Article ‣ Top-down Visual Framework for Optometric Vision Therapy for those with Traumatic Brain Injury

Amy Chang, OD, Fort Bragg, North Carolina
Allen H. Cohen, OD, SUNY-College of Optometry, New York, New York
Neera Kapoor, OD, MS, SUNY-College of Optometry, New York, New York

ABSTRACT

Vision therapy has been successful in reducing visual symptoms experienced by patients with sensorimotor visual deficits since the early twentieth century. Recently, there has been a surge of scientific research in the area of neuroplasticity demonstrating physiological changes evident following rehabilitation in those with traumatic brain injury. This research has revealed changes to the brain after therapy in the areas of language and motor function, which could also apply to vision rehabilitation. This article provides an overview of the concept of neuroplasticity, along with the contemporary research, which supports the importance of top-down, visual information processing in optometric vision therapy. Based upon this neuroplasticity research, a template will be proposed to assist the vision rehabilitation practitioner in developing protocols and enhancing vision therapy procedures to address visual processing deficits as a result of traumatic brain injury more effectively.

Keywords: brain injury, diffuse axonal injury, multi-sensory integration, neuroplasticity, top-down, vision rehabilitation, vision therapy

Introduction

The Centers for Disease Control and Prevention estimate that 1.7 million people in the United States sustain a traumatic brain injury (TBI) every year.[1] This estimate excludes the unknown number of people incurring mild concussive events who do not report to the emergency department for assessment. Symptoms evident following TBI are often referred to as post-concussive symptoms and include deficits of cognition, affect, and multimodal sensorimotor function. The period of natural recovery following TBI is reported to be as long as one to two years post-injury, but this recovery may remain incomplete.[2] An incomplete recovery of function following TBI supports the requisite evaluation, rehabilitation, and monitoring of residual persistent deficits, which may otherwise hinder activities of daily living (ADLs), quality of life (QOL), and possible return to work. For example, post-concussive symptoms persisting beyond one year post-injury have been reported in approximately 10-15% of those with mild TBI (mTBI).[3] Many patients with TBI, including those who recover well with rehabilitation, are susceptible to persistent post-concussive impairments. These impairments can become manifest under circumstances of physiologic or psychological stress[4] and make sustaining a job or living independently challenging. In the moderate to severe TBI population, the majority of post-concussive symptoms persisting more than one year post-injury[5] prevent the individual from living independently and contributing to society economically.

In terms of persistent sensorimotor anomalies, the reported frequency of sensorimotor visual deficits in TBI ranges from 20 to 85%, depending upon the nature of the visual deficit and the criteria used in the study.[6-10] Many visual problems can be addressed with standard optometric modalities such as refractive correction, prismatic correction, or varying degrees of occlusion.[11] However, there is a high prevalence in the TBI population of convergence insufficiency (30%), deficits of saccades (19.6%), and deficits of accommodation (21.7%),[11] all of which impact visual motor integration and higher-level visual processing. These sensorimotor visual deficits, which cannot always be corrected with a simple refractive or prismatic correction, often require vision therapy as a treatment option.

Recently, there has been an increase of neuroscience research demonstrating how rehabilitation can, through neuroplasticity, facilitate neural changes.[12,13] This research, in conjunction with the existing body of knowledge regarding the use of prism, tints, and basic vision therapy protocols for the treatment of those with TBI, has provided more insight into how visual processing possibly occurs at a cortical level. Further, this research results in a better understanding of the visual symptoms and allows optometrists to apply this information in the development of more effective vision therapy procedures for this population.

Mechanism of Visual Consequences of TBI

Mild traumatic brain injury is the most common type of TBI by far.[1] While the majority of patients with mTBI recover to a significant degree, approximately 20% will be unable to return to work, and even more remain symptomatic.[14] Diffuse axonal injury (DAI) has been identified as a significant process underlying the consequences of TBI.[15] Diffuse axonal injury affects processing streams in the brain[16] through mechanical forces that result in shearing of the axonal fibers. This injury occurs at the moment of impact.[17]

Diffusion tensor imaging (DTI), which measures the mobility of water molecules through white matter tracks,[18] is one means of visualizing the disruption to processing streams evident in mTBI.[19] The impact of DAI on visual processing streams has been documented, and the consequences can be best understood by first understanding the roles of these streams.[17]

Neuroanatomy of Visual Processing

It is well established there are two major visual processing streams in the cortex: the ventral and dorsal streams.[20] Both streams originate in the occipital cortex. The ventral stream and its connections to the temporal lobe are important primarily for object recognition, while the dorsal stream and its association with the parietal lobe are more specific for processing the spatial aspects of the visual input.[21]

Recent research suggests that after reaching the posterior parietal cortex (PPC), the dorsal stream trifurcates into distinct pathways: the parieto-prefrontal pathway, the parieto-premotor pathway, and the parieto-medial temporal pathway.[22] Each pathway mediates different aspects of visuospatial function, and understanding these pathways and the associated processes leads to a greater understanding of the visual symptoms experienced by those with TBI.

The parieto-prefrontal pathway is involved in two main functions: the selective control of eye movements, which is important in reading eye movements, and spatial working memory, which is important for navigating through a new environment. Lesions of the PPC are associated with deficits in these functions.[23]

The parieto-premotor pathway has projections to both the dorsal and ventral premotor cortex, receiving vestibular input from the cerebellum. The parieto-premotor pathway is responsible primarily for visually-guided action by maintaining online coordinated maps of space and body position. This pathway is important for navigation, the integration of body movement with vision. Deficits here would result in difficulties with activities such as reaching and grasping, as well as walking down staircases.

The parieto-medial temporal pathway, with connections to the limbic areas, is the most complex and least understood of the three pathways. Studies indicate that it is crucial for navigation, but it is unclear if and how this pathway contributes to other visuospatial functions.

As the source of these three branches of the dorsal stream, the PPC may be viewed as a "neural nexus of visuo-spatial processing"[20] with connections across multiple areas of the brain. The PPC also receives input from the auditory cortex, making this "neural nexus" important for intermodal processing.[24,25] An analogy would be to think of the PPC as a hard drive, which contains long-term storage of spatial information within and across the sensory modalities.

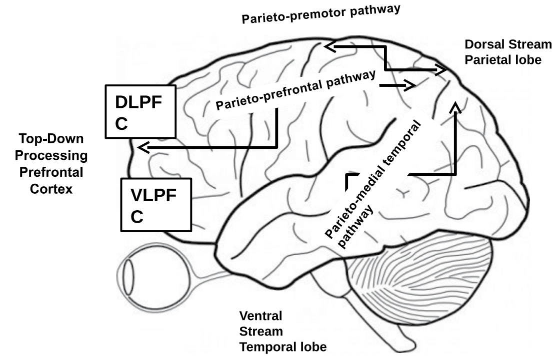

Figure 1: Projections from the posterior parietal cortex

Damage to the parietal lobe can lead to impairments in many visual tasks, such navigating through a crowded supermarket, reaching and grasping objects, and learning from past visual experiences.[12] In addition, the speed of visual information processing along these pathways can be impacted so that there is a delay in the performance of these tasks.

Pre-Frontal Cortex

The parieto-prefrontal pathway relays information to the prefrontal cortex. It may be easier to understand the role of the dorsal lateral prefrontal cortex (DLPFC) with an analogy of a conductor. Its role is in the preparation of eye movements. It has direct connections with the main cortical oculomotor areas which are the frontal eye fields (FEF) and the supplementary eye fields (SEF) in the frontal lobe.[26] It also makes several connections with the parietal eye field in the PPC, cingulate eye field in the anterior cingulate cortex, and the superior colliculus in the brainstem. With this understanding, one may appreciate the many actions that the DLPFC controls. For example, the DLPFC is involved in the inhibition of unwanted reflexive saccades and the triggering of correct intentional saccades, which are the main functions of the FEF and SEF. These are the major components of visual attention.[27] Visual attention is goal-directed behavior that focuses conscious awareness towards relevant stimuli and away from irrelevant or competing stimuli.[28]

The DLPFC also controls working memory, which is involved in memory-guided saccades, and is used temporarily to maintain and manipulate the attended information when it is no longer accessible in the environment. The DLPFC is the primary facilitator for top-down processing, and this manuscript will focus on the relay of information to and from the parietal lobe via the parieto-prefrontal pathway.[27] The analogy would be to think of the pre-frontal cortex as the conductor and the PPC and parieto-prefrontal pathway as the symphony orchestra.

Visual Processing: Bottom-up and Top-down

Visual processing involves an interaction between automatic (bottom up) processes and strategic, voluntary (top-down) control of visual processes and decision-making

(Figure 1). Bottom-up processing is reactive and depends primarily on the brain's reception of stimulus information from sensory receptors.[29] An example of a deficit in bottom-up visual processing is in end-stage glaucoma, where the peripheral field is no longer intact. Impaired peripheral vision due to pre-chiasmal optic nerve damage would result in a deficit of bottom-up visual processing, such as difficulty initiating saccades in the direction of an oncoming car when trying to cross a street.

On the other hand, top-down visual processing is dynamic and always changing. It uses prior experience, existing knowledge, expectation, and motivation to permit the performance of a broader range of behaviors and faster adaptation to changing environmental conditions, such as navigating through a crowded environment and driving a car.[18]

The dorsal stream plays a major role in top-down processing and is vulnerable to diffuse axonal injury because of the vastness of its connections. The authors of this manuscript hypothesize that a disruption in top-down visual processing, which consequently results in more pronounced bottom-up visual processing, may impair the ability to form an accurate spatial representation of the visual image. This hypothesis corroborates the common visual symptoms reported by those with TBI of becoming distracted easily and overwhelmed in multiple visually-stimulating environments, such as busy shopping malls and streets, as well as their inability to see pictures as a whole.

Post Trauma Vision Syndrome

Post trauma vision syndrome (PTVS) has numerous signs and symptoms (Table 1). All of these symptoms are associated with cortical areas vulnerable to DAI. For example, a few of the most striking symptoms experienced by patients with TBI are dizziness; discomfort associated with excess visual, auditory, and motor stimulus in their spatial world; and difficulty navigating when in a crowded environment. The ability to navigate through a visually-stimulating environment requires visual attention in order to attend to the necessary features of the visual space while reducing attention to competing features. In addition to visual attention, active working memory is important for interpreting the visual space as one navigates through the environment. These are all features of the DLPFC, which is vulnerable to diffuse axonal injury.

The PPC is important for flawless integration of intermodal sensory inputs, allowing for a stable cohesive internal map to guide oneself through the environment.[30] Damage as a result of DAI to the parieto-prefrontal and parieto-premotor pathways often interferes with this integration and may result in a sense of imbalance and confusion.

Symptoms associated with reading difficulties correlate to deficits in the control of voluntary eye movements, which is integrated in the frontal eye fields of the prefrontal cortex.[31] Other issues, such as anomalies of vergence, accommodation, and cognition, may also confound reading-related ability in those with TBI.[32,33] The neurological components of vergence do not lie solely in the brainstem, but have significant cortical inputs as well. The parietal lobe contains neurons responsible for changes from retinal- to body-centered coordinates, so that objects can be located in three-dimensional space. The frontal lobe contains neurons that discharge for convergence and divergence movements during smooth pursuit of an object in depth, as well as predictive vergence tracking.[34] The authors hypothesize that this could be the explanation for why vergence disorders are so prevalent in this population.

The group of symptoms associated with poor eye-hand coordination and handwriting (e.g., visual-motor integration) is mediated to a degree by the parieto-premotor pathway,[27] which shares connections with the DLPFC and therefore is susceptible to diffuse axonal injury.[13]

Learning-dependent Neuroplasticity

Studies in learning-dependent neuroplasticity show that it is possible to re-learn behaviors that were lost following injury. There is a difference between learning in an intact brain versus relearning in a damaged brain. Unlike in normal learning conditions, rehabilitation can use learned behaviors that are still stored within the neuronal circuitry of the damaged brain. The process by which rehabilitation is able to use or to access learned behaviors is through recruitment.[35] In recruitment, areas of the cortex that can, but may not have been making significant contributions to that behavior prior to the injury are activated after training. It is now understood

Table 1: Symptoms associated with Post Trauma Vision Syndrome

Blurred vision, Distance viewing	Face or head turn	Disorientation	Discomfort while reading	Easily distracted	Loss of balance	Dizziness
Blurred vision, Near viewing	Head tilt	Bothered by movement in spatial world	Unable to sustain near work	Decreased attention span	Poor eye-hand coordination	Poor Coordination
Slow to shift focus, near to far to near	Covering, closing one eye	Bothered by noises in environment	General fatigue while reading	Reduced concentration ability	Poor handwriting	Clumsiness
Difficulty taking notes			Loss of place while reading	Difficulty recalling what has been read	Poor posture	
Pulling or tugging sensation around eyes			Eyes get tired while reading	Easily distracted		

that the damaged neurons can re-establish functional connectivity through the process of axonal and dendritic sprouting and synaptogenesis, which reinforces specific synaptic connections.[36] In unilateral motor deficits, the recovery is shown to be mediated by the premotor cortex.[37] In higher cognitive function, which includes language and vision, there has been research showing recruitment of the frontal cortex in the recovery of language function.[38] This is a very important point because the therapy outlined below is based on this concept of recruitment. This concept is that through top-down processing, we are able to recruit the prefrontal cortex to utilize and access the visual processes that have been impaired.

Top-down Processing

Recent research in neuroplasticity has demonstrated that therapy which enhances top-down processing results in recovery of function and reduction in symptoms.[39] Other research studies have demonstrated that increased prefrontal parietal integration and increased connectivity in the DLPFC result in recovery of cognitive function.[19] An example is a study done with subjects who have recovered language function after suffering a stroke. The investigators used positron emission tomography scanning to map out neural activation while subjects performed tasks on heard words designed to direct attention either to meaning or to sound structures. These two conditions were compared to specific brain regions involved in processing the meaning of words. They found that increased integration of frontal and parietal lobe function during language processing was associated with recovery in stroke patients with aphasia.[40] Using functional magnetic resonance imaging (fMRI), another study was performed on schizophrenic patients with working memory impairments where cortical activation changes were monitored while the subjects performed a short-term memory task. The results showed significant functional connectivity between the left DLPFC and other areas of the cortex involved in processing verbal stimuli.[41] These are just two of the many studies that show increased connectivity between the prefrontal cortex and associated regions after practice of a cognitive task. These studies demonstrate neuroplastic changes to the brain after practice of tasks that employ the use of top-down processing. There has also been a study performed that used fMRI and showed increased functional activity within the frontal areas, cerebellum, and brainstem in patients with convergence insufficiency after completion of vision therapy.[42] Clinical practice is beginning to embrace these concepts as the basis for effective visual rehabilitative therapy for TBI patients.

Components for Effective Vision Therapy

To be effective when treating patients with TBI, vision therapy techniques must incorporate the newly understood mechanisms of top-down visual processing and neuroplasticity. Cohen refers to five components of effective vision therapy: motivation, feedback, repetition, sensory-motor mismatch, and intermodal integration.[43] Each component involves some degree of top-down processing. By incorporating these components into a vision therapy program, neuroplastic changes can be enhanced, resulting in a more effective treatment program. Each component is discussed in detail along with the associated neuroscience foundation.

Motivation/Active participation

This is conscious, goal-directed effort, which results in the activation of the prefrontal cortex[44] to effect neuroplastic changes in the complex processing streams involved in visual perception. Motivation drives the patient to be an active participant in therapy, and understanding the goals and process of each procedure helps to sustain this level of participation at a therapeutic level. Studies have shown that prefrontal parietal integration resulted in recovery of function in aphasics.[40] Activation of the prefrontal cortex coupled with visually guided movement is the visual correlate to that study and is thought to promote recruitment and recovery of function.

Repetition

Repetition is the next component and is necessary for neuroplastic changes to occur. Kandel's research in neuroplasticity demonstrated that repeated stimulation of a neuron resulted in increased synaptic strength.[45] He also found that repeated stimulation interspersed with periods of rest resulted in changes that lasted much longer than larger but less frequent periods of stimulation. The research that Kandel performed was on a simpler organism, the Aplysia; however, similar research performed on humans (with a much more complex neurological system) corroborates his findings.[46]

Feedback

Feedback is the utilization of information to recalibrate and to refine encoded responses. The speed and accuracy of top-down processing is modulated and refined by sensory and motor feedback, such as auditory, visual, and proprioceptive cues. One excellent visual feedback mechanism is to use physiological diplopia in developing the sensorimotor tasks of triangulating the visual system to an area in space. Spatial working memory and accurate spatial localization are important in guiding the ocular motor system for convergence to a near object. The polarized vectogram is a good example of using this high-level feedback. By developing the awareness of physiological diplopia with a pointer, the patient learns to use physiological diplopia as feedback to guide and to confirm the location of the virtual projection within the spatial horopter. Auditory feedback can be introduced in many of the Neuro-Vision Rehabilitator software (NVR)[a] modules. In the Visual Motor Enhancer module, the patient maintains eye fixation on a designated letter that is displayed on a rotating pegboard. When the patient guides the remote control outside of the designated letter, the patient will hear a sharp beeping tone which will continue until the patient guides the remote control back inside the designated letter. This top-down visual motor adjustment which is initiated by auditory cues is an example of an auditory feedback procedure.

Motor match to a sensory mismatch

Performance in the multisensory world requires input from many areas, including the visual cortex, premotor cortex, motor cortex, basal ganglia, cerebellum, and brainstem. All of these areas relay information to the parietal cortex. Subsequently, the parietal cortex relays this information to the different visual processing pathways, including the parietal-prefrontal and parietal-premotor pathways. The parietal and cerebellar regions are activated in the initial error-correction phase.[47] Since the visual pathways that originate in the parietal cortex are affected by TBI, the ability to make these rapid adaptations is diminished. Therefore, one of the deficits evident in those with TBI is reduced speed of retrieval of these learned, visually-guided motor skills, which may contribute to the disequilibrium that those with TBI experience. Loading visual therapy procedures with filters, yoked prism, stereoscopic cards used in a stereoscope, and various lens combinations can manipulate the visual input. Then, with appropriate feedback modalities, the patient guides their motor response to this input, which is important in enhancing sensorimotor recalibration.

Multi-sensory integration (intermodal)

As discussed earlier, TBI often affects pathways associated with the parietal and prefrontal lobes, resulting in reduced speed of processing. As a result of the reduced speed and inefficiency of the parietal lobe and associated processing streams, those with TBI often feel overwhelmed and disoriented, especially when there are unpredictable visual changes, smells, and sounds in their environment. By systematically loading vision therapy procedures with balance, vision, motor, and auditory inputs, the speed of visual information processing may be enhanced. Any therapy procedure which incorporates the use of a balance board and metronome with ocular motility may be used to develop this important neuro-processing skill.

An example of a procedure incorporating this concept is the Ocular Vestibular Integrator (OVI) module of the NVR. The patient views a large projection of multiple targets and is instructed to fixate a central point while being aware of, but not distracted by, peripheral targets. As the targets located peripherally light up, the patient experiences the awareness of the spatial position of the target. This awareness of the peripheral spatial position of the target is utilized to direct the patient's eyes to the target. Once their eyes are on the target, the patient attempts to eliminate the target by using their visual system to guide their hand, which is holding a remote control device. The accuracy of the elimination is confirmed by an auditory beep. This procedure can be made more challenging by adding distracters, which serve as bottom-up stimuli, that appear at random times. Improved performance enhances peripheral awareness, visual attention, accurate visually-guided saccades, and visual-motor control, all of which are important in rebalancing top-down and bottom-up visual processing.

A more general guideline to procedures that incorporate multisensory integration is the use of multiple Post-it notes, labeled with either numbers or letters, which are randomly placed on a wall. These act as both central and peripheral targets, meaning that the patient first has to find the designated character with their peripheral vision then make an accurate saccade to that Post-it and fixate on it with their central vision. To make this more challenging, the patient can be instructed to use a laser pointer in order to use eye-directed (goal-directed top-down) motor movement to place the laser directly on the designated Post-it note. The OEP clinical curriculum has standardized the Central-Peripheral saccades and flashlight pointing procedures that incorporate the same concepts listed above.[48] Other instruments that can be used are the Wayne Saccadic Fixator, stick ups, and the space localizer. Adding a balance board further integrates the vestibular system to this procedure, and having the patient wait a specified number of metronome beats before moving on to the next target allows auditory integration.

Conclusion

Diffuse axonal injury can result in permanent damage to large pathways and has a predilection for the frontal lobe. Visual processing symptoms of which TBI patients often complain can be explained due to the fact that visual processing permeates all four lobes, with the frontal lobe being central for top-down processing. Recent research concerning neuroplasticity related to language and short-term memory rehabilitation has shown that top-down processing and multisensory integration is important in effecting neural changes. Based on these current concepts of the importance of top-down visual processing, vision therapy procedures have been proposed to take advantage of neuroplasticity to alter the connections along neural pathways. As top-down processing is enhanced, many visual symptoms experienced by those with TBI may reduce in intensity and frequency, thereby improving their basic activities of daily living and overall quality of life.

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a. HTS Inc. 6788 S. Kings Ranch Rd. Suite 4 Gold Canyon, AZ 85118

Correspondence regarding this article should be emailed to achang05@gmail.com or sent to Amy Chang, OD, 147 Mallard Cove, Vass, NC 28394, Tel: 718-269-9168. *All statements are the authors' personal opinions and may not reflect the opinions of the the representative organizations, ACBO, COVD, or OEPF, Optometry & Visual Performance or any institution or organization with which the author may be affiliated. Permission to use reprints of this article must be obtained from the editor.* *Online access is available at www.acbo.org.au, www.covd.org, and www.oepf.org.*

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