Article

Vestibular Function, Sensory Integration, and Balance Anomalies: A Brief Literature Review

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ABSTRACT

The essence of this paper is to review selective research articles that relate to vestibular functioning, sensory integration, and balance anomalies in children and adults. Studies that involve the role of the optometrist have been quite sparse. Special effort is made to distinguish between developmental and acquired brain injuries (ABI). While the former often are traced to pre-, peri- and postnatal disorders, traumatic brain injuries are the consequence of sports, motor vehicular and industrial accidents. Delayed vestibular maturation correlates significantly with sensory integration dysfunctions, slow vision processing, impaired hearing, and reading disability. Because of overlap in cortical systems, uncorrected vestibular disorders may affect attention processes and result in cognitive dysfunctions. The clinical value of several therapeutic procedures is discussed in the context of controlled studies. Successful rehabilitation may require treatment for vestibular *and* visual systems since the former may have provided only a partial cure. Future sensorimotor research should stress Optometry's role in this important aspect of vision care.

KEY WORDS

vestibular function, sensory integration, balance, brain injury, rehabilitation, cognitive processing, vestibular ocular reflex (VOR), hearing impairment, reading disability, visual function

INTRODUCTION

As early as the pre-school level, an intact vestibular system contributes to sensory integration and the maturation of eye-movements that are required for efficient reading and learning. The vestibular apparatus has been identified as the sensory organ that detects sensations concerned with an individual's balance and equilibrium. The vestibulo-ocular reflex (VOR) generates the rapid compensatory eye movements that support stable vision while the head is in motion. That is, the VOR functions to prevent head movements from disturbing retinal images. Thus, the visual image is held steady on the retina allowing clear single vision.[1, 2] During its course in the internal auditory canal that it shares with the cochlear nerve, the vestibular nerve also may affect hearing through efferent olivocochlear connections. Although either of these complementary dependent variables, *vision and hearing*, may function independently, together, they dominate our primary learning processes

The predominance of visual-vestibular control of balance gives way to a somatosensory-vestibular dependence by age three, but the transition to adult like balance responses is not complete for all sensory conditions even by age six.[3] Since vestibular responses are associated with eye movements and hearing, they contribute to visual *and* auditory processing. Phylogenetically, the vestibular function appeared early; and ontogenetically, vestibular related tracts are one of the earliest to myelinate in fetal life, at about twenty weeks.[4] In the normal healthy infant, the reflexes occur developmentally first in the vestibular and auditory systems, but later in tactile and visual analyzers. There remains a question, however, as to whether myelination

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Solan HA, Shelley-Tremblay J, Larson S. Vestibular Function, Sensory Integration, and Balance Anomalies: A Brief Literature Review Optom Vis Dev 2007;38(1):13-17.

serves as an index of maturation that contributes to cognitive functioning in early postnatal life.

Related Literature

Clinical experience supports the notion that delayed vestibular maturation may be associated with sensory integrative dysfunctions, slow vision processing, and delayed acquisition of reading skills in primary and middle grade elementary school children. According to Ayres,[5] among learning disabled (LD) children, the presence of hearing impairment may compound the assessment and interpretation of the relationship between vestibular disorders and gross motor-balance activities such as rail-walking and one-foot standing. Although the ubiquitous vestibular system primarily is a somatosensory and motor system, sensation, digestion, and state of mind may be affected.

Malamut[6] emphasizes the complexity of the vestibular system. It involves interconnections with the inner-ear, superior temporal cortex, insula and the temporal-parietal junction within the cortex, and the postural and extraocular muscle systems, all of which contribute to balance and vestibular reflexes. In part, because of the overlap in cortical systems, uncorrected vestibular disorders may ultimately affect attention processing and result in cognitive dysfunctions.[7,8] Smith, Zheng, Horii, and Darlington[7] have reviewed extensive animal and human studies. They provide evidence that, in addition to more commonly known deficits in balance and posture, problems with vestibular function can be seen to be associated with deficits in object recognition, spatial navigation, learning and memory. Most severely affected in these studies were tasks directly measuring attention, such as the Digit Span test from the Weschler Intelligence Scale for Adults. These authors conclude that one mechanism by which vestibular disorders adversely affect attention is the distracting influence of increased body sway and postural lean. Additionally, the psychological sequelae of vestibular disorders, which may include anxiety and depression, could negatively affect the cognitive resources available for information processing.

There are major differences between developmental vestibular and traumatic acquired brain injuries (ABI). The latter, traumatic brain injuries (TBI), are more often the consequence of sports, motor vehicular, and industrial accidents.[9] They include closed and penetrating head injuries as compared to a history of prenatal and neonatal complications of pregnancy in children.

Horak, Shumway-Cook, Crow, and Black[10] reported significant differences when they compared 54 normal children, ages 7–12 years (M = 9.2 $\pm$ 2.3), with 30 hearing impaired children (M = 9.2 $\pm$ 1.8) who were of normal intelligence, and 15 LD participants (M = 9.4 $\pm$ 1.5) with coordination and clumsiness problems, but normal hearing. Twenty of the 30 hearing impaired participants (67%) had abnormal vestibulo-ocular reflexes (VOR). A majority of the 30 hearing-impaired children was affected, *but* 20% (3 of 15) of motor impaired LD children and 7% of normals (4 of 54) *also* had depressed vestibular function as measured by VOR tests. These motor-impaired LD children were at least two years delayed in two or more subjects. They were not diagnosed as minimal brain damaged (MBD), but could be classified as experiencing significant neuro-maturational lags associated with sensory-motor deficits.[11]

In summary, two-thirds of hearing impaired subjects had significant vestibular deficits, *and in addition* twenty percent of LD motor impaired children (as measured with the Bruininks-Oseretsky Test[12]) had peripheral vestibular disabilities. Predictably, the hearing impaired and the LD samples showed significant difficulties in organizing vestibular inputs.[8,13] These results revealed a vestibular hypofunction in the hearing impaired group with accompanying balance deficits. However, the study fails to focus on reciprocal interaction between the visual and vestibular systems.

It has become increasingly clear that stimulation of one sensory system may affect other sensory systems (See Figure 1). For example, Dieterich and Brandt[13] reported that vestibular stimulation deactivates the visual cortex, and visual stimulation deactivates the vestibular cortex. Fortunately, the system as a whole can withstand and adapt to significant amounts of peripheral vestibular dysfunction. Often vestibular dysfunctions appearing early are ameliorated in the course of normal neuromaturation.

However, it is important to recognize that mental development and learning are different phenomena and each is influenced by distinct antecedents. Piaget conceptualized mental development as *embryogenesis.*[14]

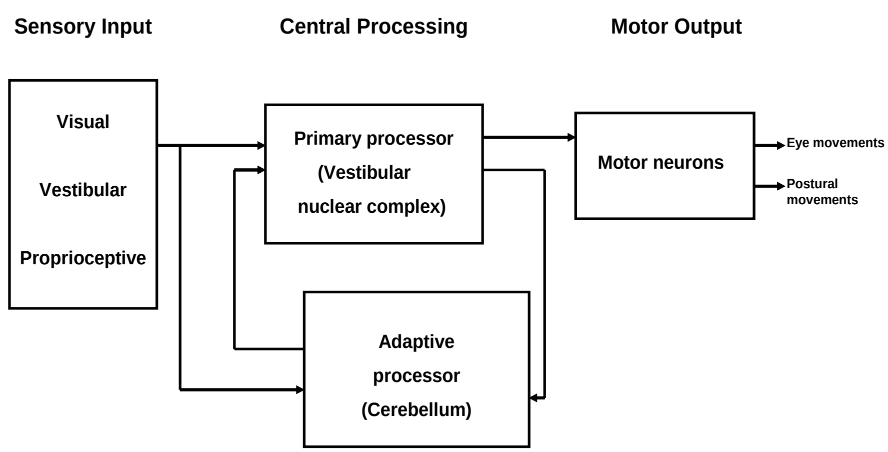

Figure 1. Block diagram illustrating the organization of the vestibular system.

It is open-ended and is concerned with the development and maturation of the nervous system, e.g.: synaptogenesis, axonal branching, and dendritic elaboration. Each element of learning occurs as a function of the individual's total developmental framework. Therefore, embryogenesis is the neuroanatomical requisite for the continuing development of mental functions. Learning in the absence of suitable developmental structures may preclude assimilation. The resulting associative learning is likely to be temporary and often fails to produce generalizations. The general concept of embryogenesis is equally applicable to the vestibular system.

Evaluating Vestibular Functioning in the Clinical Contexts

Based on the interrelationships of LD, cognitive processing, and vestibular functioning research, it follows that clinical LD evaluations should include some measures that are sensitive to possible vestibular disorders.[15] Two standardized diagnostic tasks that have been staples of perceptual-motor analysis are the Walking Rail and the One Foot Balance Tests. The former provides a preliminary measure of the ability to maintain dynamic balance while walking a rail, heal to toe, with both hands on hips. The test employs a 12 foot 2 x 4 inch board firmly supported with three brackets. For Task A, the wide side is used; in Task B, the narrow side is used. The patient is expected to complete this timed test with a maximum of 24 steps, heel to toe, in each direction. The tests are discontinued when the patient loses balance or removes hands from hips. Sensory inputs related to equilibrium include vision, vestibular, proprioception, and hearing.

The One Foot Balance with Eyes Open and Eyes Closed Test provides the examiner with basic impressions of the child's static balance. These multifactorial tests, drawn from the Southern California Sensory Integration Tests[16] rely on visual, vestibular, and somatosensory inputs. They require the patient to balance on the dominant foot, hands on hips, with the top of the other foot placed behind the knee of the opposite leg. The score is the total number of seconds the patient maintains standing balance up to a maximum of 30 seconds each with eyes open (SBO) and eyes closed (SBC). The tests are discontinued when the patient touches the other foot to the floor, removes either hand from hips, hops about, or otherwise indicates loss of balance. Equilibrium measures have been shown to discriminate clinically between normal children and children with CNS dysfunction.

Bundy et al[17] discussed the outcome of six different equilibrium measures administered to 50 boys with LD (25 with and 25 without suspected vestibular system dysfunction). They found that only 3 of the 10 obtained correlation coefficients were greater than r=0.5 which yields a maximum percent of shared variance (r^2) equal to 25%. The relatively low magnitude of the correlation scores suggests that different tests of equilibrium measure different balance related competencies. Furthermore, competency in one area does not indicate competence in another. Therefore, vestibular rehabilitation should include several activities to treat vertigo, balance problems, functional limitations, and disabilities caused by impairments of the vestibular system.[18]

Rine[19] reported that relatively few controlled studies have been conducted to examine vestibular function in children with CNS disorders. Although some studies do document postural control and sensory organization deficits in children with learning disabilities or cerebral palsy, others failed to formally test vestibular function. In order to establish the prognosis and to plan effective vestibular rehabilitation, it is important to identify and quantify the vestibular deficits precisely. The range of disorders extends from poor balance (disequilibrium) and the illusion of self motion (vertigo) to inflammation or disease of the vestibular labyrinth of the inner ear (labyrinthitis). Symptoms also include nystagmus and subjective oscillopsia that result in vision impairment due to the illusion of object motion on the retina during head movement. Clinical investigators have reported that vestibular rehabilitation may improve the visual and motor abilities in children who have a history of low birth-weight, prematurity, and oxygen deprivation.[7] Although some of these children are identified as having developmental anomalies, a careful review of the pregnancy and birth histories could reveal that aberrant pre-natal complications may have contributed to the acquisition of the so-called developmental delay. Herdman proposes that the development of more precise clinical procedures to identify and treat children in need of additional testing and intervention is warranted. She specifically recommends that vestibular rehabilitation includes modification of saccadic eye movements and substitution of visual and somatosensory cues for lost vestibular cues in disequilibrium and balance disorders.[20]

Rine et al[21] examined gross motor development and the effect of age, sex and vestibular function of 39 children (ages 2 to 7 years old) who had sensorineural hearing impairment. Repeated testing was completed subsequently on 18 of these children. Delayed gross motor development was evident regardless of age, but only children less than age 5 years had developmental balance deficits on initial testing. Both, gross motor and balance development scores were lower on repeated testing. In general, vestibular scores differentiated children with balance deficits from those with a progressive delay in motor development. A second interesting finding was the excellent sensitivity of vestibular function testing for the identification of progressive delays.

Therapy

It is not unusual for a patient with balance disorders to show significant improvement following vestibular and binocular vision therapy since the two systems are closely related physiologically and functionally.

However, in order to maintain the child's interest, therapeutic activities should be appropriate for the patient's age and intellectual level whenever possible. In general, vestibular rehabilitation is effective therapy for many patients with disequilibrium and balance disorders, especially if the patient has residual vestibular function.

In their follow-up study, Rine et al[22] determined the value of "exercise intervention" on progressive motor development delay in children with sensorineural hearing loss and concurrent vestibular impairment. The exercises consisted of compensatory training that emphasized enhancement of visual and somatosensory function and balance training. A placebo group received intervention that focused on language development activities. The post-intervention motor development scores significantly improved in the exercise, but not the placebo group ($P < 0.004$). The investigators concluded that exercise intervention focusing on the enhancement of postural control abilities is effective for the arrest of progressive motor development delay in children with vestibular impairment and sensorineural hearing loss.

The elements of developmental and learning disabilities are not one-dimensional. The treatment of visual skills deficits, other than specific vestibular anomalies, is a concern to the patient and the optometrist. Binocular vision and accommodation disorders have been reported to be among the most common vision problems occurring in this population.[23] The need to see clearly and comfortably at all distances for extended periods of time remains a primary consideration. Normal binocular vision is a complex psycho-physiological process that is not always attained to its fullest extent by all who see with both eyes.

The experience of Rosen, Cohen, and Trebing[24] in rendering vision therapy supports the notion that a successful rehabilitation program may require treatment for both the vestibular and visual systems, since the former may have provided only a partial cure. Lenses, prisms, and vision therapy for ABI patients who have residual vestibular disorders may be required to enhance balance and a stable visual environment. The development of fusional vergences and focusing skills necessary to relieve the patient's symptoms and maintain comfortable single vision for extended periods of time provides additional benefits. Although the treatment of binocular insufficiency is usually successful, variables such as patient motivation and intelligence are difficult to quantify *a priori*.[25]

Konrad et al[15] recommend that vestibular rehabilitation should play an important role in patient care. Therapy must be performed on the basis of specific diagnostic findings in order to be effective. *It is not that therapy is to be tried when all else fails.* However, there exists a continuing need for further research to classify, standardize, and validate diagnostic and therapeutic procedures according to age groups and medical histories in children and adults.

It is noted that successful recovery could be attributed to adaptation of the vestibular system itself. An improved understanding of the various compensatory mechanisms and their limitations for improving gaze and postural stability will lead to more effective treatment of these patients.[18]

SUMMARY

The authors have reviewed some of the relevant research that relates primarily to the diagnosis and treatment of anomalies in vestibular and visual functioning. Of special interest have been the effects of these anomalies on sensory integration and balance. The concurrent presence of auditory and oculomotor deficits requires further investigation. Although acquired brain injuries that result from traumatic events such as automobile accidents usually are explainable, the diagnoses of apparent neuromaturational delays in children are indeed more subtle. Some developmental delays associated with vestibular and sensorimotor integration disorders may be traced to low birth weight (prematurity) and prenatal aberrations.

Additional research is warranted to develop valid sensorimotor age-expected norms that are based on standardized testing procedures. Since the patient's presenting problems often involve cognitive and/or learning delays, the availability of reading test levels usually is helpful to establish a baseline for future comparison. Interdisciplinary controlled clinical research should include the effect of developmental vision disorders that heretofore have been represented sparsely. The outcomes reported in this review suggest that enhancing visual processing, vestibular, sensory-integration, and balance functions can be therapeutically rewarding.

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