Neuro-optometric diagnosis, treatment and rehabilitation following traumatic brain injuries: a brief overview

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ABSTRACT FOR TABLE OF CONTENTS (five sentences):

All sensory systems connect and interact. Traumatic Brain Injuries (TBI) commonly impact on these systems and therefore on the signals transmitted by the thousands of retinal fibers that are part of the visual system but not necessarily involved in eyesight. In the majority of TBI cases there are retinal signal processing problems, both visual and non-visual, that are often overlooked. This dysfunction of sensory and motor systems integration, which can include, for example, problems of spatial orientation, auditory localization or motor function, is generally not visible on CAT scans or MRI and is not discernible by neuro-ophthalmological or standard optometric or ophthalmological testing. Neuro-optometric intervention can profoundly affect diagnosis and treatment following TBI and an interdisciplinary team that includes a neuro-optometrist is essential to the best possible diagnostic and rehabilitation outcome in most TBI patients.

KEYWORDS AND PHRASES

neuro-optometric, traumatic brain injury, peripheral retina, rehabilitation, sensory pathways, retinal processing

NEURO-OPTOMETRIC DIAGNOSIS, TREATMENT AND REHABILITATION FOLLOWING TRAUMATIC BRAIN INJURIES: A BRIEF OVERVIEW

> 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

INTRODUCTION

Retinal processing problems affect a majority of patients following Traumatic Brain Injuries (TBI)[1]. All sensory systems interact and process stimuli transmitted via retinal fiber pathways [2] and, thus, are susceptible to these TBI related retinal processing dysfunctions. Retinal processing problems can be visual or non-visual, or both [3]. There are thousands of retinal fibers that are part of the visual system but not necessarily involved with eyesight [4]. It is well known, for example, that the retino-hypothalamic tract (RHT) is a non-visual pathway, that there is a specific mammalian non-visual irradiance detection pathway, a complex non-visual photoreceptive system in the inner retina and that there are visual functions that do not require image formation on the retina [5][6][7][8]. Signals transmitted through these fibers affect balance, posture, motor function, sensory integration, visualization and sleep and emotion centers in the brain and can function even with the eyelids closed [9].

Retinal related symptoms are generally not visible on computerized axial tomography (CAT) scans or magnetic resonance imaging (MRI)[10] and, therefore, these processing problems are often overlooked during the initial phase of diagnosis and treatment. Also, there are many retinal processing related problems that are not discernable by standard central eyesight or visual field testing or by eye health testing. For example, regardless of any visual acuity or other eye health issues, and even if standard

1 Padula W.V., Shapiro J.B. and Jasin P. Head injury causing post trauma vision syndrome. New England Journal of Optometry (1988) 41 (2): 16-21

2 Portas C.M., Rees G., Howseman A.M., Josephs O., Turner R. and Frith C.D. A specific role for the thalamus in mediating the interaction of attention and arousal in humans. Journal of Neuroscience (1998) 18 (21): 8979-8989

3 Klemm W.R. Understanding Neuroscience (1996) St. Louis: Mosby; p. 150-151

4 Casagrande V.A. and Royal D. Parallel visual pathways in a dynamic system. In: Kaas J.H. and Collins C.E., editors, The Primate Visual System (2003) Philadelphia: CRC Press; p. 1-28

5 Van Gelder R.N., Wee R., Lee J.A., Tu D.C. Reduced pupilary light responses in mice lacking cryptochromes. Science (2003) 299 (5604): 222

6 Brainard G., Hanifin J., Gresson J., et al. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. Neuroscience (2001) 21 (16): 6405-6412

7 Pickard G. Studies of circadian rhythms. As reported in Insight (2002) 29 (2), the College of Veterinary Medicine and Biomedical Sciences, Colorado State University: 4-5

8 Thapan K., Arendt J. and Skene D.J., An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. Journal of Physiology (2001) 535 (1): 261-267

9 Mosley M.J., Bayliss S.C. and Fielder A.R. Light transmission through the human eyelid: in vivo measurement. The British Journal of Physiological Optics (1988) 8 (2): 229-230

10 Padula W. V., Argyris S. and Ray J. Visual evoked potentials (VEP) evaluating treatment for post-trauma vision syndrome (PTVS) in patients with traumatic brain injuries (TBI). Brain Injury (1994) 8 (2): 125-133

visual acuity testing shows 20/20 eyesight, often an incorrect assumption is made that there are no retinal system connected problems. Thus, subtle visual and other processing problems can remain undetected.

Because of continual stimulation to the dysfunctional non-visual retinal pathways, these undiagnosed patients may experience various symptoms or behaviors that are easily misdiagnosed, including, for example, muscle spasms or dizziness, comprehension or attention difficulties or even acute anxiety that can be misdiagnosed as a panic disorder [11]. 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 rehabilitation. Neuro-optometric intervention can often have a significant positive impact on these retinal processing dysfunctions.

It should be noted at the outset that this chapter deals with neuro-*optometry*, not neuro-*ophthalmology*. The neuro-ophthalmologist specializes in locating a disease or disruption of a *structure* in the visual pathways. Once located, for example, medication might be prescribed, or surgery might be performed to repair the damage or lenses could be prescribed to maximize central eyesight. The neuro-optometrist works with brain *function* and sensory and motor integration and information processing, and specifically, with perception of external and internal stimuli. Both structure and function can play a role in rehabilitation following TBI.

The following examples of visual and non-visual retinal related symptoms are common patient complaints following a TBI [12]:

Possible *visual* retinal related symptoms:	Possible *non-visual* retinal related symptoms:
Blurred vision	Persistent headaches
Intolerance to light	Memory problems
Double vision	Comprehension and attention difficulties
Loss of visual field	Balance problems
Binocular vision problems	Abnormal posture
Focusing difficulties	Persistent clumsiness
Eye aiming difficulties	Persistent motion sickness
Spatial perception difficulties	Concentration or anxiety problems
Eye movement difficulties	Disorientation or disorganization
Visual recognition/memory problems	Subcortical eye aiming difficulties (nystagmus)
Inability to distinguish colors	Persistent dizziness and nausea
Inability to visually guide body movements	Persistent muscle tension

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[11] Padula W.V. and Argyris S. Post trauma vision syndrome and visual midline shift syndrome. Neurorehabilitation (1996) 6: 165-171

[12] Padula (1994) op. cit.: 6

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 not only retinal signals with other sensory 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. Thus, sensorimotor responses are sometimes influenced by these emotions via the limbic system and its interaction with retinal signal transmissions.

Neuro-optometric tests can be used to diagnose and treat visual and non-visual 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 will be discussed herein:

(1) The Yoked Prism Walk, which evaluates gross body movements at a reflexive level, spatial orientation while the patient is moving and can demonstrate how poor stability may impair higher level perception.

(2) The Padula Visual Midline Shift Test, which measures spatial perception, showing how the patient is organizing space while he is stationary and there is an object moving in front of him.

(3) Super's Fixation Disparity Test© which 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, thus, within the operations of both central and limited peripheral systems and central and expansive peripheral systems.

(4) The Z-Bell© Test, which evaluates the interaction between auditory localization ability and visual input [15], thereby helping to identify dysfunctional integration of sensory systems and can determine the kind and amount of intervention by lenses, prisms, filters or occluders.

Neuro-optometric intervention can affect changes to brain processing via both the autonomic and central nervous systems, for example, by utilizing lenses, filters, prisms and occluders to alter light and thereby other sensory inputs. 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 non-visual retinal systems are interacting [16]. Information processing, perception and motor disorders

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[13] Itaya S.K., Van Hoesen G.W. and Jenq C.B. Direct retinal input to the limbic system of the rat. Brain Research (1981) 226(1-2): 33-42.

[14] Conrad C.D. and Stumpf W.E. Direct visual input to the limbic system: crossed retinal projections to the nucleus anterodorsalis thalami in the tree shrew. Experimental Brain Research (1975) 23(2):141-149

[15] Poirier C. et al. Specific activation of the V5 brain area by auditory motion processing: an fMRI study. Cognitive Brain Research (2005) 25: 656

[16] Grill-Spector K. The occipital lobe. In: Aminoff M. and Daroff R., editors, The Encyclopedia of Neurological Sciences (2003) Academic Press: 653-660

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 non-visual processing affects many motor and sensory systems. Dysfunctional processing 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 percent of the human cortex is devoted to vision and visual processing connections with non-visual systems [17]. Even without sight this capacity is utilized in other aspects of sensory processing. An integrated approach to patient testing will include all dimensions of neurological, endocrinal and emotional possibilities that can reveal previously undetected processing dysfunctions. Since effective visual processing and sensory integration are such important elements in patient rehabilitation following most TBIs, an interdisciplinary 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 retina has two types of receptive fields, central and peripheral, 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. The more nerve endings, the more sensory overlap. The visual system is most notable for sensory receptivity and overlap since each retina has more than 100 million receptor cells in a relatively small area. The size is such that even a 0.1mm dot of light covers the receptive field of many retinal output ganglion cells, some of which are excited and others inhibited by the light [18]. Additionally, each point on the retina sends signals through parallel channels from each type of receptive field.

Receptive fields on each retina combine their information at both subcortical and cortical levels to determine eye aiming and fusion, which is measured within the tolerance range of fixation disparity, i.e., 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 much more quickly than it does cortical information. Thus, it is the subcortical signals, which are most likely to be distorted following a TBI, that will first affect retinal image disparity. If this is the case, then the patient will not be able to

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[17] Gilbert S.J. and Walsh V. Vision: the versatile ‘visual cortex’. Current Biology (2004) 14 (24): R1056-R1057
[18] Klemm op. cit. 101-102
[19] Schor C. Fixation of disparity: a steady state error of disparity-induced vergence. American Journal of Optometry and Physiological Optics (1980) 57 (9): 618-631

function within a normal range of fixation disparity. If the amount of fixation disparity between the eyes is past the tolerance range then the image for central eyesight will not be comfortable, single or clear. 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 the more than one million retinal ganglion fibers per eye that are involved in processing light [20] 80 percent travel to the visual cortex, to be used in eyesight [21]. The signals are very specifically bundled or grouped; signals representing details travel from the visual cortex to the temporal lobe and others, signals of position, speed and size, travel from the visual cortex to the parietal lobe. The majority of retinal signals from the remaining 20 percent (approximately 200,000 fibers) of the one million retinal ganglion fibers branch off to non-visual structures such as the hypothalamus and to atypical visual structures, such as the superior colliculus, where a majority of visually responsive neurons receive non-visual sensory signals. These multi-sensory neurons are cross-modal and their non-visual inputs can have significant impact on visual as well as non-visual responses (at a conscious cortical level), reactions (at a subconscious cortical level) or reflexes (at an unconscious subcortical level) [22]. The superior colliculus (SC) processes retinal signals at reflexive subcortical and both intentional and subconscious cortical levels. It functions independently of and parallel with the visual cortex. The SC 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 plays a significant role in vision and is involved in rapid eye movement (REM). Melatonin is linked with thyroid development and the thyroid hormone receptor is involved in retinal cell proliferation [23][24]. 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 as important is the fact that what the patient sees, and how it is processed, can affect his attention and consciousness [25]. In summary, there are approximately 1,000,000 retinal ganglion fibers per eye, 800,000 of which are from the central retina. The remaining 200,000 are from the peripheral retina and a majority of these are used for non-visual functions. All cortical areas have significant non-visual inputs and major feedforward and feedback connections to numerous non-visual

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[20] Atkins D.L. The eye and sense of vision, Part 3: central visual pathways. Survey of Neurobiology (1998) George Washington University, Washington D.C.

[21] Lane K. Developing ocular motor and visual perceptual skills. (2004) Thorofare, NJ: Slack Inc.; Ch 3

[22] Stein B.E., Jiang W., Wallace M.T. and Stanford T.R. Nonvisual influences on visual-information processing in the superior colliculus. Progress in Brain Research (2001) 134:143-156

[23] Scher J., Wankiewicz E., Brown G.M. and Fujieda H. MT Melation receptor in the human retina: expression and localization. Investigative Ophthalmology and Visual Science (2002) 43: 889-897

[24] Harpavat S. and Cepko C.L. Thyroid hormone and retinal development. Thyroid (2003) 13 (11): 1013-1019

[25] Atkins (1998) op. cit.

(subcortical) structures in the thalamus, midbrain and brainstem, including the LGN, 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.

PERIPHERAL RETINAL SIGNALS

The retina is an extension of brain tissue and has both 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 [28] [29]. Retinal sensors transmit information to both visual and non-visual centers and connect with the other sensory systems. 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 both at 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.

The three levels in the hierarchy of visual processing can be summarized, as follows. First, the brain processes *unconscious* subcortical brainstem, cerebellar and vestibular reflexes. Second, it processes *subconscious* cortical reactions for peripheral awareness and organization. Last it processes *conscious* central cortical responses for attention, identification and interpretation.

As our environment continues to become more visually demanding, with the concomitant necessity to organize more and more sensory input, the need 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 we relied primarily on subcortical and subconscious cortical functions.

A TBI usually results in retinal processing problems, which 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

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[26] Van Essen D.C. and Anderson C.H. Information processing strategies and pathways in the primate visual system. In: Zornetzer et al, editors, An Introduction to Neural and Electronic Networks, 2nd Edition (1995) Philadelphia: Academic Press; p. 45-76

[27] Kolmac C. and Mitrofanis J. Organization of brain stem afferents to the ventral lateral geniculate nucleus of rats. Visual Neuroscience (2000) 17 (2): 313-318

[28] Grill-Spector (2003) op. cit.

[29] Grill-Spector K., Kushnir T., Hendler T., Edelman S., Itzchak Y. and Malach R. A sequence of object processing stages revealed by fMRI in the human occipital lobe. Human Brain Mapping (1998) 6: 316-328

interferes with the patient's ability to concentrate on central cortical inputs, thus, causing problems with central attention and overall awareness. For example, those peripheral non-visual 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 is able to select where to place his attention and, finally, where to aim and focus his eyes.

In other words, symptoms of both visual and non-visual systems dysfunctions following TBI often derive from subcortical or subconscious pathways dysfunctions that can be neither diagnosed nor treated by standard central eyesight testing or prescriptions.

The brainstem deals with low-level, unconscious life-sustaining functions. When these functions are out of control due to TBI, the lack of stability will force the conscious level to take attention away from higher level needs and to focus on these low-level functions. For example, if the patient's lower level motor system is not able to keep him balanced, then his conscious attention will be pulled away from other information inputs in order to reorient his body in space. This need for reorientation will detract from his ability to concentrate on other stimuli or to maintain a smooth stream of information, thus affecting everyday life as well as the increased demands of TBI rehabilitation.

The *unconscious* peripheral non-visual retinal signals that are processed in subcortical structures account for a significant majority of the total peripheral retinal fibers and provide information for spatial orientation, balance and integration with other sensory signals, such as magnocellular auditory (spatial orientation and organization), cerebellar (balance and coordination of movements and thoughts), vestibular (sense of balance) and somatosensory (discriminative touch, pain and temperature, muscle location and tension). 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 interdependence as well as on their signal integration.

When a TBI disrupts unconscious habits such as posture or unconscious automatic functions such as muscle tone, reflexes, balance or gait, these habits and functions are often replaced with new, 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 posture or balance. This complex integration of information ultimately governs reflexive motor control and the effects are circular. Since the eyes are connected to 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. Thus, 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 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. It aids a person in organizing his environment and enables him to judge object location. These signals lead to eye aiming. 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.

To summarize, eighty percent of the retinal signals are processed cortically and twenty percent subcortically. Most retinal signals are processed via the reticular system [30], which affects muscle and posture control and the arousal and suppression of cortical activity (see p. 13, herein), through the following pathways and have multiple feedback and feedforward connections [31]:

RETINAL SIGNAL PATHWAYS [32**]**

SUBCORTICAL

Retino-Tectal (Collicular) Pathway
SPATIAL ORIENTATION
Neuro-muscular (Balance and Posture)

Retino-Hypothalamic Pathway
CIRCADIAN RHYTHMS
Biochemistry (Emotional behavior, Sleep, Energy)

Accesory 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, Shape)

Retino-Geniculo-Striate Pathway (for Central Eyesight)
IDENTIFICATION
Attention (Detail and Color Awareness)

Thus, eighty percent of the retinal ganglion fibers transmit signals to the visual cortex; twenty percent of the retinal ganglion fibers transmit signals to subcortical structures where visual processing integrates with non-visual signals. Light entering

[30] Scheibel M.E. and Scheibel A.B. Anatomical basis of attention mechanisms in vertebrate brains. In: Quarton G.C., Melnechuk T. and Schmitt F. O., editors, The Neurosciences (1967) New York: Rockefeller University Press; p. 577-602
[31] Klemm op. cit. 149-152
[32] Retinal Pathways Chart courtesy of The Mind-Eye Connection, P.C., 2006

the retina stimulates the brain both 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 being evaluated during a standard visual 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 sensory and motor systems [33]. It is a dynamic reflex or reaction 'stimulus-change-new response' cycle with feedforward and feedback from many processing pathways. For example, prior to 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 very precisely mapped onto the superficial layers of the superior colliculi where intact retinal ganglial cell axons arborize preferentially [34][35][36][37][38][39]. Therefore, when light is angled onto the retina in different ways, different parts of the brain are being stimulated [40][41][42][43], 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 (ventral stream); 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 (dorsal stream). Additionally, filters can be used to bend the light in more specific ways.

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[33] Klemm op. cit. 119

[34] Luo L. Developmental neuroscience. Nature (2006) 439 (7072): 23-24

[35] Cramer S.C. and Chopp M. Recovery recapitulates ontogeny. Trends in Neuroscience (2000) 23: 265-271

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[37] Finlay B. L., Schneps S.E., Wilson K.G. and Schneider G.E. Topography of visual and somatosensory projections to the superior colliculus of the golden hamster. Brain Research (1978) 142: 223-235

[38] Tiao Y. C. and Blakemore C. Functional organization in the superior colliculus of the golden hamster. Journal of Comparative Neurology (1976) 168: 483-503

[39] Siminoff R., Schwassmann H.O. and Kruger L. An electrophysiological study of the visual projection to the superior colliculus of the rat. Journal of Comparative Neurology (1966) 127: 435-444

[40] Grill-Spector (2003) op. cit.

[41] Grill-Spector K., Kourtzi Z. and Kanwisher N. The lateral occipital complex and its role in object recognition. Vision Research (2001) 41: 1409-1422

[42] Downing P. E., Jiang Y., Shuman M. and Kanwisher N. A cortical area selective for visual processing of the human body. Science (2001) 293: 2470-2473

[43] Epstein R. and Kanwisher N. A cortical representation of the local visual environment. Nature (1998) 392: 598-601

Blue filters bend the light more sharply than red filters and angle the light away from the retinal periphery. The longer wavelength of the red filters angles the light more toward the far 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 [44][45][46][47]. (As signals from the light travel deeper into the brain the receptive fields become larger and thereby 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 (LGN) and the visual cortex. Axons from the temporal retina (medial visual field) always project to the same (ipsilateral) side of the LGN 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 [48]. Thus, light is bent from the retina to V1 (primary visual cortex) and eventually to V5/Middle Temporal (MT) [49] via the right or left dorsal stream or right or left ventral stream, depending on which eye and which combination of temporal and nasal or superior and inferior locations.

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

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. In other words, the thicker base of the prism is in the same position in front of both eyes. The yoked prism bends the

[44] Wilson C.L., Babb, T.L., Halgren E. and Crandall, P.H. Visual receptive fields and response properties of neurons in human temporal lobe and visual pathways. Brain (1983) 106 (2): 473-502

[45] Tusa R.J. and Palmer L.A. Retinotopic organization of areas 20 and 21 in the cat. Journal of Comparative Neurology (1980) 193 (1): 147-164

[46] Sereno M.I., Pitzalis S. and Martinez A. Mapping of contralateral space in retinotopic coordinates by a parietal cortical area in humans. Science (2001) 294 (5545): 1350-1354

[47] Falchier A., Clavagnier S., Barone P. and Kennedy H. Anatomical evidence of multimodal integration in primate striate cortex. Journal of Neuroscience (2002) 22 (13): 5749-5759

[48] Yale University Center for Advanced Instructional Media. Retinal projections to the primary visual cortex. Cranial Nerve II–Optic Nerve (1998) Yale University School of Medicine: 6

[49] Bullier J. RIVAGe feedback during visual integration: toward a generic architecture. In: The Odysee Project, Paris (2003): 10

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 responds atypically. A different direction of yoked prism can bend the light to a non-damaged area of the brain, which would, of course, elicit a more favorable patient response. For example, a stroke patient with TBI might feel unsteady and dizzy with base left (BL) and base down (BD) yoked prisms but balanced and steady with base right (BR) and base up (BU) yoked prisms. This 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 [50][51][52]:

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… (BDR) ...….Right temporal lobe

Base Down and Left….. (BDL) ..…. Left temporal lobe

Base Up and Right. …... (BUR) ....…Right parietal lobe

Base Up and Left …….. (BUL) ....Left parietal lobe

OPTOMETRY AND THE SENSORY AND MOTOR SYSTEMS

External stimuli enter the body through two pathways in each of the senses. There is 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 the central nervous systems simultaneously and the interaction between the two.

The autonomic nervous system (ANS) 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.

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[50] Yale (1998) op. cit.
[51] Ramachandran V.S. Plasticity in the adult human brain. In: Julez B. and Kovacs I., editors, Maturational Windows and Adult Cortical Plasticity Proceedings of the Santa Fe Institute, (1995) Vol. XXIII, Reading, MA: Addison-Wesley; p. 179-197
[52] Grill-Spector (2003) op. cit.

Neuro-optometric testing can quantify changes in the ANS 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 (CNS) constantly converts external sensory signals into electrical (neurological) 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 (RAS). The more activated the system is, the more the person is able to place attention on his environment. The reticular system can also suppress sensory signals. This arousal and suppression is controlled by defense mechanisms, previous experiences, energy levels and the person's state of mind. Traumatic Brain Injuries (TBI) will typically disrupt sensory signals and processing in some way. A TBI patient can have some systems suppressed (hyposensitive) and others overactivated (hypersensitive). Neuro-optometric probes of the visual sense and its intersensory pathways can determine where damaged pathways are located and lenses, prisms or filters can be used to redirect light away from hypersensitive pathways or toward hyposensitive ones.

Posture and balance are often affected by visual systems 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. Also, proprioceptors in each muscle, including the eye muscles, are critically important. Signals from the extra-ocular muscles are used in eye aiming and are a precondition for the intra-ocular muscles to be used in focusing. This process of interconnected sensory systems is easily interrupted by TBI. The result is a visual systems dysfunction that can affect visual processing, balance and movement. For example, a patient, in order to walk in a straight line, might have to run his hand along a wall at the same time. The additional sensory input from his hand supplements or replaces the faulty visual input and allows for smoother motor output. Without the kinesthetic feedback the brain is often receiving partial or mismatched information causing the patient to wobble or lose his balance.

TBI patients are often abnormally affected by changes in light input. Light travels in a sensory-motor loop and when it strikes the retina, it stimulates reflex pathways and affects eye movements, among other functions. Thus, the patient will sometimes alter the position of his body in an attempt to redirect incoming light to more efficient retinal locations, or he will attempt to suppress the stimuli. There are a number of neuro-optometric tools and tests available to alter the direction of light striking the retina.

The Padula Visual Midline Shift Test, the Yoked Prism Walk, Super’s Fixation Disparity Test© and the Z-Bell© Test create a diagnostic picture that can have a significant impact on rehabilitation outcomes and on the quality of patient life. These tests are discussed on pages 15-19.

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 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 the patient perceives himself and his 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 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 surroundings then 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 the nervous system has tolerance ranges that fluctuate depending on the patient's internal state and external stimuli. In other words, 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.

ROUTINE EYE EXAMINATIONS ARE INADEQUATE FOR TBI PATIENTS

Normally an optometrist measures eye aiming and focusing, which are controlled by the CNS and ANS, 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 neurological testing, such as pupil testing, extra-ocular 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 both moving and static targets, and introduce light alterations to influence and enhance the patient's physical and mental reactions to changes in his 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 world. This, in turn, affects the nervous systems and, thus, concentration 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 deviating from the patient's habitual muscle postures and expectations, the patient's ranges of comfort and tolerance are challenged. Since 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 or occluders. Thus, neuro-optometric testing can reveal and define current visual and non-visual functioning and concomitant goals for treatment.

Non-visual pathways have an enormous impact on the patient's lifestyle. Routine eye examinations assess neither the majority of the peripheral retinal ganglion fibers that lead to non-visual pathways nor the interactions of peripheral and central visual systems.

NEURO-OPTOMETRIC TESTS

There are four neuro-optometric tests discussed herein that 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, Super’s 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 one meter away and the light bouncing off of it travels through a prism that displaces the light 2 cm, then the prism is 2 prism diopters.

A yoked prism alters light sent to the retina, which changes information sent to the brainstem level. But it also creates an environmental skew at a cortical level. Some patients will be unaware of these subtle changes in their environment; 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 his body to account for the perceived slant of the room, his responses will indicate whether he is paying more attention to the environment or to his body; whether he emphasizes the room or floor shift (external) or his 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; base-down causes the light to be perceived from above; base-left alters the light so it appears to enter from the right; and base-right 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 which is causing him to be uncomfortable or disoriented. While all patients will initially be disoriented by the yoked prism, a patient without peripheral retinal problems will be able to quickly adjust to the distortions.

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

> Lower brain functions involve information processing systems changes at a *reflexive* level. The patient will lean forward, putting weight on the balls of his feet or lean backward putting weight on his heels. He may also use counterbalancing skills by tipping or leaning his body or bending at the waist, putting out his arms to steady himself, complaining of being dizzy or feeling as if he is falling. The lower-level (non-visual) 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 his rehabilitation process.
>
> Higher-level brain functions involve information processing systems changes at a *subconscious or conscious* level. The patient will describe changes in distortions in his environment or he will perceive objects as being slanted, closer or farther, and/or appearing to be bigger or smaller. In other words, changes in his peripheral retinal signals impact on information regarding location, speed, size and shape and can also cause emotional disorientation. These changes can be more significant on a day-to-day basis since they distract from the processing of higher-level central eyesight that is more critical for interacting with his environment.

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

PADULA VISUAL MIDLINE SHIFT TEST

The Padula Visual Midline Shift Test measures both central and peripheral spatial perception. The test analyzes patient response to the location of a moving target in the environment and how he is organizing space in front of him. With the patient seated, a pencil is moved in front of his face and he is instructed to say 'stop' when he perceives the pencil to be lined up directly in front of his nose. Visual Midline Shift Syndrome is said to occur when the test results in a perceived midline shift, either vertical or horizontal.

There are three basic patient responses to the test:

> The most efficient response is for the patient to use peripheral eyesight (peripheral retinal receptors) to judge the target location while he looks straight ahead. Thus, he uses his peripheral visual system to determine when the target is centrally located, and says 'stop'.
>
> A less efficient response is for the patient to subconsciously use his central eyesight (central retinal receptors) to judge the target location, leaving his head straight and moving his eyes toward the target until he perceives it to be directly in front of him. Thus, the patient avoids the peripheral retinal sensors, preferring instead to use central eyesight. The background will move but he is fixated on the object with little or no regard for the movement in his periphery.
>
> The least efficient response is for the patient to turn his head toward the target, using his neck proprioceptors to decide when the target is directly in front of him. Thus, he does not differentiate between proprioceptive information and visual information and, therefore, is less likely to be able to visually organize his surrounding environment.

If the patient cannot accurately assess when the target is in front of him, an analysis of his responses can indicate how he organizes his environment and which lenses or prisms would therefore be most helpful in achieving an integration of the systems or an accommodation to the dysfunction. For example, if the patient is able to judge side to side accurately but not up and down, he might have difficulty visually shifting his attention from far to near (anterior/posterior axis) such as those movements necessary while driving a car and alternately looking at the road, the speedometer and the rearview mirror. If he accurately assesses up and down but not side to side (lateral axis) then he might have difficulty looking easily from right to left or left to right, which could affect his ability to read or follow a lateral moving target.

Results from the Padula Visual Midline Shift Test provide another piece of diagnostic information. Not only does the test indicate an inability to differentiate between sensory information but it also measures which receptors are transmitting accurate or erroneous information for processing.

SUPER'S FIXATION DISPARITY TEST©

Super's 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 visuo-spatial orientation. The amounts of disparity are measured in each of nine positions and accurate centration and the elimination of undesirable disparities may be achieved by the application of lenses, prisms, filters or occluders [53]. 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 non-visual retinal fibers to the thalamus and other nuclei where visual, auditory and the other sensory signals meet. Thus, changing the way light enters the retina changes a patient's orientation and, therefore, his organization of space.

Visual and auditory pathways interact and distinct verbal and non-verbal systems are simultaneously involved in perception, memory, language and thought. The non-verbal systems include integration of environmental information involving different sensory modalities [54][55]. 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. Since some reading and/or 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 [56]. The auditory

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[53] Super, S. Super Fixation Disparity Test (2002) Los Angeles: Research Publications

[54] Luria A.R. The Working Brain: An Introduction to Neuropsychology, (1973) New York: Basic Books; p. 145

[55] Falchier, Clavagnier, Barone and Kennedy, op. cit.

[56] Schott J.M. and Rossor M.N. The grasp and other primitive reflexes. Journal of Neurology, Neurosurgery and Psychiatry (2003) 74: 558-560

component consists of asking the patient to close his eyes and localize a sound in front of him (between the top of his head and his collarbone, from shoulder to shoulder, avoiding 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. In the visual component, the patient is asked to look at a nonmoving target in the same space in front of him, close his 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 if neck and shoulder or head and eye movements are isolated one from the other, i.e. 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 [57].

By performing the test while the patient is standing, sensory linkages can be examined both 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, for example, 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.

While 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. The Z-Bell© Test 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 visuo-spatial perception. If visuo-spatial perception does not dominate then a sensory integration dysfunction is indicated [58].

CONCLUSIONS

The visual system is involved in much more than seeing. More than 30 percent of the human cortex is devoted to vision

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[57] Ibid.

[58] McGurk H. and MacDonald J. Hearing lips and seeing voices. Nature (1976) 264: 746-748

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 extra-ocular muscles are transmitted to the brainstem and are reflexively used in body orientation. Signals to the extra-ocular muscles are used to aim the eyes; signals to the intra-ocular muscles are used in focusing. Traumatic Brain Injuries can affect any aspect of this sensory/motor processing.

TBI patients can be thought of as being either hypersensitive (overwhelmed) by peripheral stimuli of any of the senses and/or hyposensitive (unaware) of necessary peripheral stimuli, thus causing incorrect spatial and temporal decisions due to a lack of pertinent information. Frustration and anxiety are often seen as primary sequelae to brain injury but those emotions might be more specifically attributed to inefficient visual processing.

Routine eye testing is often inadequate for a TBI patient since the peripheral retina's processing pathways are not typically addressed. Neuro-optometrists can evaluate the peripheral retinal systems 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 non-visual 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 neurological systems. In TBI diagnosis and rehabilitation, neuro-optometric procedures and interventions can provide a direction and framework for enabling a patient to make his own accommodations as he becomes better able to manage the new amount and organization of stimuli during the rehabilitative process.

It is beyond the scope of this chapter to detail specific advancements in the field of brain plasticity in adult human beings. Suffice it to say that 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; that beyond childhood the brain cannot develop new neural connections. In fact, the opposite is true and the implications for the treatment of TBI patients are manifold. Recent neurological studies [59] [60] [61] [62] and the profound pursuits of V.S. 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

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[59] Ramachandran V.S. op. cit.

[60] Melzack R. Phantom limbs. Scientific American (1992) 266: 120-126

[61] Halligan P.W., Marshall J.C., Wade D.T., Davey J. and Morrison D. Sensory reorganization and perceptual plasticity after limb amputation. Neuro Report (1993) 4 (3): 233-236

[62] Aglioti S., Cortese F. and Franchini C. Rapid sensory remapping in the adult human brain as inferred from phantom breast perception. Neuro Report (1994) 5 (4): 473-476

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 [63][64][65]. The brain is a dynamic mechanism and neuro-optometrists are among those at the forefront of applying these new understandings, with special relevance for TBI patient rehabilitation.

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

NORA: AN IMPORTANT REHABILITATIVE ORGANIZATION

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 [66][67]." 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 fifteen years, NORA has been in 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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[63] Ramachandran op.cit.: 195

[64] Kourtzi Z. and Grill-Spector K. fMRI adaptation: a tool for studying visual representations in the primate brain. (2005) Max Planck Institute for Biological Cybernetics, Stanford University: 1

[65] Cramer and Chopp op.cit.

[66] See the Rehabilitation professional's guide to post traumatic vision syndrome and visual midline shift syndrome. Published by NORA and available through their website, www.nora.cc

[67] Padula (1988) op. cit.