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Neuro-optometric Diagnosis, Treatment and Rehabilitation Following Traumatic Brain Injuries: A Brief Overview

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“Myopia is not just a problem of vision. It is a problem of the whole body and mind... For the practitioner, it is sometimes the point at which a conclusion is reached, where one has stopped thinking.”

—Dr. Albert A. Sutton, 1968

Retinal processing problems affect a majority of patients following traumatic brain injury (TBI) [1,2]. Sensory, motor, emotional and cognitive systems interact and process stimuli transmitted via retinal fiber pathways [3]; therefore, these systems are susceptible to TBI-related retinal processing dysfunctions. Retinal processing problems can be visual, nonvisual or both [4]. Thousands of retinal fibers are part of the visual system but not necessarily involved with eyesight [5]. For example, the retinohypothalamic tract is a nonvisual pathway, and there is a specific mammalian nonvisual irradiance detection pathway, a complex nonvisual photoreceptive system in the inner retina and visual functions that do not require image formation on the retina [6–9]. Signals transmitted through these fibers affect balance, posture, motor function, sensory integration, visualization, sleep and emotion centers in the brain and can function even with the eyelids closed [10].

Retinal-related symptoms are generally not visible on CT scans or MRI [11]; therefore, these processing problems are often overlooked during the initial phase of diagnosis and treatment. Also, many retinal processing related problems are not discernible by standard central eyesight, visual field, or eye health testing. Regardless of any visual acuity or eye health issues that might be diagnosed and treated, subtle visual and other processing or linkage problems can remain undetected and often an incorrect assumption is made that there are no other retinal system connected problems.

Because of continual stimulation to the dysfunctional nonvisual retinal pathways, patients with undiagnosed conditions may experience various

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symptoms, such as muscle spasms, dizziness, comprehension or attention difficulties, or they may exhibit abnormal behaviors, the causes of which are easily misdiagnosed. A frequent example is acute anxiety that can be misdiagnosed as a panic disorder [12]. The patient might be referred for treatment for the wrong primary diagnosis while the actual underlying cause of the problem remains untreated.

Patients frequently complain that everything “looks” peculiar, yet they cannot articulate what exactly is wrong. The resultant stress and confusion can significantly alter the patient’s comfort level and lifestyle and affect the quality and duration of his or her rehabilitation. Neuro-optometric intervention can often have a significant positive impact on these retinal processing dysfunctions.

Box 1 lists examples of visual and nonvisual retinal-related symptoms that are common in patient complaints following a TBI [11].

These symptoms can, of course, reflect other stress or trauma induced physical, emotional or chemical imbalances. An added complexity in recognizing and isolating the cause of these symptoms is the fact that conscious recognition occurs through the interaction of retinal signals not only with other sensory, motor or cognitive signals but also with the limbic system [13,14], which is linked with various memories, emotions and feelings, such as anxiety, fear, pleasure, depression and anger. Sensorimotor or cognitive responses are sometimes influenced by these emotions via the limbic system and its interaction with retinal signal transmissions.

The focus of this article is on neuro-optometry, *not* neuro-ophthalmology. The *neuro-ophthalmologist* specializes in locating a disease or disruption of a *structure* in the visual pathways. Once it is located many treatment options are available. For example, medication might be prescribed, surgery might be performed to repair the damage or lenses may be prescribed to maximize central eyesight. The *neuro-optometrist* works with brain *functions*, such as sensory, motor and information processing, and specifically, with the perception of external and internal stimuli. Both structure and function can have a role in rehabilitation following TBI.

Neuro-optometric tests can be used to diagnose and treat visual and nonvisual retinal signal processing dysfunctions following TBI. These tests, separately and, more importantly, in the aggregate, can provide information not otherwise available from standard examinations. Four of these tests are discussed herein:

The Yoked Prism Walk evaluates gross body movements at a reflexive level and spatial orientation while the patient is moving. It can demonstrate how poor stability may impair higher level perception such as spatial organization.

The Padula Visual Midline Shift Test measures spatial perception and shows how the patient is organizing space while he or she is stationary and there is an object moving in front of him or her.

Box 1. Examples of visual and nonvisual retinal-related symptoms common after TBI

Possible visual retinal-related symptoms

- Blurred vision
- Intolerance to light
- Double vision
- Loss of visual field
- Binocular vision problems
- Focusing difficulties
- Eye-aiming difficulties
- Spatial perception difficulties
- Eye movement difficulties
- Visual recognition problems
- Inability to distinguish colors
- Inability to visually guide body movements

Possible nonvisual retinal-related symptoms

- Persistent headaches
- Memory problems
- Comprehension and attention difficulties
- Balance problems
- Abnormal posture
- Persistent clumsiness
- Persistent motion sickness
- Concentration or anxiety problems
- Disorientation or disorganization
- Subcortical eye-aiming difficulties (nystagmus)
- Persistent dizziness and nausea
- Persistent muscle tension

Courtesy of The Mind-Eye Connection Professional Corporation, Northfield, Illinois.

The Super Fixation Disparity Test© identifies and quantifies sensory misalignment of the visual axes in the presence of binocular vision. It measures the disparity of foveal alignment at both near and far distances and therefore within the operations of both central and limited peripheral systems and central and expansive peripheral systems.

The Z-Bell© Test evaluates the interaction between auditory localization ability and visual input [15], helps to identify dysfunctional integration of information processing systems, and can determine the kind and amount of intervention necessary through the use of lenses, prisms, filters, and/or occluders.

Neuro-optometric intervention can affect changes to brain processing via the autonomic and central nervous systems, for example, by using lenses, filters, prisms, and occluders to alter light and thereby sensory systems integration. By controlling the amount and direction of light input, the patient's reactions to new environmental stimuli can be measured to determine how well, and in what areas, the visual and nonvisual retinal systems are interacting [16]. Information processing, perception and motor disorders can thereby be identified and modified. As an aid to rehabilitation, lenses can be designed to eliminate or reduce some of the systemic stress deriving from the TBI.

Visual and nonvisual processing affects many sensory, motor, cognitive and emotional systems. Dysfunctional processing or linkages can cause a distortion in spatial or temporal orientation and an overall diminution in the patient's ability to perform even simple everyday tasks.

More than 30% of the human cortex is devoted to vision and visual processing connections with nonvisual systems [17]. Even without eyesight, this capacity is used in other aspects of information processing. Recent research indicates that some segments of the blind population show an improvement in auditory processing when compared with sighted individuals that may derive from the ability to use the occipital cortex for non-visual tasks [18]. An integrated approach to patient testing should include all dimensions of neurologic, endocrinal and emotional possibilities to reveal previously undetected processing dysfunctions. Because effective visual processing and sensory integration are such important elements in patient rehabilitation following most TBIs, a multidisciplinary team that includes a neuro-optometrist is essential for the best possible diagnostic and rehabilitation patient outcome.

Retinal processing

All sensory systems have receptive fields, many of which overlap. The more nerve endings, the more the sensory overlap. The visual system is most notable for sensory receptivity and overlap because each retina has more than 100 million receptor cells in a relatively small area. The size is such that even a 0.1-mm dot of light covers the receptive field of many retinal output ganglion cells, some of which are excited and others inhibited by the light. Additionally, each point on the retina sends signals through parallel channels from each type of receptive field [4].

The retina has two types of receptive fields, each with two concentric and opposite zones. In one field, light striking the inner circle causes an output signal; in the outer circle, light suppresses output. In the opposite field, light striking the periphery triggers an output signal while the inner circle suppresses output.

Receptive fields on each retina combine their information at subcortical and cortical levels to determine eye aiming and fusion, which is measured within the tolerance range of fixation disparity, that is, the range within

which a patient can maintain coordinated eye aiming. A normal range of fixation disparity is achieved by a two-speed mechanism [19]. There is a faster response to retinal image disparity and then a slower response for binocular alignment. The timing and balance of this sequencing is dependent on retinal signal information that is processed by the brain, also within a two-speed sequence. The brain processes subcortical information more quickly than it does cortical information; therefore, subcortical signals, which are most likely to be distorted following a TBI, first affect retinal image disparity. In this situation, the patient might not be able to achieve a normal range of fixation disparity. If the amount of fixation disparity between the eyes is past the tolerance range, the image for central eyesight will not be comfortable, single or clear unless binocular vision is suppressed. Even a mild concussion or stroke for example, can easily disrupt the interaction of these fragile fields and their integration with other sensory systems, causing a sensory integration imbalance.

Of approximately 1 million retinal ganglion fibers per eye that are involved in processing light, more than 80% travel to the visual cortex to be used in eyesight [20,21]. The signals are specifically bundled or grouped. Signals representing details and color travel from the visual cortex to the inferior temporal lobes, whereas others, signals of position, speed and size, travel from the visual cortex to the superior and middle temporal lobes. The retinal signals from the remaining 20% (approximately 200,000 fibers) of the 1 million retinal ganglion fibers branch off to nonvisual structures such as the hypothalamus and to atypical visual structures, such as the superior colliculus, where a majority of visually responsive neurons receive nonvisual sensory signals. These multisensory neurons are cross-modal and their nonvisual inputs can have a significant impact on visual as well as nonvisual responses (at a conscious cortical level), reactions (at a subconscious cortical level) or reflexes (at an unconscious subcortical level) [22]. The superior colliculus processes retinal signals at reflexive subcortical and subconscious and conscious cortical levels [23]. It functions independent of and parallel with the visual cortex. The superior colliculus links incoming sensory information with motor output. For example, it is integral to head and eye orientation toward an object or sound being seen or heard.

The retina and its connecting systems are also directly involved in the body's chemical functions. For example, the melatonin chemical receptor has a significant role in vision and is involved in rapid eye movement. Melatonin is linked with thyroid development, and the thyroid hormone receptor is involved in retinal cell proliferation [24,25]. Retinal signals can directly affect mood, posture, hearing, memory and body chemistry. Thus, in addition to attention and consciousness affecting what the patient sees, equally important is the fact that what the patient sees, and how it is processed, can affect his or her attention and consciousness [20].

In summary, there are roughly 1 million retinal ganglion fibers per eye, approximately 200,000 of which are from the peripheral retina and used

mostly for nonvisual functions. All cortical areas have significant nonvisual inputs and major feedforward and feedback connections to numerous nonvisual (subcortical) structures in the thalamus, midbrain and brainstem, including the lateral geniculate nucleus, superior colliculus, pulvinar, basal ganglia and pons [26,27]. These remaining peripheral retinal fibers in each eye affect balance, posture, reflexes, emotions, muscles (especially neck muscles), sleep and auditory processing. They function with minimal light and even with the eyelids closed.

Retinal signals

The retina is an extension of brain tissue and has cortical and subcortical feedback and feedforward loops. It converts light energy into electrical signals that are transmitted to precisely mapped sections in the various regions of the brain [16,28]. Retinal sensors transmit information to visual and non-visual centers and connect with the other sensory systems. As is true for the peripheral retinal fibers discussed previously, they function even when the eyelids are closed.

Retinal signals can be classified according to their processing level in the brain. Unconscious (non-planned) reflexes are processed subcortically; subconscious (learned) reactions and conscious responses are processed in the cortex.

Specifically, peripheral retinal signals are processed at both cortical and subcortical levels. The peripheral information that is processed subcortically determines unconscious reflexes; those signals processed in the cortex influence decisions about speed, location, size and shape.

There are three levels in the hierarchy of visual processing. First, the brain processes *unconscious* subcortical brainstem, cerebellar, proprioceptive and vestibular reflexes. Second, it processes *subconscious* cortical reactions for peripheral awareness and organization. Third, it processes *conscious* central cortical responses for attention, identification, and interpretation.

As our environment continues to cause more stress, with the concomitant necessity to organize more and more sensory input, the demand for a stable linkage between peripheral and central eyesight becomes more critical. Also, the interaction of the subcortical and cortical systems becomes more important, yet, the hierarchy of visual processing does not change. It remains the same as when our requirements for basic survival were more primitive and humans relied primarily on subcortical reflexes and subconscious cortical reactions.

A TBI usually results in retinal processing problems that cause a sensory mismatch at subcortical and subconscious cortical levels. Signals from these now dysfunctional levels are naturally processed at a much faster rate than are signals received by central eyesight (at a higher conscious cortical level). The resultant immediate and continual stimulation to the peripheral pathways interferes with the patient's ability to concentrate on central cortical inputs, causing problems with central attention and overall awareness.

For example, the peripheral nonvisual retinal signals that are linked with body posture at a reflexive level trigger eye and head movement. The head and eye position determines the volume of space available within which a person can select where to place his or her attention and, finally, where to aim and focus his or her eyes. The symptoms of visual and nonvisual system dysfunction following TBI often derive from subcortical or subconscious pathways dysfunctions that can be, by standard central eyesight testing or prescriptions, neither properly diagnosed nor treated.

The brainstem deals with low-level, unconscious life-sustaining functions. When any of these functions are out of control owing to a TBI, the lack of stability may force the conscious level to take attention away from higher level needs and to focus on these low-level functions. For example, if a patient's lower level motor system is unable to keep him or her balanced, his or her conscious attention will be pulled away from other information inputs to reorient his or her body in space. This need for reorientation will detract from the patient's ability to concentrate on other stimuli or to maintain a smooth stream of information, affecting everyday life as well as the increased demands of TBI rehabilitation.

The *unconscious* peripheral nonvisual retinal signals that are processed in subcortical structures account for a significant majority of the total peripheral retinal fibers. They provide information for spatial orientation, balance and integration with other sensory signals, including, cerebellar functions that involve coordination of balance, movements, and thoughts. Functionally, the fundamental senses (vision, olfactory, auditory, tactile, gustatory, vestibular, proprioceptive, and the other parts of the somatosensory systems) are not separate. The sensory totality links within the brain and there are myriad interconnections and interactions. TBI usually impacts on this signal interdependence and integration.

When a TBI disrupts normal unconscious automatic functions, such as muscle tone, reflexes, balance, gait or postural alignment, these functions are often replaced with new and frequently maladaptive patterns. One of the manifestations of these changes is increased or decreased subcortical sensitivity as a result of processing dysfunctions, such as nausea during normal head movement or midline posture shifts in an attempt at spatial reorientation. If the maladaptive behavior occurs at this reflexive brainstem level it can cause unconscious alterations of postural alignment or balance. This complex integration of information ultimately governs reflexive motor control and the effects are circular. Because the eyes interact with the neck muscles, eye movement causes the neck muscles to tighten and loosen. As neck muscles move to maintain balance and head position, the eyes move. The retinal signal dysfunction that usually follows TBI affects the entire gamut of sensory integration and impacts negatively on the patient's lifestyle in general and specifically on his or her rehabilitation process.

Subconscious peripheral visual retinal signals are processed in the visual cortex. This process is commonly called "peripheral eyesight" and includes

information not being attended to but occurring in the periphery. These signals lead to eye aiming. They aid a person in organizing his or her environment and enable him or her to judge object location. What is commonly known as “eyesight” is the *conscious* central retinal signals that are also processed in the visual cortex. These signals are stimulated after attention is shifted and aiming is completed.

Approximately 80% of the retinal ganglion fibers transmit signals to the visual cortex; approximately 20% transmit signals to subcortical structures where visual processing integrates with nonvisual signals. Cortical and subcortical retinal signals are linked through the pathways listed in **Box 2** via the reticular system [29], which affects muscle control, postural alignment, and arousal and suppression of cortical activity, and have multiple feedback and feedforward connections [4].

Box 2. Retinal signal pathways [30]

SUBCORTICAL

Retino-tectal (collicular) pathway

SPATIAL ORIENTATION

Neuromuscular (balance and posture)

Retino-hypothalamic pathway

CIRCADIAN RHYTHMS

Biochemistry (emotional behavior and sleep patterns)

Accessory optic system

SPATIAL VISUALIZATION

Internal organization (memory and emotions)

Retino-pretectal pathway

VISUAL-MOTOR REFLEXES

Instinct (avoidance and attraction behaviors)

CORTICAL

Retino-geniculo-striate pathway for peripheral eyesight

LOCALIZATION

External organization (speed, location, size and shape)

Retino-geniculo-striate pathway for central eyesight

IDENTIFICATION

Attention (detail and color awareness)

Adapted from Retinal pathways chart, courtesy of The Mind-Eye Connection Professional Corporation, Northfield, Illinois, 2006.

Light entering the retina stimulates the brain at a reflexive subcortical level and a reactive or responsive cortical level. It is the relationship between the faster subcortical and the slower cortical processing that is often

disturbed as a result of TBI and neither these unconscious pathways nor the interaction between sensory inputs is evaluated during a standard neuro-ophthalmologic, ophthalmologic or optometric examination.

Information differentiation and processing

Information processing within and between sensory, motor, emotional and cognitive pathways is not a simple linear stimulus-response mechanism but rather a combined expression of many functional processing systems [4]. It is a dynamic reflex or reaction “stimulus-change-new response” cycle with feedforward and feedback from many processing pathways. For example, before conscious eye aiming and focusing as the eyes move subcortically in an attempt to maintain the body in a stable and balanced position, various sensory signals continue to be transmitted via the nervous systems to the brain for differentiation and processing. The brain responds to these internal and external sensory signals, which are continually changing. The nervous systems and then the body react to those responses.

Mapping the brain

The retina is precisely mapped onto the superficial layers of the superior colliculi where intact retinal ganglial cell axons arborize preferentially [31–36]. When light is angled onto the retina in different ways, different parts of the brain are stimulated [16,37–39], both chemically and electrically. When light is angled downward, the inferior retina is stimulated, which, in turn, sends signals to specialized layers in the visual cortex that link with the temporal lobes. An upward angle stimulates the superior retina, which, in turn, sends signals to other specialized layers in the visual cortex that link with the parietal lobes. Additionally, filters can be used to bend the light in more specific ways. Blue filters bend the light more sharply than red filters and angle the light toward the center of the retina. The longer wavelength of the red filters angles the light more toward the retinal periphery.

Signals from the retina are transferred via predictable bundled retinal fiber pathways, point to point, to predictable locations in the primary visual cortex (V1), the superior colliculi, the superior parietal cortex and the temporal lobe [40–43]. As signals from the light travel deeper into the brain, the receptive fields become larger, and the representation is more to an area rather than specifically point to point.

Each retina and its corresponding visual field can be divided into four quadrants: superior, inferior, nasal, and temporal. From the midline, the nasal and temporal quadrants are medial and lateral to the fovea, respectively; the superior and inferior quadrants are referenced above and below the fovea, respectively.

Ganglial cell axons from the nasal retina (lateral visual field) project to the opposite (contralateral) side of the lateral geniculate nucleus and the visual

cortex. Axons from the temporal retina (medial visual field) always project to the same (ipsilateral) side of the lateral geniculate nucleus and visual cortex. Axons from the inferior retina (upper visual field) project via the temporal lobe; axons from the superior retina (lower visual field) project via the parietal lobe [44]. Light is bent onto the retina and signals are sent to V1 (primary visual cortex) and eventually to V5/middle temporal (MT) [45]. Neuro-optometric testing can use this “mapping” to aid in determining the area of brain damage and the method and direction of neuro-optometric intervention.

Retinal mapping and yoked prisms

The use of yoked prisms to identify and treat vision disorders is well known and the successful use of yoked prisms in treating patients who have a TBI has been broadly documented [1,12,46–48]. A yoked prism is defined as two identical lenses that are thicker on one edge and identically positioned in front of the patient’s eyes. The thicker base of the prism is in the same direction in front of both eyes. (In a non-yoked prism, either two different prisms are used, or the same prism is used in different positions in front of each eye.) The yoked prism bends the light up or down or at an angle from the side, the direction being determined by the placement of the thicker edge. The retina converts light into electrical signals, which can be directed via the optic nerve axons and the visual cortex to an injured part of the brain where the patient may respond atypically. A different direction of yoked prism can bend the light to a non-damaged area of the brain, eliciting a more favorable patient response. For example, a stroke patient during the Yoked Prism Walk, might feel unsteady and dizzy with base left (BL) or base down (BD) yoked prisms but balanced and steady with base right (BR) or base up (BU) yoked prisms. This finding would most likely indicate damage to the left temporal lobe and prisms could be prescribed to angle light away from that area and to an unaffected area of the brain.

In general, the following prisms will cause light to interact with the corresponding brain locations [16,44,49]:

Base Up	(BU)	Parietal lobes
Base Left	(BL)	Left side of cortex
Base Down	(BD)	Temporal lobes
Base Right	(BR)	Right side of cortex
Base Down and Right (right oblique down)	(BDR)	Right temporal lobe
Base Down and Left (left oblique down)	(BDL)	Left temporal lobe
Base Up and Right (right oblique up)	(BUR)	Right parietal lobe
Base Up and Left (left oblique up)	(BUL)	Left parietal lobe

Optometry and the sensory and motor systems

External stimuli enter the body through two pathways in each of the senses—a lower brainstem (reflexive) level and a higher cortical (developed)

level. In this context, the eyes provide for quick and accurate evaluations of the autonomic and central nervous systems simultaneously and the interactions between the two.

The autonomic nervous system governs a person's internal body chemistry and is composed of a complex balance of fluids, hormones, and neurotransmitters. Each component has a range of tolerance to internal and external changes. Neuro-optometric testing can quantify changes in the autonomic nervous system by providing measurements of pupil reactions and focusing abilities. Also, changes in breathing rate heart rate and blood pressure can be assessed by evaluating how the patient responds while wearing various lenses and filters.

The central nervous system constantly converts external sensory signals into electrical signals that travel through the spinal cord and brainstem, alerting the person's internal systems to changes in the external environment. The individual's ability to differentiate or become aware of these changes depends on the reticular activating system. The more activated the system is, the more the person can place attention on his or her environment. TBI typically disrupts sensory signals and processing in some way. A patient with a TBI can have some systems suppressed (hyposensitive) and/or others overactivated (hypersensitive). Neuro-optometric probes of the visual sense and its intersensory pathways can determine where damaged pathways are located. Combinations of lenses, prisms, occluders and/or filters can then be used to redirect light away from hypersensitive pathways or toward hyposensitive ones.

Postural alignment and balance are often affected by visual system disruptions following TBI. Motor fibers transmit the signals that determine eye movements and visual axis. The eyes will then be directed toward a point of acceleration or impact. These signals are influenced by the vestibular apparatus, which responds to the head and neck positions that affect balance and therefore, gait. Additional sensory input via the spino-tectal pathway affects reflex movements of the head and, thereby, eye pointing. Proprioceptors in each muscle, including the eye muscles, are also critically important. The extraocular muscles are used in eye aiming and are a precondition for the intraocular muscles to be used in focusing. This process of interconnected sensory systems is easily interrupted by a TBI or even a mild brain injury. The result is a visual system dysfunction that can affect visual processing, balance and movement. For example, for a patient to walk in a straight line, he or she might have to run his or her hand along a wall at the same time. The additional sensory input from his or her hand supplements or replaces the faulty visual input and allows for smoother motor output. Without this kinesthetic feedback, the brain is often receiving partial or mismatched information causing the patient to wobble or lose his or her balance.

A patient with a TBI is often abnormally affected by changes in light input. Light travels in a sensory-motor loop. When it strikes the retina, it

stimulates reflex pathways and affects eye movements, among other functions. The patient will sometimes alter the position of his or her body in an attempt to redirect incoming light to more efficient retinal locations, or will attempt to suppress the stimuli. Several neuro-optometric tools and tests are available to alter the direction of light striking the retina.

The Padula Visual Midline Shift Test, the Yoked Prism Walk, the Super Fixation Disparity Test®, and the Z-Bell® Test create a diagnostic picture that can have a significant impact on rehabilitation outcomes and the patient's quality of life.

The interaction of external and internal sensory stimuli

An important factor in determining the course and success of rehabilitation following TBI is the patient's attitude, stamina and comfort level. The patient's tolerance level usually fluctuates with overall physical and mental health. Someone who is wide awake, comfortable and in general good health will probably tolerate external distractions or other stimuli more easily than someone who is sleepy, uncomfortable or in general poor health. A patient with a restricted comfort range will reach his or her "give-up" point much sooner than a patient who is otherwise relatively at ease. Past experiences also influence personality and affect an individual's tolerance level. Posture, attention, and movement can be affected by how patients perceive themselves and their environment. Rehabilitation is essentially the internal processing of new or reintroduced stimuli. The processing systems must be substantially in balance before the body can comfortably integrate the incoming information. A TBI disorients a person and usually reduces his or her range of tolerance. Integration of peripheral retinal systems is essential in achieving reorientation in space and in time. If the patient is not comfortably oriented in his or her surroundings, the rehabilitation process suffers.

After a TBI, a patient will often complain of a significantly increased effort required to complete formerly simple tasks. Within that context there are tolerance ranges that fluctuate depending on the patient's internal state and external stimuli. The mind's interpretation of the environment sometimes controls what the body is willing to accept or perform. Thus, the patient's perceptions and comfort ranges are important elements that affect the work of the rehabilitation specialist, and these factors are inextricably dependent on functional and integrated peripheral retinal systems. Measuring the function or dysfunction of the peripheral retinal systems is the undertaking of neuro-optometry.

Standard eye examinations: necessary but insufficient for patients with traumatic brain injury

Normally, an optometrist measures eye aiming and focusing, which are controlled by the central and autonomic nervous systems, respectively, while

working in front of a Phoropter filled with lenses, with the patient sitting behind it. Peripheral vision functions are largely excluded. Although optometrists routinely include in their examinations some basic neurologic testing, such as pupil testing, extraocular muscle testing or tests of near focusing ability, this is not the comprehensive neuro-optometric survey to which we refer and which is vital following TBI. A neuro-optometric examination would include habitual eye position in both standing and seated postures, with moving and static targets, and introduce light alterations to influence and enhance the patient's physical and mental reactions to changes in the environment. By altering the direction and amount of incoming light, sensory input changes can be made in a patient's unique decision-making system. The evaluation of this "mind-eye connection" becomes an important tool in diagnosis and treatment. An evaluation of body posture and mental reaction to changes enables the neuro-optometrist to measure and alter the distortion a patient perceives in his or her world. This distortion, in turn, affects the nervous systems and thus, the concentration on and performance of daily tasks, including the patient's ability to assimilate rehabilitative input.

The patient who has experienced a TBI often has limited ranges of comfort and varying compensatory body positions. When the patient must deviate from habitual muscle postures and expectations, his or her ranges of comfort and tolerance are challenged. Because a goal of rehabilitation is to correct newly acquired maladaptive habits and patterns, it is first necessary to identify and alter the extant ranges and thereafter measure and observe the new motor responses (new compensatory habits). The neuro-optometric examination can measure these behavioral changes, diagnose subtle vision dysfunctions and identify and modify visual symptoms commonly associated with TBI by intervening with lenses, prisms, filters, and/or occluders. Thus, neuro-optometric testing can reveal and define current visual and nonvisual functioning and concomitant goals for treatment.

Nonvisual pathways have an enormous impact on the patient's lifestyle. Standard eye examinations do not assess the majority of the peripheral retinal ganglion fibers that lead to nonvisual pathways or the interactions of peripheral and central visual systems.

Neuro-optometric tests

Four neuro-optometric tests discussed herein can be used to evaluate the stability or dysfunction of sensory integration and retinal receptor sensitivity: the Yoked Prism Walk, the Padula Visual Midline Shift Test, the Super Fixation Disparity Test©, and the Z-Bell© Test.

Yoked Prism Walk

The Yoked Prism Walk tests the patient's stability while performing low-level functions and can demonstrate how poor stability impairs higher-level

functions. The test measures both subcortical reflexes and cortical reactions and responses. It evaluates gross body movements and spatial orientation and balance at a subcortical reflexive level and spatial organization and perception at a cortical level. It reveals how the patient reacts, responds and reorients to various directions of light changes and how well the body reflexes combine with spatial perception. These changes in performance can be actual or perceived by the patient. Either way they can result in incorrect muscle or anticipatory muscle movements.

The test begins with the patient being asked to walk a straight line while wearing a frame with a 20-prism diopter yoked prism. A prism diopter is a unit of measurement used in eyeglasses. It is a ratio of image displacement in centimeters to target distance measured in meters. For example, if a target is 1 m away and the light bouncing off of it travels through a prism that displaces the light 2 cm, the prism is 2 prism diopters.

A yoked prism alters light sent to the retina, which changes information sent to the brainstem level. It also creates an environmental skew at a cortical level. Some patients will be unaware of these subtle changes in their environment, whereas others will be hypersensitive. The room in which the patient is tested can appear to be distorted in size or shape; the floor can appear to tilt downhill, uphill, or slanted to the left or right. As the patient attempts to walk a straight line, counterbalancing the body to account for the perceived slant of the room, his or her responses will indicate whether he or she is paying more attention to the environment or to his or her body; whether the patient emphasizes the room or floor shift (external) or his or her own shift (internal). The responses are measured four different times with prisms that are base up, base down, base right and base left. A base-up prism angles incoming light from below; a base-down prism causes the light to be perceived from above; a base-left prism alters the light so it appears to enter from the right; and a base-right prism causes the light to appear to enter from the left. The patient's posture during each segment of the test can reveal dysfunctional retinal processing that is causing him or her to be uncomfortable or disoriented. Although all patients will initially be disoriented by the yoked prism, a patient without peripheral retinal problems will be able to adjust quickly to the distortions.

Responses can be categorized qualitatively to indicate changes in lower-level (brainstem) and higher-level (cortical) brain functions:

1. Lower brain functions involve information processing systems changes at a reflexive *unconscious* level. The patient may rotate his or her body, lean forward, putting weight on the balls of his or her feet or lean backward, putting weight on the heels. The patient may also use counterbalancing skills by tipping or leaning the body or bending at the waist, putting out his or her arms to steady himself or herself and/or complain of being dizzy or feeling as if they are falling. The lower-level (nonvisual) brain functions process faster than the higher-level (visual) eyesight

functions and can have a more immediate and significant impact on the patient's behavior and, by extension, on the rehabilitation process.

2. Higher-level brain functions involve information processing systems changes at a *subconscious* or *conscious* level. The patient may describe changes in distortions in the environment or will perceive objects as being slanted, closer or farther and/or appearing to be bigger or smaller. Changes in peripheral retinal signals impact on information regarding location, speed, size and shape and can often cause emotional disorientation. These changes can be more significant on a day-to-day basis because they distract from the processing of higher-level central eyesight that is more critical for interacting with the environment.

The Yoked Prism Walk provides general information about how the patient processes information while *he* or *she* is moving. The three other neuro-optometric tests measure higher-level brain functions while the *targets* are moving or stationary and help determine specific treatment. In the aggregate, results from the four tests are combined to form a diagnostic picture.

Padula Visual Midline Shift Test

The Padula Visual Midline Shift Test measures the interaction between the focal and ambient visual systems. While the focal visual system provides information to the brain at a conscious level concerning an immediate visual target, the ambient visual system provides both the midbrain and cortex information about the space in which the body exists. That information is then processed to aid in balance, coordination and posture. The test analyzes the patient's response to the location of a moving target in the environment and how the patient is organizing space in front of him or her. With the patient seated, a wand is moved, both vertically and horizontally, in front of his or her face. Patients are instructed to say "stop" when the wand is perceived to be lined up directly with his or her eyes or nose, respectively. Visual Midline Shift Syndrome is said to occur when the test results in a perceived midline shift, either vertical or horizontal.

The Super Fixation Disparity Test©

The Super Fixation Disparity Test© allows for the measurement of misalignment of the visual axes using biocular testing in a binocular field with both central and expansive peripheral vision in operation. It provides information about how other sensory and motor systems may be influencing spatial orientation and perception at near and far distances, even if input from one eye is suppressed. The test uses a colored laser light projected within a peripheral field allowing for an evaluation of patient visuospatial orientation. The amounts of disparity are measured in each of nine positions. Accurate centration and the elimination of undesirable disparities may be achieved by the application of lenses, prisms, filters, and/or occluders [50]. A patient

with fixation disparity difficulties could experience perceptual confusion, such as, a midline shift or problems with figure-ground differentiation.

Z-Bell© Test

Some of the light striking the peripheral retina travels through nonvisual retinal fibers to the thalamus and other nuclei where visual, auditory and other information signals meet. Changing the way light enters the retina can change a patient's orientation, his or her organization of space and, therefore, his or her information processing and motor output.

Visual and auditory pathways interact and distinct verbal and nonverbal systems are simultaneously involved in perception, memory, language and thought. The nonverbal systems include integration of environmental information involving different sensory modalities [43,51]. In the same manner, there is a connection between auditory localization ability and visual input.

The Z-Bell© Test was developed to evaluate this auditory-visual connection to determine how well the two systems are integrated and to quantify the prescription required to establish equilibrium. The test also evaluates compensatory body posture and weight shifting in relation to sensory mismatches. Because some reading and speech problems often follow TBI, with concomitant dysfunctional integration of the auditory and visual systems, the test is often a useful tool in attempting to localize and quantify sensory mismatch and its impact on perception, concentration and focus.

The Z-Bell© Test has two components. It uses both auditory and visual localization to determine the stability of sensory integration and receptor sensitivity and to evaluate the presence of residual primitive reflexes [52]. The auditory component consists of asking the patient to close his or her eyes and to localize a sound in front of him or her (between the top of the head and collarbone, from shoulder to shoulder, avoiding the midline) by using one finger to touch a ringing bell or other sound source. Different results can be exhibited depending on the frequency of the sound used and the lighting condition. In the visual component, the patient is asked to look at a nonmoving target in the same space in front, to close his or her eyes and then use one finger to reach for the target. The test is repeated, in each component in four positions, two on each side (inner and outer quadrants).

By observing the manner in which the patient attempts to reach for the various sound locations it can be determined whether neck and shoulder or head and eye movements are isolated one from the other, that is, if neuromuscular differentiation is normal. If not, residual primitive reflexes might be indicated by this lack of differentiation. Residual primitive reflexes sometimes emerge following TBI, particularly with frontal lobe damage [52].

By performing the test while the patient is standing, sensory linkages can be examined subcortically and cortically by varying light direction, posture and weight shifting and placement during the test. An evaluation of the autonomic versus the central nervous systems can be made by a refinement

of the application of blinders, visors, yoked and non-yoked prisms and tints, or a combination of the above, within the Z-Bell© Test protocols. Also, the effectiveness of intervening with an asymmetric amount of prism or other lens, filter or occluder applications can be monitored by observing patient accuracy during the test. Neutral density filters reduce light of all wavelengths or colors equally, lessening the overall amount of retinal stimulation. This procedure can have a positive effect on many patients with processing dysfunctions or postural or sensory imbalances following TBI. The Z-Bell© Test can help distinguish the precise amount and effectiveness of filtering needed to balance the processing systems.

These tests not only indicate an inability to differentiate between sensory information, but they also measure which receptors are transmitting accurate or erroneous information for processing.

Although the permutations of patient responses can be myriad, usually there are qualitative trends to aid in diagnosis and treatment. For example, visual and posture changes have a direct impact on information transmitted at the midbrain via the auditory, visual, vestibular, proprioceptive and motor pathways. The mind is confused by sensory mismatches and tries to compensate. These two tests can detect a mismatch in spatial organization and evaluation of test data provides an aid in formulating remedial or compensatory treatment. The mind readjusts perceived auditory location when perceived visual location is shifted and tries to avoid a mismatch by emphasizing the dominant perception. If visuospatial perception does not dominate, a sensory integration dysfunction is indicated [53].

Summary

The visual system is involved in much more than seeing. More than 30% of the human cortex is devoted to vision and visual processing and the myriad connections to other processing systems. Vision continuously interacts with multiple sensory, motor, endocrinal and emotional systems, even during sleep. When light strikes retinal sensors it triggers multiple responses affecting posture, balance, eye and body position, limbic system activity, information processing and other sensorimotor integration. The portion of the retina that is stimulated is determined by head, neck and eye position. Proprioceptive signals from the extraocular muscles are transmitted to the brainstem and are reflexively used in body orientation. Signals to the extraocular muscles are used to aim the eyes; signals to the intraocular muscles are used in focusing. TBI can affect any aspect of this sensory-motor processing.

Patients with TBI can be thought of as being hypersensitive (overwhelmed) by peripheral stimuli of any of the senses and/or hyposensitive (unaware) of necessary peripheral stimuli, causing incorrect spatial and temporal decisions owing to a lack of pertinent information. Although frustration and

anxiety are often seen as primary sequelae to brain injury, those emotions might be more specifically attributed to inefficient visual processing.

Standard eye testing is, of course, necessary but often inadequate for a patient with TBI because the peripheral retina's processing pathways are not typically addressed. Neuro-optometrists can evaluate the ambient visual system by testing with the Yoked Prism Walk, Padula's Visual Midline Shift Test, Super's Fixation Disparity Test®, and the Z-Bell® Test, among others. An analysis of visual and nonvisual patient responses from these tests can help determine treatment modalities that can lead to reorientation or an increased range of tolerance in the emotional, endocrinal and neurologic systems. In TBI diagnosis and rehabilitation, neuro-optometric procedures and interventions can provide a direction and framework for enabling patients to make their own accommodations as they become better able to manage the new amount and organization of stimuli during the rehabilitative process.

It is beyond the scope of this article to detail specific advancements in the field of brain plasticity in adults. It has been an incorrect popular notion that the human brain changes only in a negative sense, that brain cells die and sensory connections are damaged, that uses cannot be restored and that, beyond childhood, the brain cannot develop new neural connections. In fact, the opposite is true and the implications for the treatment of patients with TBI are manifold. Recent neurologic studies [49,54–56] and the profound pursuits of Ramachandran and the Center for Brain Research and Cognition at the University of California at San Diego perhaps provide a final punctuation mark to the long process of laying waste to that popular notion. The adult brain is not a static system of unchangeable circuits; rather, it is a dynamic mechanism that is constantly changing, in part, as a result of new sensory inputs. Its sensory maps are not “hardwired,” and “short circuits” can sometimes be redirected or otherwise modified. This remapping can be surprisingly precise and accomplished over a relatively short period of time [32,49,57]. The brain is a dynamic mechanism and neuro-optometrists are among those at the forefront of applying these new understandings, with special relevance for the rehabilitation of a patient with traumatic brain injury.

Given the high incidence of visual and nonvisual systems dysfunctions following TBI, neuro-optometric testing should be routinely considered in patients with brain trauma. Including a neuro-optometrist in a multidisciplinary approach to TBI diagnosis and treatment can have a significant effect on the direction and duration of TBI rehabilitation.

The Neuro-Optometric Rehabilitation Association

The Neuro-Optometric Rehabilitation Association (NORA) was founded in 1989 by Dr. William Padula to “...promote treatment modalities designed to optimize the frequently neglected visual-motor,

visual-perceptual and visual-information processing dysfunctions in the neurologically affected person. Integration of these unique neuro-optometric treatment modalities maximizes the effectiveness of the rehabilitation team within a multidisciplinary approach” [1,58]. The organization includes optometrists, neurologists and other medical doctors, physiologists, audiologists, nurses, occupational therapists, physical therapists, physiatrists and other members of a rehabilitation team. NORA approaches TBI with an understanding that vision is interconnected with many other functions, including balance, hearing, posture, visualization and attention and that optimum rehabilitation requires the coordinated efforts of professionals in the various disciplines addressing TBI diagnosis and treatment.

Within the field of optometry, the certification process for the specialty of neuro-optometry has yet to be completely standardized, although the final stages can be expected to reach fruition in the next few years. During the past 15 years, NORA has been at the forefront of this specialty and is currently working with the various optometric colleges in finalizing these standards for board certification.

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