Journal of Mental Health and Behavioural Science

Open Access

Lack of Exercise: A Link Between the Sensorimotor System, Behaviour, Cognition, Emotions, and Nociplastic Pain

Mini Review

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Received: 11 June, 2026; **Accepted:** 09 July, 2026; **Published:** 14 July, 2026.

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Abstract

Physical activity is a key feature of lifestyle, interacts intensively with all other lifestyle factors, and thus has a strong influence on the biopsychosocial model.

The aim of this mini-review is to describe the sensorimotor development and the factor of physical activity for the formation and promotion of cerebral functions and behaviour in ontogenesis.

The woman's physical activity induces a positive epigenetic status, which can be passed on to a child as a preventive biological strategy. The physical activity of a pregnant woman supports the cerebral development of the unborn child through muscle signaling molecules, as well as through nutrition and social behaviour. Sensorimotor development in unborn child includes the neural basis of pain inhibition as a component of all sensorimotor activities, as well as cognition, executive functions, and later behaviour. After birth, cognition, attention, and awareness are essential for voluntary motor control and behavioural formation, and emotional support and social factors become important.

The interrelationships between sensorimotor skills, psychophysical and cognitive-emotional development, as well as lifestyle factors, need to be intensively analyzed for a public health concept.

Sensorimotor Function, Cognition, and Emotion - A Functional Unit

Sensorimotor function [1], a central characteristic of behaviour, encompasses cognition and emotion in the planning and execution of actions, orientation in time and space, and the anticipation and evaluation of situations and outcomes. In ontogenesis, sensorimotor function assumes the leading role in development from the earliest stages. Based on genetics, epigenetic status, and subsequent social influences, the highest cerebral structures are integrated into a physiological unit. The interactions among sensorimotor function, behaviour, cognitive-emotional status, and the development of nociplastic pain can be understood in terms of the following aspects:

1. The physiological development of the brain,
2. Disrupted brain development, and
3. The influence of physical activity or inactivity on brain function across the lifespan.

Early Brain Development and Maternal Sensorimotor Activity

Figure 1 shows, that the guiding role of sensorimotor activity in brain development begins before birth, with the mother's lifestyle and activity levels prior to and during pregnancy. Physical activity during pregnancy enhances neurogenesis and neural growth in the child [2], due in part to the capacity of myokines to cross the placenta. The "Developmental Origins of Health and Disease" (DOHaD) framework, encompassing the related concepts of fetal programming and developmental epigenetics, holds that the early developmental environment exerts lasting influences on brain function, health, and behaviour across the lifespan. Conversely, the same mechanisms may equally confer upon the child a predisposition to disease. [3-6]. Epigenetic mechanisms convey a biologically preventive or predisposing strategy to the child [7], a relationship that appears relevant even to the processes of aging [8].

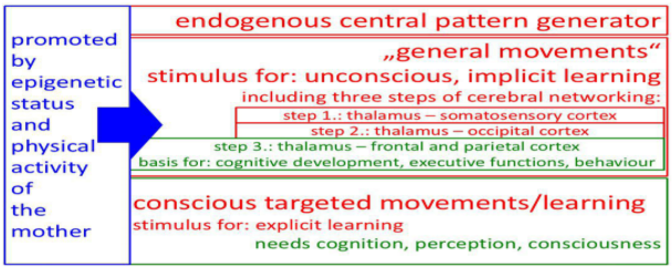

Fig 1: The sensorimotor development: The sensorimotor development of offspring is already supported by the physical activity of the expectant mother, which establishes a heritable, favorable epigenetic pattern. Physical activity during pregnancy promotes the somatic and cerebral development of the unborn child through myokines that cross the placenta. The embryo initiates motor activities in the 7th to 8th week of pregnancy through an endogenous central pattern generator. These spontaneous activities are soon replaced by reflexive, diverse, and highly variable movements known as general movements. These complex reflexive movements constitute implicit training and ensure the connectivity of the thalamus with the somatosensory cortex (stage 1), the thalamus with the occipital cortex (stage 2), and the thalamus with the frontal and parietal cortex (stage 3). Stage 3 of development is also the foundation for the development of cognition, executive functions, and later behaviour. After birth, general movements transform into perception- and situation-dependent movements. The acquisition of postnatal sensorimotor skills requires conscious perception, cognition, and awareness.

Sensorimotor Development - Outcome and Stimulator of Brain Development

Figure 1 also discribes the sensorimotor development of the unborn child and in the neonatal window. It was recognised as early as the nineteenth century [9] that embryonic motor activity is primarily spontaneous, a finding subsequently confirmed in animal models [10,11] and extended to humans [12]. Motor activity begins in the 7th or 8th week of gestation, driven by an endogenous central pattern generator or intrinsic autonomous neural mechanism [10,12,13].

Endogenous motor activity rapidly evolves into reflex-based global movement patterns known as general movements [12]. General movements are characterized by a high degree of spatial and temporal complexity and variability [13,14]. They serve as implicit genetically and epigenetically regulated sensorimotor training, and shape embryonic and fetal behaviour [15]. As shown in Figure 1, the result is progressive networking between the thalamus and the sensorimotor cortex (Stage 1), the occipital cortex (Stage 2), and the frontal and parietal cortices (Stage 3) [16], continuing until approximately the second to fourth month of postnatal life [17]. Sensorimotor activity thereby stimulates brain maturation and lays the foundations for subsequent behaviour [18]. Conversely, disruptions in maturation lead to altered executive function and behavioural patterns [19]. Pre-conscious sensorimotor activity – both prior to birth and during a brief neonatal window - carries equivalent significance for bodily function and, above all, for brain development, as conscious sensorimotor activity does across the remainder of the lifespan.

From Implicit to Explicit: The Development of Perception and Consciousness

Implicit, pre-conscious learning mediated by general movements gives way to explicit learning between the second and fourth months of life. This transition requires the engagement of both cognitive and affective capacities. Phylogeny has prepared the brain well for this shift: even in newborns, the regions governing adaptive behaviour, sensory information processing, and self-awareness are already extensively interconnected [20].

The emergence of conscious awareness and mindfulness can be understood through the principles of Perceptual Control Theory [21]. From around the 24th week, behaviour becomes progressively goal-oriented [22]. The executive brain network governing attention, cognitive control and action regulation, and enabling novelty-seeking, error detection, and conflict resolution, develops during infancy [23,24]. This developmental progression constitutes what [22] describe as the "ontogenetic clock of perceptual control development." Higher-order consciousness - grounded in memory, self-reflection, and the capacity to conceptualize the future - systematically becomes a function of the cerebral cortex [25].

Integration of Sensorimotor Function, Nociception, and the Emergence of Pain Perception and Inhibition

The subplate modulation hypothesis proposes that subplate neurons (located beneath subcortical structures) may support nociceptive experience during the first trimester. However, thalamocortical connectivity - widely considered a prerequisite for conscious pain perception - begins to develop from approximately the 24th week of gestation [25,26]. Figure 2 highlights that healthy sensorimotor development includes endogenous pain inhibition. The connectivity between the primary motor cortex (M1) and the primary somatosensory cortex (S1) and the networks associated with both pain inhibition and the reward system

[27,28] provide the neural substrate through which spinal sensory sensitivity can be modulated downward and negative emotional valence attenuated. Pain inhibition is therefore not a separate system but an integral component of the sensorimotor action program, embedded within the affective-emotional dimension of pain from the earliest stages of cortical development.

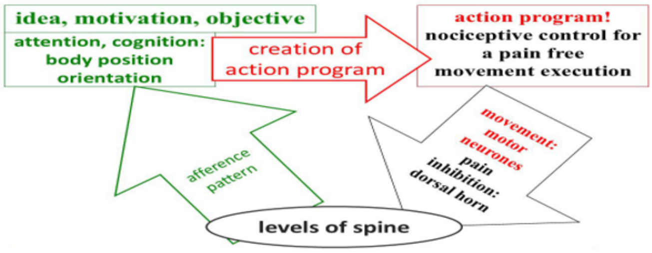

Fig 2: Pain inhibition, an integral function: The pain inhibition and modulation develop as an integral part of sensorimotor function, with cerebral development linking the responsible networks. Thus, sensorimotor function and pain inhibition become a functional unit. The brain generates movement ideas, the motivation for them, and the goals. The afferent information pattern is filtered by the mechanism of "selective attention," and a cognitive process ensures orientation in time and space as well as the recognition of body posture. The brain then designs the action program, integrating nociceptive control. Simultaneously, signals for muscle activity are sent to the pools of motor neurons in the anterior horn, and signals for pain inhibition are sent to the neural network in the posterior horn. As a result, the movement can be executed painlessly.

Delayed and Disrupted Brain Development – Global Integrative Effects

Postnatal sensorimotor maturation can be impaired by a range of factors, and disrupt the integrated development of perception, language, academic performance, stress tolerance, and social-emotional behaviour. These deficits typically become apparent during the early school years. Where such disruption is substantial, altered brain development shapes the neuromatrix in the sense of Melzack's pain theory [29-31], forming the basis for ineffective endogenous pain inhibition, a nociplastic pain disorder [32,33], and impaired executive function [34].

Sensorimotor Development and Executive Function after Birth

Figure 3 gives an overview about the sensorimotor activities as stimuli of development, maturation, growth and delay of aging process. By the end of infancy, the first planned actions begin to emerge. The preschool years and puberty represent formative stages in the maturation of the prefrontal cortex and, consequently, of executive function. One hour of moderate-to-vigorous physical activity per day serves as a crucial stimulus during this period [35]. Maturation is completed approximately in the middle of the third decade of life.

Sensorimotor activities in children, such as creative and intensive play in early childhood followed by structured training in later years, are the essential driving forces of brain development, cognitive-emotional function, and endogenous pain inhibition. The cerebral foundations of academic performance are built and promoted through sensorimotor activity, but must be realized through non-sensorimotor cognitive activities such as reading, writing, speaking, arithmetic, questioning, and problem-solving. Notably, each of these tasks retains a sensorimotor component, through which cognitive performance becomes externally visible or recognizable. Maturation, growth, and the slowing of aging all require systematic sensorimotor activity.

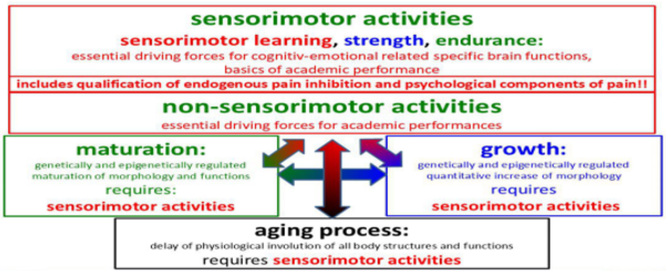

Fig 3: Sensorimotor activities: development, maturation, growth, aging process: Sensorimotor activities (children: creative, intensive playing, later training) are the essential driving forces of the brain development, cognitive-emotional function, and they also lay the foundation for academic performance. Sensorimotor development and function integrate pain inhibition and modulation, as well as the psychological components of pain processing. Physical activities stimulate, among other things, memory function and thus the functional basis of academic performance; however, there is no direct correlation between each other, as each skill must be learned specifically. Sensorimotor activities are necessary for genetically and epigenetically regulated maturation and growth and slow down the physiological aging process.

Between the ages of 6 and 17, physical activity, including intense strength-based and highly fatiguing endurance activities, serves as training stimulus for refining endogenous pain inhibition and the cognitive-emotional processing of pain. Sport increases pain thresholds and pain tolerance [36,37]. Both activity types promote neurogenesis during this period and confer neuroprotection across the lifespan. The also increase tolerance to physical and psychological stress, improve cerebral microcirculation and positive tissue crosstalk, and generate an anti-inflammatory, antinociplastic, and antidegenerative status.

Figure 4 summarizes the effects of physical activity or inactivity. Inactivity is responsible for a chronic inflammation process, the chronic degenerative diseases and reduces pain-inhibiting capacity and when this is chronically exceeded and social factors intervene, the brain responds with nociplastic changes. Adults with chronic pain exhibit cerebral alterations characteristic of both accelerated aging processes and neurodegenerative mechanisms [38]. Whether through active participation or chronic inactivity, physical activity levels fundamentally shape the brain.

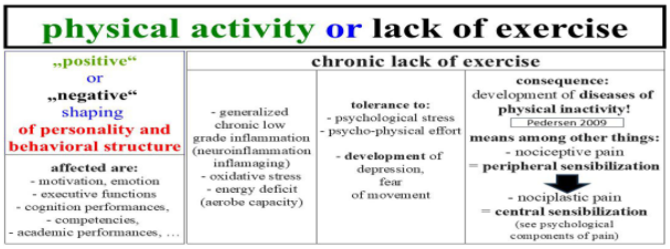

Fig 4: The effects of physical activity and inactivity on brain development, pain inhibition, chronic degenerative diseases, and neurodegeneration across the lifespan: Regular physical activity or inactivity positively or negatively shapes personality and behavioural patterns. All of the brain's highest functions are involved. Chronic inactivity is responsible for generalized, chronic, low-grade inflammation, which is associated with chronic oxidative stress and a deficit in aerobic capacity. Cerebrally, this leads to reduced tolerance to psychological and psychophysical stress, a depressive development, and anxiety related to movement. As a result, diseases of physical inactivity develop (Pedersen 2009). Nociceptive pain arises, initially triggering peripheral and subsequently central sensitization, leading to cerebral pain disorders.

Physical Activity and Academic Performance are not Equivalent

In the 12–18 age group, physical activity (and structured physical training in particular) benefits mental health, cognitive flexibility, executive functions, psychological well-being, and academic performance [39-45]. However, physical activity and training must not be equated with academic performance itself; it fosters the prerequisites for learning, not the performance outcomes.

Both academic and sensorimotor performance require a specific learning process to structure the brain for the intended function. "Whatever a person wishes to know and whatever sensorimotor skills they wish to acquire, they must explicitly learn."

Clinical Implications

Sensorimotor activity, as regular psychophysical activity [35] that trains all body structures, is an important lifestyle factor that is closely and mutually interrelated with all other factors [46] in favor of life expectancy and the reduction of the risk of non-communicable chronic degenerative diseases [47,48]. The intensity of this activity is of crucial importance. Equivalent values can be given for the duration of intense and moderate exercise. For general mortality, the equivalent is 1:4.1 minutes, for diabetes 1:9.4 minutes, and for cancer mortality 1:3.5 minutes. Low-intensity physical activity has a significantly weaker dose-response relationship [49] or requires a disproportionately large amount of time, and the majority of everyday physical activities remain ineffective. It is important to note that a mother's healthy lifestyle (physical activity, nutrition, etc.) before and during pregnancy provides biological developmental benefits, and that these benefits are subsequently augmented by the psychosocial aspect. Therefore, public health concepts for health, including beneficial neurocognitive development in offspring, must already be aligned with women's lifestyles. Age-appropriate physical activity is a necessary strategy for the development of executive and cognitive functions, educational outcomes, and overall health [50,51]. Physical activities promote neuroplasticity and thereby improve emotional regulation, attention and cognition via memory [52].

There are six factors that contribute to a healthy lifestyle [46]. Since physical activity promotes cognitive functions but is not synonymous with them, a seventh lifestyle factor should be considered: "a harmonious, empathetic, and socially supportive environment particularly during childhood and adolescence, together with non-sensorimotor cognitive activities across all age groups."

Discussion of Limitations

This article examines sensorimotor function as a fundamental function and a crucial central realizer and modulator of the integral development of neurocognitive and emotional functions and behaviour during ontogenesis. The implicit sensorimotor function of the developing child, and the explicit sensorimotor function after birth, interact throughout life with other lifestyle characteristics within the framework of the biopsychosocial model. The highly complex interrelationships between sensorimotor function and lifestyle factors, as well as among the factors themselves, have not yet been sufficiently analyzed and represent important research challenges for the future. Accordingly, it is essential to substantiate and validate the described relationships in detail through both experimental and long-term observations.

Summary and Outlook

A woman's physical activity before pregnancy is responsible for an epigenetic status that can be transferred to a child as a health-preventive biological strategy. During pregnancy, due to the capacity of myokines to cross the placenta, nutrition, and social behaviour promote the cerebral development of the unborn child. In the unborn child, reflex-based sensorimotor activities are the constant stimulus for cerebral development and create the neural foundations for pain inhibition as an integrated part of sensorimotor activities, pain perception, cognition, executive functions, and behaviour after birth. In infancy, reflexive sensorimotor activity transforms into situation- and perception-dependent sensorimotor activity, which requires cognition, attention, and awareness. Parental affection, social conditions, and lifestyle become important developmental factors for the child. The child's physical activity promotes neuroplasticity and provides the neural basis for academic achievement, which, however, must be acquired through a specific learning process.

The highly complex interrelationships between sensorimotor function and lifestyle factors, as well as among the factors themselves, have not yet been sufficiently analyzed and represent important research challenges for the future. Accordingly, it is essential to substantiate and validate the described relationships in detail through both experimental and long-term observations.

Integration into engineering and infrastructure standards

Large-scale implementation across digital and public systems

There is also scope for collaboration between behavioural science, engineering, accessibility research, and infrastructure planning to further strengthen neuro-inclusive system design approaches.

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Citation: Laube W. “Lack of Exercise: A Link Between the Sensorimotor System, Behaviour, Cognition, Emotions, and Nociplastic Pain.” J. Mental Health Behav. Sci (2026): 112. DOI: 10.59462/JMHBS.2.2.112