Neurobiology and Ballet

The study of ballet is intrinsically reliant on the central nervous system and requires simultaneous activation of many neurobiological pathways. The central nervous system, composed of the brain and spinal cord, provides functional support to a dancer. This support is accomplished through activation of the sensory systems, the motor system, and cognitive areas. The sensory systems include auditory, visual, vestibular and somatosensory systems and allow for expressive artistry and balance. The motor system allows for both movement planning and execution. Cognitive aspects of the brain provide a dancer with the motivation and memory necessary to perfect and perform movement. The simultaneous activation of multiple central nervous system motor and sensory systems allows for the masterful execution and finesse typically associated with ballet.

Current national and international research has identified dance as a preventive activity for dementia. In addition, researchers at Washington University in St. Louis recently published a study on tango and its correlation to improved balance and mobility in patients with Parkinson's.[1] These studies focus on single neurological diseases. The identification of the many areas of the brain involved in dance may lead to the use of dance in the treatment or even prevention of other neurological diseases and other applications in the fields of medicine and education. In light of the recent study of dance and neurobiology, this paper seeks to examine and catalog the brain functions integral to ballet.

SENSORY SYSTEMS

The movement of dance, controlled by the motor system, is intrinsically dependent on sensory perception specifically relating to the auditory, visual, vestibular and somatosensory systems. Various stimuli are simultaneously transmitted and processed in these systems, which are responsible for rhythmic movement, spatial awareness, and balance.

The auditory system transmits pressure waves of musical sound through the outer, middle, and inner

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ear to the cochlea. The cochlear ducts contain endolymph, which cause the basilar membrane to vibrate. This vibration controls the mechanotransduction channels in hair cells and ultimately the release of Ca^{++} channels. The influx of Ca^{++} triggers a release of glutamate and sends an action potential to the brain. The acoustic nerve forms at the center of the cochlea and joins the vestibular nerve at the internal auditory cortex thus forming the auditory nerve. The auditory nerve enters the midbrain and splits in many directions. It travels ventrally and dorsally to the cochlear nucleus. Other fibers travel to the opposite hemisphere by way of the trapezoid body. Still others terminate in the superior olivary complex, a nucleus in the pons, or in the nucleus of the lateral lemniscuses. Both the superior olivary complex and the nucleus of the lateral lemniscuses send fibers to the inferior colliculus, followed by the medial geniculate nucleus. The medial geniculate nucleus is thought to be responsible for detecting frequencies, intensity, and relaying this information to the auditory cortex.[2]

The auditory cortex, also called Brodmann's area 41, is located in the temporal lobe. It contains a topographical map of the cochlea and performs sound analysis by combining distributed but coordinated neuronal responses. The belt and parabelt regions are involved in processing rhythm.[3] The secondary auditory cortex receives input from the primary auditory cortex and processes melody, rhythm, and harmony. The superior lobe is involved in recognizing timbre. A short retention of auditory information and pitch relativity is processed in the right temporal neocortex.[4]

Sensory information received in the visual, vestibular and somatosensory systems play an integral role in movement, posture and balance. Visual stimuli are received in the ganglion cells of the eye, which extend to the retina and project information to the optic tract by way of the optic nerve and optic chiasm. Axons from the optic tract form connections with cells in the hypothalamus and midbrain but most innervate the lateral geniculate nucleus of the dorsal thalamus. Axons from the lateral geniculate nucleus then project to the visual cortex, which receives information from both retinas. The primary visual cortex is Brodmann's area 17, located in the occipital lobe, which requires first a slight convergence in the striate cortex and next a huge divergence of information as information is passed on to higher, and as yet unknown, cortical areas. Brodmann's area 17 produces two large streams of visual processing: dorsal and ventral. The dorsal stream analyzes visual motion and the visual control of action. Thus it plays a role in navigation, motion perception, and eye movement. Eye movement is controlled by six extrinsic muscles, which respond to stimuli from both the dorsal stream and the vestibular system. The ventral stream is involved in perception of the visual world.[5]

Spatial perception occurs in both the cerebellum and the parietal cortex.[6] The cerebellum is involved in judgment of spatial orientation, made possible by its connection with the bilateral parietal lobe.[7] The parietal cortex is involved in spatial perception specifically during movement, translating visual stimuli into motor commands. The posterior parietal is active in egocentric, self-centered, spatial movement and body orientation. The precuneus, another part of the parietal cortex, is also involved in egocentric spatial perception. The precuneus is thought to present a map, providing body

awareness in regards to spatial positioning. This perception is important in ballet for control and correct orientation of the body. Navigating space during a leap or turn requires keen spatial awareness and direction.

The hippocampus, located in the parietal cortex, receives input from many sources and its ability to relate and combine this information is necessary for spatial memory tasks. The hippocampus is involved in allocentric, not self-centered, processing of spatial location and geometry of spatial scenes. Accurate navigation is associated with the right hippocampus and the right inferior parietal cortex.[8]

Spatial awareness is intricately linked to balance. The visual system maintains balance by perception of an individual's position location relative to their surroundings. The vestibular system detects movement of endolymph in the inner ear and as a result perceives equilibrium. The inner ear components involved in this perception are the semicircular canals and otolith organs. The semicircular canals detect rotational acceleration, or acceleration produced during a turn. The otolith organs sense linear acceleration and calculate the direction of gravity.[9] This positional perception contributes to the balance and spatial awareness required to execute a turn or leap.

The somatosensory system includes both the proprioceptive and tactile sensory systems. It includes afferent and efferent pathways, central integration and processing. These components make the system a paramount contributor to physical stability. The tactile system is stimulated by rotation or weight shift. These stimuli trigger peripheral receptors. Receptors are located throughout the body and mechanoreceptors play a specifically

important role in ballet through the tactile system. These receptors are composed of a peripheral axon whose cell body is located in the dorsal root ganglion, from which the thick myelinated nerve fibers of the mechanoreceptor enter the dorsal root of the spinal cord. This transmission of information next travels to the ipsilateral dorsal nuclei of the medulla oblongata.[10] Information passes from the medulla to the thalamus and ends in the primary somatosensory cortex located in the post central-gyrus of the cerebral cortex. This information, processed in other areas of the spinal cord, brain stem, and cerebral cortex, is transmitted to associated motor areas like the cerebellum and basal ganglia that are responsible for additional processing and regulation of motor responses. The spinal cord responds to muscle activation through reflex pathways. The brain stem is responsible for integration of stimuli from the visual, vestibular, and somatosensory systems to control posture. Both the spinal cord and brain stem act unconsciously to control balance and posture.[11]

The proprioceptive system reports the relative location of body parts and plays a role in physical stability. The system receives sensory information from nerves inside the body, located primarily in muscle spindles and joint receptors.[12] This sensory information is carried to the spinal cord and to the brain via the central ascending pathways. The motor system works closely with the proprioceptive system during ballet to constantly monitor and adjust movement for changing velocity, direction, and sequence.

MOTOR SYSTEM
Immediate planning and decision-making also are required before successful completion of a turn or leap is possible. For example, a leap

is initiated long before the dancer begins to transfer weight and initiate movement. The decision to perform a leap occurs simultaneously in the superior parietal cortex, premotor cortex, and prefrontal cortex of the brain.[13] The axons that extend from these brain areas converge in area 6 in the motor cortex. Area 6 is the junction that converts the decision for movement into a physical act.

Neurons located in the lateral region of area 6, the premotor area, are stimulated during the decision-making process. These neurons are discharged once the task is initiated and then cease firing. The process of movement decision processing occurs in a motor loop that extends from the motor cortex to the basal ganglia, followed by the thalamus and culminating back in the motor cortex. The basal ganglia consist of the striatum, composed of the caudate nucleus and putamen, globus pallidus, and subthalamic nucleus.[14] The basal ganglia, in conjunction with the subthalamus, are involved in motor planning, eye movement, and management of skeletal muscle movement.

The information transmitted at the end of the motor loop travels to the lower motor neurons by way of cortical layer V of area 6. A leap, which requires very disciplined, precise, and large movement, involves a large neuron population. Individual pyramidal cells also are involved and drive motor neurons from different muscles involved in movement of the leg in a turn or leap.

The axons projecting from the layer V pyramidal cells in area 6 form a cluster in the pons and stimulate the cerebellum. The cerebellum is involved in control of critical motor control and is necessary for the execution of planned, voluntary, multi-jointed movements such as a turn or leap. The signal received in the cerebellum instructs the primary motor cortex in regards to movement direction, timing, and force.[15] The practice of both turns and leaps, which are repeated during each class, allow for the generation of a new motor program in the cerebellum that generates the appropriate movement without scrupulous conscious control. This programming is modified by practice and forms as a result of previously discussed synapse alteration.

The brain controls movement through innervation of the spinal cord. Axons from the brain travel to the spinal cord in two pathways: the lateral pathway, which controls voluntary movement, and the ventromedial pathway, which controls posture and locomotion.[16] The lateral pathway axons originate in the motor cortex, areas 4 and 6, and end in the dorsolateral region of the ventral horns of the spinal cord. The lateral pathway itself, or corticospinal tract, originates in the neocortex and travels through the internal capsule that bridges the telencephalon and the thalamus. The pathway travels from the internal capsule through the cerebral peduncle, the pons, and ends in the medulla. Axons cross at the medulla, so the right motor cortex controls the left side of the body.[17] The ventromedial pathway originates in the brain stem and ends in the spinal interneurons that control proximal and axial muscles. The vestibulospinal tract functions to keep the head balanced on the shoulders as the body moves. The vestibulospinal tract originates in the medulla, where the lateral pathway ends, and projects bilaterally down the spinal cord to activate the cervical spinal circuits that control neck and back muscles. The tectospinal tract, also part of the ventromedial pathway, originates in the midbrain where it receives input from the sensory system. The tectospinal

tract is involved in orientating the head and eyes. Additional tracts, the pontine and medullary reticulospinal tracts, originate in the brain stem. The pontine reticulospinal tract involves antigravity reflexes of the spinal cord, specifically the ventral horns. The axons facilitate extensors of the lower limbs and help to maintain a standing posture. The ventral horns thus help to maintain rather than change muscle length. The medullary reticulospinal tract frees antigravity muscles from reflex control.[18] Both leaps and turns require the use of each of these pathways and associated tracts to control voluntary muscle movement and maintain balance and posture.

Once information has passed from the brain to the spinal cord, motor neurons innervate the somatic musculature. Lower motor neurons are located in the ventral horn of the spinal cord. The axons, which extend from these lower motor neurons, form bundles and create ventral roots that connect with dorsal roots and form spinal nerves. Among the 30 spinal nerves there is an uneven distribution due to the uneven distribution of skeletal muscle in the body. The spinal nerves contain both sensory and motor fibers that innervate distal and proximal musculature, such as the legs in a leap. Alpha motor neurons specifically control the generation of force by muscles. An alpha motor neuron and the muscle fibers it innervates create a motor unit. Varying the firing rate of motor neurons allows for graded contractions, which result from the release of the neurotransmitter acetylcholine. Sustained muscle contraction or increased force requires the summation of action potentials. In a leap, large muscles are innervated to shift weight and propel movement. These large muscles of the leg require thousands of muscle fibers. Leaps and turns are often accented and accompanied by music. This rhythmic movement relies on the intrinsic pacemaker properties of individual neuron membranes and on synaptic interconnections.

COGNITIVE ASPECTS

The physical execution of ballet is intricately tied to motivation and memory. Motivation is affected by emotion, which is a driving force of behavior. Emotion determines what is important, what deserves attention, and subsequently what is to be learned and remembered. The limbic system is responsible for emotion and therefore motivation.[19] It is composed of the amygdala, hippocampus, thalamus and hypothalamus. Sensory information enters the thalamus and is then moved to the amygdala for an emotional response and to the sensory and frontal lobes for fixated attention.[20] These regions and all other areas of the limbic system converge at the hypothalamus.[21]

The limbic system drives motivation through rewarding effects felt strongly by stimulation of the hypothalamus, and in a lesser degree by stimulation of the amygdala and hippocampus. The stimulation of the hypothalamus creates positive reinforcement through pleasure and consequently produces motivation. This motivation also has been shown to influence an individual's willingness to engage or disengage in activities.[22] The practice of ballet requires determination and persistence, traits developed and maintained in the limbic system. Enkephalins and opiates are thought to be the transmitters involved in this reward mechanism. However, the neural aspect of pleasurable reactions is not well understood.

The amygdala also is involved in emotion, specifically positive emotion and reward.[23] Like the hypothalamus it alters an individual's

willingness to respond to novel tasks and movements. In addition, the amygdala is involved in learning and retention of learned behaviors. The ability to apply learned behaviors in different situations and adjust to new environments also is accomplished by the amygdala. A ballet class utilizes repeated fundamental movements to produce innovative choreography. The ability to adjust a known movement to new criteria and spatial constraints allows a dancer to excel and succeed in the demands of this art form. The amygdala is intricately connected to many other brain regions, specifically the hippocampus, and for this reason the amygdala also serves a large role in memory.

The limbic system produces positive reinforcement for activities accompanied by pleasure. A release of dopamine during ballet creates positive feelings, promotes pleasure and increases motivation for continued pursuit and practice. This desire for determined activity then becomes reliant on memory and learning for continued progression and mastery of the art form.

Memory is another cognitive aspect active in ballet. Memories are formed in the medial temporal lobe, specifically the hippocampus, basal ganglia, amygdala, and entorhinal and perirhinal cortices. The hippocampus is important in declarative memory processing and contains the dentate gyrus, cornu ammonis, subiculum, and entorhinal cortex.[24] The dentate gyrus is one of the few regions of the brain that allows for neurogenesis and is located where nerves enter the hippocampus. The cornu ammonis is the main site of memory processing and is important in recalling memories from partial representations. Neurons loop back on themselves in this area creating an expanded output. The subiculum connects the hippocampus to the entorhinal and perirhinal cortices and consequently allows for the integration of information from several areas. The entorhinal cortex transmits both input and output from the hippocampus and controls learning, which requires repeated experiences. The information gathered by the hippocampus from various sources contributes to rapid and unstructured memories. The hippocampus is actively involved in the process of memory storage but is not where memories are stored.[25] Each area of the hippocampus is actively involved in ballet, which relies on repetition and memory recall.

For example, turns and leaps can be broken down into fundamental movements of ballet, which are practiced routinely and repeatedly in class. This repetition allows for precise and perfected movement. Memories are produced by varying the firing rates of a neuron population stored by associative synaptic modification, which allows for later recall. The specific activity of the hippocampus and associated regions is useful in the remembrance of an entire combination when only specific components are initially remembered. A proper preparation or weight bearing can trigger appropriate movement recall and successful execution of leaps and turns.

The neocortex, specifically the prefrontal cortex, plays a role in working memory. It receives input from many sensory systems and involves the temporary storage of information and decision-making. This temporary storage is useful for the short-term memory required for many combinations given in class.

Repetition contributes to the formation of implicit memories such as skills, habits, and behaviors, which rely on the basal ganglia and neocortex. The basal ganglia are involved in both memory and movement. This region is useful in learning

sequential movement and plays a role in procedural learning. A region of the basal ganglia, the striatum, is composed of the caudate nucleus and the putamen and is located in the motor loop. This region receives input from the frontal and parietal cortex and transmits information to the thalamic nuclei and other cortical areas. The function of the frontal cortex, a region in the neocortex, is poorly understood but is thought to provide additional memory storage. The caudate nucleus is involved in learning and memory, specifically feedback processing. Coupled with the putamen, which regulates movement and learning, the striatum plays a large role in learning and memory because of its connection to many other brain regions.[26] The formation of memories is a result of synapse alteration. This marked change allows for recall and eventual mastery of specific ballet movements such as leaps and turns. Many details such as placement, force, and balance can be perfected through long-term memory formation and performed relying on only short-term memory.

SUMMARY

This paper is a reflection of the various activities of the central nervous system during ballet. Successful execution of movement relies on the integration of sensory input, motor planning, and cognitive aspects. Sensory input is received and processed in the auditory, visual, vestibular and somatosensory systems. The motor system facilitates movement planning and execution and relies on multiple brain regions including the superior parietal, premotor, prefrontal and motor cortexes. The cognitive aspects of ballet, motivation and memory, are controlled by the limbic system and various brain regions including the hypothalamus, hippocampus, amygdala, and basal ganglia. The concurrent integration of various sensory stimuli and movement requires simultaneous activation of many components in the central nervous system to produce functional support and finesse in a ballet dancer.

END NOTES

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