants without TBI.

ID	Age (years)	Education (years)	Mini Mental State Exam
NT1	56	18	30
NT2	57	16	30
NT3	44	18	30
NT4	52	14	30
NT5	52	16	30
NT6	65	16	29
NT7	51	14	30
NT8	44	18	30
NT9	56	12	30
NT10	42	18	30
NT11	46	16	30
NT12	47	12	29
NT13	47	14	30
NT14	49	14	30
NT15	65	20	29

Materials

Stimuli. The experimental materials were adopted from a previous study by Brown, Hux, Knollman-Porter, & Wallace (2015) and included 60 total stimulus sets presented on the Tobii Tx300^{TM} eye-tracking system across three experimental conditions (i.e., main action sentences, background sentences, and inferential sentences). Each stimulus set contained four images in a 2x2 grid with one written sentence located above the images (See Figure 1). We systematically randomized the 60 stimulus sets were randomized into five different orders as to ensure sets with the same sentence type did not appear more than twice in succession. Each participant was assigned to a randomization on a rotating basis (i.e., participant one was assigned to randomization one, and so on).

Figure 1. Example main action stimulus set.

Written Sentences. All sixty sentences were written in white, size 24, un-bolded Arial font presented against a black background. The 60 sentences addressed both explicit (n = 40) and inferential (n = 20) information about the target image. Specifically, 20 sentences depicted the main character or action of the target image. An example of this sentence type is, “The man is talking to the boy.” Another 20 sentences addressed a background detail shown in the target image, such as, “The building is made of stone.” The final 20 sentences described a physical or mental state of the character in the target image. A physical state refers to the assumed action or location of an event; a mental state refers to an internal belief, emotion, feeling, or desire of the main character. An example of an inferred mental state is, “The man is sad about fishing in the rain;” an example of an inferred physical state is, “The boy is running away from home.”

All 60 stimulus sentences were simple and active, following the subject-verb-object word order. An example of an active sentence is, “The boy is standing on the chair.” All sentences also contained a linking verb, as in, “The boy is standing.” The sentences were all four to nine words in length ($M = 6.43$, $SD = 1.28$) and written in the present tense. Computation of a one-way ANOVA revealed that the sentence stimulus sets did not differ significantly in number of words, $F(3, 56) = 2.330$, $p = .084$.

Images. Experimental images included digital copies of 133 high-context Norman Rockwell paintings; of these, 119 comprised experimental stimuli, 12 comprised practice stimuli, and 2 were used for a vision screening. High-context images are pictures depicting the relationship between main characters or objects and the environment and activity happening within the scene (Dietz, McKelvey, & Beukelman, 2006). Within the 2x2 grids, one Norman Rockwell image served as the target (i.e., directly matched the written sentence) and the three remaining Norman Rockwell images served as foils. We systematically alternated the target image location such that it appeared within each position on the 2x2 grid an equal number of times throughout the experiment. Each individual Norman Rockwell image appeared between one and three times across all 60 trials; no image appeared statistically more times than any other. A single image was never used as a target more than one time across all sets. The foil images for each trial were systematically chosen to resemble one characteristic of the written sentence and followed these rules: (a) at least one foil contained a main character that matched the one in the target image; (b) if the object was mentioned in the written sentence, at least one foil contained a matching object; (c) if location was mentioned in written sentence, at least one foil contained a matching location; and (d) if either a physical or mental inference was mentioned in the written sentence, at least one foil contained a matching inference.

Equipment. The Tobii Tx300™ eye tracking hardware was used to complete the experimental task and present the written sentence and image sets. The equipment included an eye tracking unit located below a 23-inch monitor for stimuli display. The Tobii Tx300™ utilized a 300 Hz sampling rate to capture fast and subtle movements, such as saccades and fixations. Fixations refer to points at which the eyes are stationary and processing information; saccades are movements between fixation points, during which no information is being encoded (Poole & Ball, 2006). The equipment was also non-restrictive, allowing for head movement without compromising data. If a participant momentarily moved out of the sampling area, eye tracking resumed instantly upon return. The power of the equipment assured that data was not compromised for participants who wore glasses or contacts, eye make-up, or for those with drooping eyelids.

The Tobii Studio software program was used to analyze the eye tracking data. Solid colored circles appeared on each screen and each circle represented one fixation. The circles contained a number in the center indicating the order of the fixations and the circles were connected by a solid line demonstrating the visualization path. The fixation filter was set to 40 milliseconds, indicating that only fixations of 40 milliseconds or longer appeared on each screen. The researchers selected a 40ms fixation filter because individuals can encode the gist of a scene in a fixation as short as 40ms (Rayner, 2009). The circles ranged in size, with larger circles indicating a longer fixation time (See Figure 3). The program allowed for gaze replay in real time as well as manual navigation of each replay from start to finish, permitting visualization and analysis of any overlapping fixation points. The software also provided visualization data in heat maps, indicating the areas of the screen each participant fixated on the most (See Figure 2). Multiple pieces of information were collected on each screen: (1) the total number of fixations, (2) the length of each fixation, (3) the number of fixations on the target image, foil images, and sentence, and (4) the number of regressions back to the sentence after the initial reading.

Figure 2. Example inference stimulus set with heat map data.

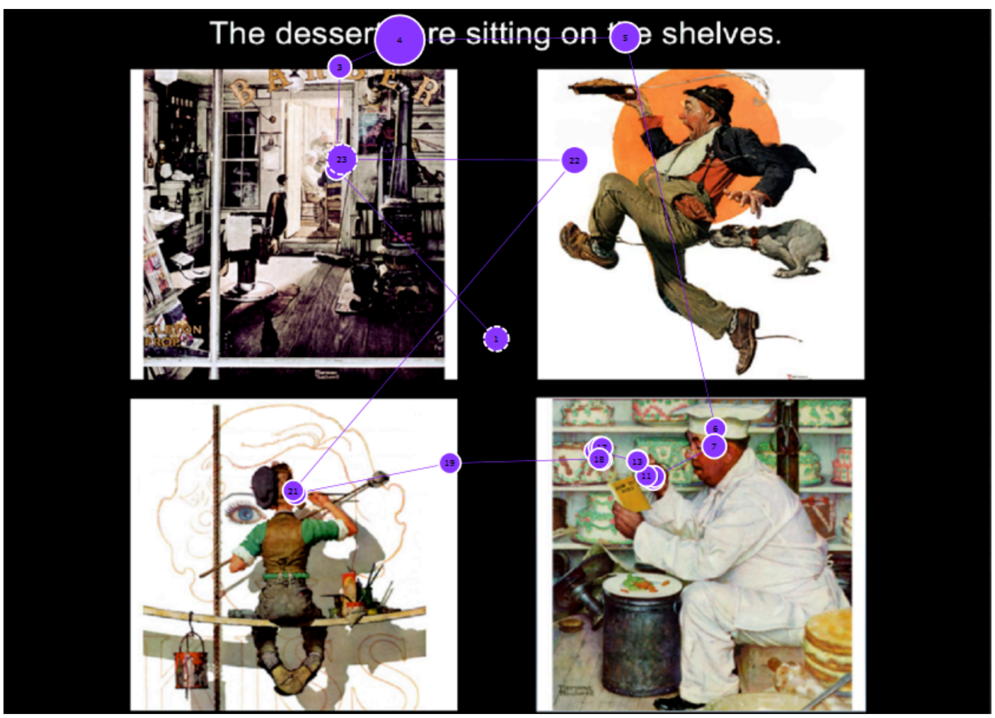

Figure 3. Example background stimulus set with fixation data.

Participants selected their answers using a four-button keypad. The buttons on the keypad were rectangular and appeared in a 2x2 grid as to reflect the same 2x2 arrangement of the pictures on each stimulus screen. The buttons were labeled “A,” “B,” “C,” and “D” and the researchers visually demonstrated the correlation between the keypad buttons and the pictures on a sample stimulus screen to ensure comprehension of the relationship between the keypad buttons and images. The buttons were large as to facilitate easier access and accommodate for any fine motor deficits.

Procedures

Participants chose whether to complete testing, screening, and the experimental task in the same day or schedule a second session to complete the experiment. The entire process of consenting, screening, testing, and experimental task completion took approximately 90 to 120 minutes. Participants who chose to complete both sessions in the same day were given a 20-minute break before beginning the experiment.

Calibration. After completion of standardized assessments, participants calibrated to the eye-tracking equipment before beginning the experimental task. To calibrate, participants visually fixated on nine orange dots as they moved to various locations throughout the screen. Participants were seated an appropriate distance from the Tobii monitor, indicated by a reading of 60 to 65cm on the Tobii Studio software. The software provided a calibration summary to assure participant fixations were accurately aligned with the target points. Re-calibration was performed when necessary until fixations were on target. All participants successfully calibrated to the Tobii software prior to experiment completion.

Vision Screenings. Participants completed two vision screenings before continuing to the experiment. For the first screening, participants visually tracked nine X's as they moved to various locations across the monitor. For the second screening, participants viewed two Norman Rockwell images and located five specific target details located within each image (i.e., "Point to the football"). These images were not used in the experimental stimuli. Participants achieved 100% accuracy on both vision screenings to move to the experimental task.

Practice trials. We provided participants three practice trials to ensure comprehension of the experimental task. The appearance of each practice trial screen mirrored that of the experimental stimuli--that is, four pictures arranged in a 2x2 grid with a written simple, active sentence presented above. The practice trial sentences only targeted explicit, main action information. We provided both oral and written instructions for participants to read the written sentence and select the picture that best matched that sentence. Participants selected their answers using the four-button key pad and were required to correctly answer all three practice trials to continue to the experimental task. No practice images or sentences appeared within the experimental stimulus sets.

Experimental task. The experimental task consisted of 60 total stimulus sets. Two additional screens appeared before each stimulus set to allow a short break before the subsequent stimulus. First, a large green arrow with the word "Go" appeared against a black background. The researcher manually controlled advancement from the "Go" screen participants stated they were ready for a trial to begin. Participants were encouraged to take breaks if needed while the "Go" screen was present. A screen with a red fixation circle in the center appeared following advancement from the "Go" screen and the researcher instructed participants to stare at the red fixation circle while this screen displayed. Such a screen provided a common initial fixation location ensuring the initial viewing point did not bias any results. This screen automatically advanced to the stimulus screen after a two second interval. We provided participants an instruction screen detailing this sequence (See Figure 4).

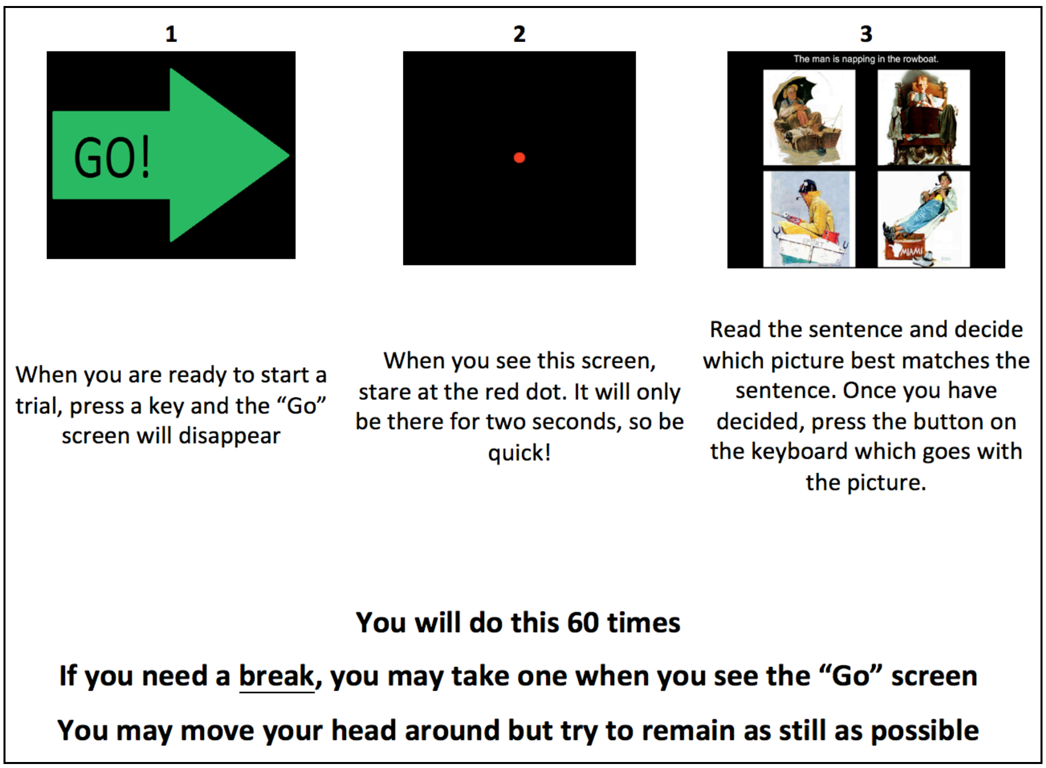

Figure 4. Participant instructions screen.

For each stimulus screen, participants were given the same instructions as they were given for the practice trials (i.e., choose the picture from the 2x2 grid that best matches the provided written sentence). Participants selected their answers using the four-button key pad. Answer selection via button press was confirmed by the researcher who observed the experiment and manually recorded participant answers to all 60 trials. Participants completed the experimental task without performance feedback. The experimental task took approximately 20 to 25 minutes to complete.

Data Analysis. We obtained data for eight dependent variables: (a) accuracy for each condition, (b) number of total fixations, (c) average fixation time, (d) percent of time fixated on the sentence, (e) percent of time fixated on the target, (f) percent of time fixated on foils, (g) percent of time fixated on other, and (h) number of regressions to the sentence. Researchers obtained data for variables (b) through (h) using the Tobii Studio software with a 40ms fixation filter. The accuracy for each condition was defined as the number of stimulus sets in which each participant selected the correct picture. The number of total fixations was defined as the number of eye gaze fixations that were 40ms or longer located within each stimulus set. The average fixation time was calculated by dividing the total time spent on a single slide by the total number of fixations on that slide. The percent of time fixated on the sentence, target, foils, and other locations were calculated by dividing the number of fixations on each variable by the number of total fixations within a single slide. The number of regressions back to the sentence was defined as the number of instances in which a participant's eyes returned to the sentence after they first viewed it.

The researchers hand coded the data in effort to minimize potential inaccuracies caused by drift (Holmquist et al., 2011; Hornof & Halverson, 2002). Drift refers to the phenomenon in which minor changes in position during the session result in less accurate calibration after calibration has already been performed. Drift ordinarily produces only minimal distortions of fixation location. The researchers hand-coded data and inserted the fixation dot screen prior to each stimulus set to minimize the potential errors caused by drift. To further assure coding accuracy, two additional trained research assistants each coded 15% of the participants' data. The researchers compared these results to their own, and any discrepancies in data coding were addressed through discussion between parties.

RESULTS

Accuracy

Regardless of group, participants achieved an overall accuracy of 98.7% (range: 90% – 100%, *SD* = 2.92) for stimulus sets targeting a main action, 96.7% (range: 85% – 100%, *SD* = 4.01) for stimulus sets targeting a background detail, and 92.3% (range: 70% – 100%, *SD* = 7.85) for stimulus sets targeting a physical or mental inference. Participants with TBI achieved an average of 97.6% accuracy (range: 90% – 100%, *SD* = 3.72) for stimulus sets targeting a main action, the highest accuracy of the three conditions. Participants' average accuracy ranged from 85% to 100% (*M* = 96%, *SD* = 5.07) for stimulus sets targeting a background detail and from 70% to 100% (*M* = 90.67%, *SD* = 9.98) for sets targeting a physical or mental inference. Similarly, participants without TBI achieved an average of 99.67% accuracy (range: 95% – 100%, *SD* = 1.29) for sentences targeting the main action, the highest accuracy of the three conditions. Participants achieved an average accuracy of 97.33% (range: 95% – 100%, *SD* = 2.58) for sentences targeting a background detail and an average accuracy of 94% (range: 85% – 100%, *SD* = 4.70) for sentences targeting a physical or mental inference.

Calculations of a between groups repeated measures 2x3 ANOVA revealed a statistically significant main effect for condition accuracy, $F(2,56) = 17.226$, $p < 0.001$. Post-hoc analyses using Tukey's HSD (HSD = 3.286) revealed a significant difference amongst accuracy between main action and inference conditions and background and inference conditions. No statistically significant differences existed for the main effect of group, $F(1,28) = 2.303$, $p = 0.140$, or the interaction between group and condition, $F(2,56) = 0.426$, $p = 0.655$.

Total Fixations

Irrespective of group, participants demonstrated an average of 14.3 (range: 4.85 – 28.15, *SD* = 5.52) fixations for the main action condition, 15.8 (range: 6.60 – 36.35, *SD* = 6.43) for the background detail condition, and 19.3 (range: 4.80 – 40.87, *SD* = 8.86) fixations for the inference condition. Participants with TBI demonstrated the highest number of total fixations for stimulus sets targeting a physical or mental inference, averaging 16.98 fixations (range: 4.80 – 32.05, *SD* = 7.80). For stimulus sets targeting a main action, participants with TBI demonstrated an average of 13.01 fixations (range: 4.85 – 20.70, *SD* = 5.58); for stimulus sets targeting a background detail, participants demonstrated an average of 14.63 fixations (range: 6.60 – 24.15, *SD* = 6.24). Similarly, participants without TBI demonstrated the highest number of total fixations for stimulus sets targeting a physical or mental inference, with an average of 21.63 fixations (range: 11.50 – 40.70, *SD* = 9.50). For stimulus sets targeting a background detail, participants without TBI demonstrated the second highest number of total fixations with an average of 16.94 fixations (range: 10.10 – 36.35, *SD* = 6.61). Finally, participants without TBI demonstrated the fewest number of total fixations for stimulus sets targeting the main action, averaging 15.46 fixations (range: 8.60 – 28.15, *SD* = 5.37).

Calculations of a between groups repeated measures 2x3 ANOVA revealed a statistically significant main effect for total number of fixations across conditions, $F(2,56) = 21.313$, $p < 0.001$. Post-hoc analyses using Tukey's HSD (HSD = 2.37) revealed a significant difference amongst total fixations between main action and inference conditions and background detail and inference conditions. No statistically significant differences existed for the main effect of group, $F(1,28) = 1.733$, $p = 0.199$, or the interaction between group and condition, $F(2,56) = 1.358$, $p = 0.266$.

Average Fixation Duration

Overall, participants demonstrated an average fixation duration of 4.64 (range: 0.22s – 1.06s, *SD* = 0.24) seconds for the main action condition, 4.52 (range: 0.26s – 1.05s, *SD* = 0.20) seconds for the background condition, and 5.22 (range: 0.24s – 1.68s, *SD* = 0.33) seconds for the inference condition regardless of group. Participants with TBI displayed the longest average fixation duration for stimulus sets targeting a physical or mental inference with an average of 0.69 seconds (range: 0.29s – 1.68s, *SD* = 0.39). For sets targeting a main action, participants with TBI displayed an average fixation duration of 0.57 seconds (range: 2.60s – 1.06s, *SD* = 0.26), the second longest average of the three conditions. Participants with TBI demonstrated the shortest average fixation duration on sets targeting a background detail, averaging 0.54 seconds (range: 0.25s – 1.05s, *SD* = 0.24). Conversely, participants without TBI displayed the longest average fixation duration for stimulus sets targeting a background detail, ranging from 0.24

seconds to 0.53 seconds (*M* = 0.36s, *SD* = 0.10). For stimulus sets targeting a main action, participants without TBI demonstrated an average fixation duration of 0.35 seconds (range: 0.22s – 0.54s, *SD* = 0.11). Participants without TBI displayed the shortest average fixation duration for stimulus sets targeting a physical or mental inference, averaging 0.35 seconds (range: 0.20s – 0.56s, *SD* = 0.11).

Calculations of a between groups repeated measures 2x3 ANOVA revealed a statistically significant main effect for average fixation duration across the three experimental conditions, $F(2,56) = 4.746$, $p = 0.012$. Post-hoc analyses using Tukey's HSD (HSD = 0.072) revealed a significant difference between main action and inference conditions only. Analysis also revealed a statistically significant difference for the interaction between group and condition, $F(2,56) = 6.274$, $p = 0.003$. Post-hoc analyses using Tukey's HSD (HSD = 0.10) revealed a significant difference between background and inference conditions as well as main action and inference conditions for participants with TBI. No such differences were found between conditions for participants without TBI. Calculations also revealed a statistically significant difference for main effect of group, $F(1,28) = 10.047$ $p = 0.004$. Post-hoc analyses using Tukey's LSD (LSD = 0.28) revealed a significant difference between groups for the inference condition only.

Percent of Time Fixated

Sentence. Regardless of group, participants dedicated an average of 15.45% (range: 3.49% – 32.20%, *SD* = 0.07) of time fixating on the sentence for the main action condition, 15.40% (range: 6.44% – 32.13%, *SD* = 6.30) for the background condition, and 15.20% (range: 3.05% – 31.27%, *SD* = 6.83) for the inference condition. Participants with TBI dedicated an average of 13.77% of time (range: 3.49% – 32.20%, *SD* = 6.73) fixating on the sentence for stimulus sets targeting a main action. Participants with TBI spent a lower percentage of time fixating on the sentence for stimulus sets targeting a physical or mental inference, averaging 12.78% (range: 3.05% – 31.27%, *SD* = 6.84), and for sets targeting a background detail, averaging 13.70% (range: 2.10% – 27.11%, *SD* = 6.39). Participants without TBI demonstrated the highest percentage of time fixating on the sentence for stimulus sets targeting a physical or mental inference, averaging 17.63% (range: 10.70% – 31.54%, *SD* = 6.10), followed by sets targeting a main action, averaging 17.13% (range: 5.91% – 32.18%, *SD* = 7.53). Participants without TBI displayed the lowest percentage of time fixating on the sentence for sets targeting a background detail with an average of 17.11% (range: 10.59% – 31.13%, *SD* = 5.96).

Calculations of a between groups repeated measures 2x3 ANOVA revealed no statistically significant main effect for percent time fixated on the sentence across conditions, $F(2,56) = 0.080$, $p = 0.923$, or groups, $F(1,28) = 2.841$, $p = 0.103$. Similarly, the interaction between group and condition did not reach significance, $F(2,56) = 0.878$, $p = 0.421$.

Target. Overall, participants dedicated an average of 29.65% (range: 21.79% – 54.39%, *SD* = 6.33) of time fixating on the target for the main action condition, 30.43% (range: 21.07% – 38.17%, *SD* = 6.02) for the background condition, and 29.31% (range: 21.90% – 46.11%, *SD* = 4.90) for the inference condition regardless of group. Participants with TBI dedicated an average of 30.20% of the total time fixating on the target image within stimulus sets targeting a main action (range: 24.58% – 54.39%, *SD* =

7.68). This value increased for sets targeting a background detail, where participants with TBI allocated an average of 30.39% of the total time fixating on the target image (range: 21.07% – 51.47%, *SD* = 7.10). Participants with TBI dedicated the highest percentage of time fixating on the target image within sets targeting a physical or mental inference, averaging 30.95% (range: 25.00% – 46.11%, *SD* = 5.62). Participants without TBI demonstrated an average of 30.47% (range: 22.93% – 38.17%, *SD* = 4.96) time fixating on the target image within stimulus sets targeting a background detail, 29.10% (range: 21.79% – 36.82%, *SD* = 4.82) within stimulus sets targeting a main action, and 27.67% (range: 21.90% – 32.98%, *SD* = 3.53) within sets targeting a physical or mental inference.

Calculations of a between groups repeated measures 2x3 ANOVA revealed no statistically significant main effect for percent time fixated on targets across conditions, $F(2,56) = 1.299$, $p = 0.281$, or groups, $F(1,28) = 0.542$, $p = 0.468$. The interaction between groups and conditions approached, but did not reach significance, $F(2,56) = 2.826$, $p = 0.068$.

Foil. Irrespective of group, participants dedicated an average of 46.83% (range: 32.64% – 60.19%, *SD* = 7.90) of time fixating on the foil images for the main action condition, 46.31% (range: 32.96% – 53.65%, *SD* = 7.02) for the background condition, and 49.97% (range: 21.52% – 64.10%, *SD* = 9.19) for the inference condition. Participants with TBI fixated on any of the foil images for an average of 49.70% of the time within stimulus sets targeting a physical or mental inference (range: 21.52% – 64.10%, *SD* = 11.22). Participants with TBI spent a lower percentage of time fixating on the foil images within stimulus sets targeting a main action, averaging 47.53% (range: 25.96% – 55.82%, *SD* = 8.41), and for sets targeting a background detail, averaging 46.98% (range: 34.10% – 54.00%, *SD* = 6.85). Participants without TBI allocated an average of 46.13% (range: 32.64% – 60.19%, *SD* = 7.58) of time fixating on the foil images within stimulus sets targeting a main action, 45.64% (range: 32.96% – 58.55%, *SD* = 7.37) within sets targeting a background detail, and 50.24% (range: 39.07% – 64.70%, *SD* = 7.00) within sets targeting a physical or mental inference.

Calculations of a between groups repeated measures 2x3 ANOVA revealed a statistically significant main effect for percent time fixated on foils across conditions, $F(2,56) = 8.559$, $p = 0.001$. Post-hoc analyses using Tukey's HSD (HSD = 0.025) revealed a significant difference amongst accuracy between main action and both background and inference conditions. No statistically significant differences existed for the main effect of group, $F(1,28) = 0.070$, $p = 0.794$, or the interaction between group and condition, $F(2,56) = 0.668$, $p = 0.517$.

Other. We recorded all fixations outside the stimulus presentation area for both participant groups, which we accounted for in our data analysis. Regardless of group, participants dedicated an average of 7.65% (range: 0.00% – 26.07%, *SD* = 5.32) of time fixating on areas other than the sentence, target, or foil images for the main action condition, 7.17% (range: 2.06% – 21.86%, *SD* = 4.11) for the background condition, and 5.77% (range: 0.92% – 17.74%, *SD* = 3.51) for the inference condition. Participants with TBI dedicated an average of 6.29% (range: 0.92% – 17.74%, *SD* = 4.64) of the total time fixating on areas other than the sentence, target image, or foil images within stimulus sets targeting a physical or mental inference. This value increased for sets targeting a main action, where participants with TBI allocated an average of 7.98% (range: 0.00% – 26.07%, *SD* = 6.07) of the total time fixating on the areas other than the sentence, target image, or foil images, followed by sets targeting a background detail, with an average of 8.07% (range: 1.27% – 21.86%, *SD* = 5.29). Participants without TBI demonstrated an average of 7.32% (range: 3.50% – 21.93%, *SD* = 4.65) of time fixating on areas other than the sentence, target image, or foil images within stimulus sets targeting a main action, 6.66% (range: 2.93% – 11.31%, *SD* = 2.28) within sets targeting a background detail, and 5.24% (range: 2.69% – 9.28%, *SD* = 1.85) within sets targeting a physical or mental inference.

Sentence Regressions

Overall, participants demonstrated an average of 0.12 (range: 0.00 – 0.80, *SD* = 0.18) regressions back to the sentence for the main action condition, 0.19 (range: 0.00 – 0.65, *SD* = 0.16) regressions for the background condition, and 0.24 (range: 0.00 – 0.85, *SD* = 0.24) regressions for the inference condition regardless of group. Participants with TBI demonstrated the highest number of regressions back to the sentence for stimulus sets targeting a physical or mental inference with an average of 0.23 regressions (range: 0.00 – 0.85, *SD* = 0.27). Participants with TBI displayed the second highest number of regressions back to the sentence for sets targeting a background detail, averaging 0.20 regressions (range: 0.00 – 0.65, *SD* = 0.18). For sets targeting a main action, participants with TBI demonstrated the lowest number of regressions back to the sentence with an average of 0.14 regressions (range: 0.00 – 0.80, *SD* = 0.20). Similarly, participants without TBI displayed the highest number of regressions back to the sentence for stimulus sets targeting a physical or mental inference, averaging 0.24 regressions (range: 0.00 – 0.65, $SD = 0.21$). For sets targeting a background detail, participants without TBI demonstrated an average number of 0.17 regressions back to the sentence (range: 0.00 – 0.50, $SD = 0.15$). For sentences targeting a main action, participants without TBI displayed an average of 0.10 regressions (range: 0.00 – 0.50, $SD = 0.16$).

Calculations of three between groups repeated measures 2x3 ANOVA revealed a statistically significant main effect for condition number of sentence regressions, $F(2,56) = 8.785$, $p < 0.001$. Post-hoc analyses using Tukey's HSD (HSD = 0.08) revealed a significant difference amongst accuracy between main action and inference conditions. No statistically significant differences existed for the main effect of group, $F(1,28) = 0.083$, $p = 0.775$, or between group and condition, $F(2,56) = 0.434$, $p = 0.650$.

DISCUSSION

Cognitive-communication and visual impairments are the most prevalent and persistent symptoms noted by individuals with TBI (Cicerone et al., 2000; Greenwald et al., 2012; Kersel et al., 2001). The combination of these impairments found in the TBI population have detrimental effects on rehabilitation as such impairments limit an individual's ability to detect and interpret stimuli within their environment, as when reading information requiring inferential reasoning. Furthermore, visual deficits often intensify the effects of cognitive impairments as they impede initial visual perception and processing during tasks recruiting attention and memory (Greenwald et al., 2012). One example of such a task is when individuals read a text. This process requires visual acuity and processing, sustained attention, memory for previous content, and integrating multiple facets of information.

Previous research performed by Brown and colleagues (2015) demonstrated the effects of visual and cognitive-communication deficits on the TBI population when participants matched a written sentence to a field of four pictures targeting explicit actions and details as well as mental and physical inferences. Within this study, the authors reported that individuals with TBI demonstrated significantly lower accuracy scores when interpreting implicit and explicit information from images than individuals without TBI. However, study implications were limited. The authors were unable to determine whether this inaccuracy was a result of challenges with successfully integrating multiple pieces of information or attending to certain components of the presented visuographic stimuli altogether.

Therefore, the current study incorporated the use of eye-tracking to provide a means of assessing how individuals with TBI visually process information that is both explicit and implied presented through text- and image-based modalities. The researchers sought to determine whether individuals with and without histories of TBI differed in the decision-making process during this task, which included analysis of variables such as organizational search patterns and processing time. In general, participants with and without TBI demonstrated significantly more regressions to the sentence, a higher number of fixations, and longer average fixation duration for the inference condition. Furthermore, participants with TBI displayed significantly longer fixations for the inference condition compared to controls, all of which suggest that the inference condition was more challenging or engaging than the explicit conditions. Additionally, all participants allocated nearly the same percentage of time fixating on the target image as they did to viewing all three foil images collectively. This information provides insight into how individuals with and without TBI make decisions.

Although data analysis did not reveal many group differences, these findings highlight important questions regarding the allocation of visual attention to various components of a task for individuals with and without TBI. Specifically, analysis of various eye movement metrics provides insight into how much time and effort individuals allot to studying various areas of interest, potentially indicating what pieces of information are more difficult or important when processing visual information to make a decision. The following sections illuminate potential reasons for the stated findings.

Explicit and Implicit Language Comprehension

Statistical analysis revealed that participants with and without TBI demonstrated significantly lower accuracy scores for the inference condition when compared to both the main action and background conditions. A likely explanation for this discrepancy is the increased language comprehension difficulty associated with inferential comprehension. Specifically, according to the “high-level language hypothesis” (Hinchliffe, Murdoch, & Chenery, 1998), complete language competence requires linguistic proficiency beyond the primary level of basic language comprehension and includes higher order language functions to interpret inferential information (Hartley, 1995). Individuals achieve such levels of linguistic proficiency through the use of metalinguistic and metacognitive skills. Use of these skills during language tasks requires that individuals apply a combination of primary language processes, cognitive processes, and executive processes, including self-monitoring and social judgement, to interpret intended meanings (Hinchliffe et al., 1998). The process is complex, which explains why interpreting inferential information is difficult. This complexity is a feasible explanation for the discrepancy in accuracy for all participants for the inference condition.

Furthermore, participants with TBI, on average, were less accurate for the inference condition than individuals without TBI. Although this difference did not reach significance, this finding is congruent with literature reporting that individuals with TBI exhibit difficulty with tasks that require proficiency in higher-order language processes, as well as cognitive and executive processes including problem solving and monitoring (e.g., Hinchliffe et al., 1998; Moran & Gillon, 2005). For example, it has been widely documented that individuals with TBI do not demonstrate the same language difficulties as those associated with aphasia (Angeleri et al., 2008; McDonald, 1993); that is, individuals with TBI do not demonstrate impairments in understanding rule-based language constructs. However, these individuals continue to demonstrate deficits in interpreting language constructs that go beyond comprehension of the literal meaning. It is important to highlight that the language itself did not differ between conditions, only the implied meaning was different for the inference condition. The fact that individuals with TBI demonstrated lower accuracy scores for the inference supports the notion that individuals with TBI exhibit cognitive-communication impairments affecting these higher-order language and executive processes.

One additional interesting finding further supports this hypothesis and elucidates the decreased accuracy of individuals with TBI in understanding inferential information: participants without TBI allocated the highest percentage of time fixating on the sentence within stimulus sets for the inference condition when compared to main action or background stimuli; conversely, individuals with TBI did not. Although this difference did not reach significance, this finding is explained by evaluating the demands of the task and the current literature detailing the effects of brain injury on the integration of higher-order language processes and self-awareness. Specifically, participants evaluated high-context images and compared these images to a written sentence to determine an appropriate answer selection. High-context images are detailed pictures depicting relationships between main characters or objects and activities happening within the scene (Dietz et al., 2006). Therefore, processing the information from these images, integrating it with the content of the written sentence, and ascertaining the implied meaning is a challenging task. It is possible that participants without TBI realized this task was more difficult within the inference condition and dedicated more time to analyzing the content of the written sentence before making a decision.

Conversely, it is reasonable to assert that participants without TBI did not adjust their performance to match the task difficulty. Specifically, it has been demonstrated that individuals with TBI retain basic reading comprehension skills after brain injury (Chapman et al., 2006; Gamino, Chapman, & Cook, 2009), while exhibiting marked difficulty forming gist-based conclusions requiring higher-level interpretation of text beyond the literal meaning (Gamino et al., 2009). Furthermore, individuals with TBI frequently demonstrate executive function deficits in awareness and self-monitoring (Spikman, Boelen, Lamberts, Brouwer, & Fasotti, 2010). Thus, the combination of impaired self-awareness and difficulty interpreting higher-level linguistic information is a plausible explanation for the difference in time allotted to reading the sentence within the inference condition between individuals with and without TBI. That is, individuals with TBI presumably accepted the sentence content at face value, foregoing the opportunity to devote more time to processing the implicit linguistic information.

Allocation of Cognitive Resources

Participants with and without TBI demonstrated significantly more regressions to the sentence within stimulus sets targeting a physical or mental inference when compared to sets targeting a main action. This discrepancy may have arisen because the complexity associated with interpreting inferential information increases strain on available cognitive resources. Research supports a hierarchical model of cognitive resource allocation, suggesting that the amount of effort individuals apply to any one task varies based on task modality and degree of difficulty (Morrison, Burnham, & Morrison, 2015). As task complexity increases, processing load increases, further depleting the amount of cognitive resources available for application to a specific task (McAllister et al., 2001); this relationship is known as the resource allocation theory (McNeill, Odell, & Tseng, 1991). Although traditionally applied to linguistic competence resulting from aphasia, the resource allocation theory may be applied to those with TBI considering the prominence of cognitive deficits associated with diffuse axonal brain injury.

This theory can be used to understand why all participants demonstrated a higher number of regressions for the inference condition. Specifically, comprehension of inferential information requires the application and integration of working memory, visual processing, attention, and problem solving processes. To complete the experimental task, participants were required to read a sentence, hold information in their working memory, visually process image content, infer a physical or mental state, and integrate all such pieces of information to make a final decision. It is feasible that stimuli within the inference condition reached a level of complexity where participants' working memory resources were taxed, resulting in failure to remember precisely the content of the written sentence. As a result, participants required subsequent confirmation of their memory for the content of the written sentence before making their answer selection.

This behavior is surprising for individuals with TBI given the lack of cognitive flexibility frequently observed in this population (e.g., Heled, Hoofien, Margalit, Natovich, & Agranov, 2012; Niemeier, Marwitz, Lesher, Walker, & Bushnik, 2007). Cognitive flexibility refers to the ability to change actions or thoughts according to varying situational demands (Canas, Antoli, Fajardo, & Salmero´n, 2005; Lezak, 2004). This involves numerous cognitive components and executive functions, including attention, monitoring, and sensorimotor input (Ionescu, 2012). If task difficulty increases, individuals must exercise cognitive flexibility by compensating for that difficulty (i.e., by regressing to the sentence). However, individuals with TBI typically exhibit decreased cognitive flexibility; therefore, this finding is unexpected considering this typical characteristic of this population.

The resource allocation theory may also be used to explain attentional capacity. Both participants with and without TBI allocated a portion of time fixating on locations other than the sentence, target image, or foil images; many of these fixations were on areas away from the stimulus screen and off the monitor altogether. This observation suggests completion of the experimental task potentially reached the participants' attentional threshold. Individuals frequently experience attentional lapses after continuous engagement in a task for an extended period of time. Furthermore, attention is affected by motivation such that low motivation to complete a task is associated with decreased attention span (Cardena, Sjostedt, & Marcusson-Clavertz, 2014). It is likely that participant motivation to complete the experiment was relatively low, considering the repetitive and decontextualized nature of the task. Therefore, the time participants spent looking at other areas within and outside the stimulus set represent transient lapses in attention over the course of the experiment. Additionally, although the value was not significant, participants with TBI dedicated a higher percentage of time fixating on these other locations than individuals without TBI. This finding is congruent with current literature indicating that participants with TBI demonstrate impairments in sustained attention (Dockree et al., 2006; Larson et al., 2011).

An additional interesting finding was that participants with and without TBI allocated nearly the same percentage of time fixating on the target image as they dedicated to all three foils combined; this was true for all conditions. Although this finding was not significant, it potentially provides insight into how both individuals with and without TBI utilize specific cognitive resources when engaging in decision-making tasks. For example, two cognitive processes individuals use to make a decision include categorization and deductive reasoning. Categorization refers to the ability to sort information or stimuli into groups to simplify the environment and reduce loads placed on working memory; deductive reasoning involves evaluating information and making inferences to draw a conclusion (Goverover, 2004). Applying the basic concepts of these processes to this finding potentially provides information regarding the decision-making process for participants completing a visual decision-making task.

Specifically, when making a decision, it is reasonable that participants initially engaged in categorization, classifying images into two groups: potential answers and obviously incorrect answers. This initial categorization potentially served as a filter, resulting in participants ignoring the foil images that they identified as not relevant. Then, participants engaged in deductive reasoning to determine a single correct answer, during which they allocated more time to looking at the target image, evaluating all the current information, and drawing a conclusion. This rationale is a reasonable explanation as to why participants dedicated the same amount of time fixating on the target as they did to all three foils, and is consistent with other literature reporting that a higher number of fixations on an area of interest indicates that area is of greater importance (Poole, Ball, & Phillips, 2004).

Processing Speed

Participants with and without TBI demonstrated a significantly higher number of total fixations for the inference condition when compared to main action and background conditions, potentially indicating reduced efficiency of the visual search (Poole & Ball, 2006). Combined with the accuracy results, this finding supports the existing literature indicating that processing speed is associated with the degree of difficulty of the information being analyzed (Houlihan, Stelmack, & Campbell, 1998). Interpretation of inferences is more difficult than comprehension of explicit facts; therefore, the higher number of total fixations demonstrated by both participants with and without TBI potentially indicates overall slower visual search and processing speed when deducing implied meaning from text and images. It is probable that both individuals with and without TBI exhibited more fixations for the inference condition because they required a more extensive visual search to locate the target image, process its detailed content, and confirm its match to the written sentence.

Analysis also revealed that participants with TBI demonstrated a significantly longer average fixation duration than controls – specifically within the inference condition. The eye-mind theory gives us a reference for interpreting these findings. This theory proposes that a single fixation indicates the area to which an individual is dedicating their utmost attention at a specific time (Just & Carpenter, 1976). The length of a single fixation potentially reveals the amount of processing resources being allocated to the specific area of viewing; longer fixations generally indicate the information is more difficult to process (Poole & Ball, 2006). Considering this, longer fixations indicate that individuals with TBI required increased time to evaluate and analyze the stimuli within the inferential condition than participants without TBI. Importantly, the images within the inference condition were not inherently different from those in the other conditions; all images were detailed, colorful, and contained multiple pieces of information to study. Yet, despite the access to both written material and visuographic image support, participants with TBI still required more time to process information in the inference condition. This finding is agreeable with existing literature reporting processing speed deficits in the TBI population (e.g., Felmingham, Baguley, & Green, 2004; Madigan, DeLuca, Diamond, Tramontano, & Averill, 2000; Mathias & Wheaton, 2007).

Limitations and Future Directions

This study analyzed fixation and regression patterns through the use of eye-tracking technology to determine how individuals with and without TBI process implied and explicit content from images; however, several limitations exist. One limitation is this study included only parametric analyses of data, which does not account for potential within-group variability. Future studies may consider the use of non-parametric analyses to account for this variability. Non-parametric analyses use a "rank order" of observations within the group rather than assuming data follows a normal distribution (Altman & Bland, 2009), which may be beneficial when analyzing individuals with TBI. The diffuse nature of traumatic brain injury inherently results in a heterogeneous group with a wide range of presenting characteristics, as both pre-injury personal characteristics and injury mechanisms affect outcomes (Corrigan et al., 2015). The use of non-parametric analyses may account for this variability and potentially produce slightly different results.

Second, the demands of the experimental task do not directly correlate with the demands of specific clinical treatment activities. The researchers utilized simple, active sentences and equally contextually-rich images and asked participants to match picture to sentence. An activity such as this is frequently used in various standardized assessments; however, generalization of findings is limited because the task does not directly inform specific treatment activities. Although we can generate potential implications for how these variables inform clinical practice, future research may consider the use of more complex sentence types or real photos to enhance ecological validity.

Third, analysis of our results did not reveal a significant difference in accuracy between the TBI and control groups for any conditions. This finding differs when compared to the previously performed study by Brown and colleagues (2015), which demonstrated that participants with TBI were significantly less accurate than individuals without TBI in interpreting inferential and explicit information. The lack of difference in accuracy is a potential consequence of the heterogeneity often noted within the TBI population (Corrigan et al., 2015). To account for this, future research may consider how accuracy correlates with specific participant characteristics, such as age, education level, and time post-onset of injury. Further analysis along these variables was not feasible within this study, as the small sample size would have resulted in inadequate power and may have contributed to type II errors in data analysis. Investigation of these characteristics in future research with larger sample sizes may highlight more significant differences between groups and across conditions.

Conclusions and Implications

The researchers utilized eye-tracking technology to evaluate the visual attention of individuals with TBI when processing implicit and explicit information utilizing measures such as fixations and regressions. The results of the study demonstrated that individuals with and without TBI demonstrated lower accuracy and required more processing time when processing implied content when compared to explicit information, suggesting that this condition was more difficult. Furthermore, individuals spent roughly an equal percentage of time fixating on the target images within sets and looking at all three of the foil images, indicating individuals spend more time analyzing information that is of greater importance. These findings have potential implications for clinicians who work with individuals with TBI.

The results of the current study provide foundational knowledge about visual processing following TBI and the use of supports in rehabilitation. Clinicians may consider the use of contextually-rich images for assessment of language and cognition after TBI. Tasks such as picture description potentially reveal valuable information about skills such as thought organization, attention to detail, and information synthesis of individuals after brain injury. Second, clinicians may utilize images to support cognition and, more specifically, memory after TBI. Incorporating real-life photos that are personally relevant to the individual may serve to enhance their memory for past events and elicit more specific, detailed language when describing these events. Finally, images may be used to enhance comprehension during various tasks. Specifically, visuographic support may serve to augment auditory and reading comprehension when engaging with more complex material involving inferencing or integration of multiple pieces of information from a lengthy text. The use of visual supports is warranted throughout the acute and late stages of recovery from TBI.

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