Active and sensitive periods in the brain development of babies

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The development of the human brain, both before and after birth, progresses through a sequence of active and sensitive periods for various brain functions. By the time of birth, 86 billion neurons already exist and have begun rapid networking through synaptogenesis, by which each neuron can connect to thousands of other neurons. In this paper, we explore how the brain is primarily programmed through the synaptic pruning process to manage its many functions, pinpointing the active and sensitive periods of this programming. The brain functions are divided into five sensory functions, as well as emotional, motor, cognitive, learning, and memory functions. Each of these functions has specific active development times, known as sensitive periods (also critical periods). Since the programming relies on experiential training of the firing pathways using sensor activation signals, the outcome is heavily dependent on the sensory signals the brain receives from its environment. Therefore, understanding how to interact with and care for a baby during these distinct sensitive periods is vital. If the environment is stable and caregivers act consistently, the baby's brain receives regular and repetitive training material, ideally strengthening and accelerating the permanent programming of the brain.

Keywords*: brain development, brain function, sensitive period, critical period*

Terms*: 'Newborn' refers to a child immediately after birth. 'Infant' means a child who is 0 to 12 months old. 'Toddler' indicates a child aged between 12 to 36 months. Lastly, 'baby' is used to describe a child from birth up to 3 years old.*

Introduction

A baby's brain grows and develops in a specific order. By the time of birth, all the neurons already exist and have begun the rapid networking process through synaptogenesis, allowing each neuron to connect to many other neurons. The number of synapses peaks during the first year of life and starts to decrease as the pruning of synapses becomes more rapid than their formation. (Fernandes and Carvalho 2016)

An individual's personality is determined only partly by genetic inheritance. A child grows and develops during the first few years of life, mainly due to the pruning of synaptic connections, which is affected by, among others, the nutrition the child receives, physical activity, sensory stimuli, and interaction with adults. Structures related to the senses, muscles, and brain activity emerge and develop at different stages. Because external stimuli during development significantly influence its trajectory, these phases are known as sensitive periods. In literature also the term "critical period" is used. Both critical and sensitive periods refer to specific developmental windows, but critical periods are more rigid and have more permanent consequences if the necessary stimuli are missed (Cisneros-Franco et al. 2020). Sensitive periods are more flexible, representing times of optimal, but not exclusive, learning or development. For simplicity, in this paper only the term sensitive period is used although some of them might be called critical periods. (Hensch 2004; Knudsen 2004)

During each sensitive period, stimuli—especially through the senses—directed at the brain may either promote or inhibit the development of that brain function (Johnson 2001; Fox, Levitt, and Nelson 2010). This paper explores the different stages of a baby's brain development from the perspective of sensitive periods, focusing on the potential for enhancement and the risks of disturbance through harmful treatments or ignorance.

Brain development

Within five weeks, the cells of the human embryo begin to specialize into neurons, and the neurogenesis starts producing cells for various brain parts. They migrate to their designated places, specialize in their functions and start building a network, with each neuron's axon seeking dendrites of neighboring neurons. Synapses form at these contact points, allowing neurons to connect. The development of brain functions begins at a very early stage, when neuronal differentiation gives neurons and various brain regions their specific abilities and functionalities Thus, the active and sensitive periods of brain development start from the first trimester of pregnancy, when the different brain regions have their specific time schedules, and continue until adolescence. (Fox, Levitt, and Nelson 2010; Knudsen 2004; Andersen 2022)

In nine months, an unparalleled and complex neural structure emerges, consisting of approximately 86 billion neurons. Each of these neurons connects to thousands of others, underscoring the extraordinary complexity of this network. Continuous firing and shuttling of nerve impulses between neurons begin, a process that only ceases upon death. Synapses that transmit nerve impulses become stronger, while those that do not transmit impulses weaken.

The development of a baby's brain functions is a complex, multifaceted, and astonishingly rapid sequence of events. Although brain functions are distributed across various regions, certain areas are specialized, serving as control centers for specific functions. Figure 1 introduces the important brain regions and their locations in the brain.

The four sensory functions—touch, hearing, taste, and vision—receive nerve impulses from the receptors in different parts of the body and the thalamus (TH) transmits them to their specific processing units and combines them to other brain activities, for example, in the frontal lobe (FL) and visual cortex (VC). The olfactory sense (smell) works through its own pathway.
In addition to the sensory functions, in this paper we highlight five higher-level brain functions: emotional processes regulated by the amygdala (A) and the limbic system, motor functions controlled by the motor cortex (MC) and the cerebellum (CB), cognitive activities governed by the frontal lobe (FL), learning functions involving many brain areas, and memory processes managed by the hippocampus (H).

By focusing on these, we overlook many important brain functions, such as the production and distribution of neurotransmitters. Along with hormones, they act as overarching coordinators, influencing not only brain functions but also the control of the entire body. They also play pivotal roles in emotional functions: endorphins produce a sense of well-being, dopamine is linked to feelings of reward, serotonin is primarily associated with mood regulation and body balance, oxytocin engenders feelings of closeness, and adrenaline is involved in the fight-or-flight response, often inducing feelings of fear. (Feldman 2015)

Sensory functions

The senses start developing very early. Touch receptors populate the fetus's skin by the 8th week of pregnancy, and the basic components of the eyes are completed by the 14th week. The receptors for smell and taste are functional by the 14th week, and the sense of hearing activates by the 20th week. The development of all sensory brain functions requires a continuous stream of sensory signals from the receptors to the brain. Even during pregnancy, the fetus feels, hears, smells, and tastes, and the associated brain functions, e.g., the somatosensory cortex (SC) in the parietal lobe, the auditory cortex in the temporal lobe, and the visual cortex (VC) in the occipital lobe, develop rapidly during the last trimester. (Vanderah and Gould 2020; Davies 2021)

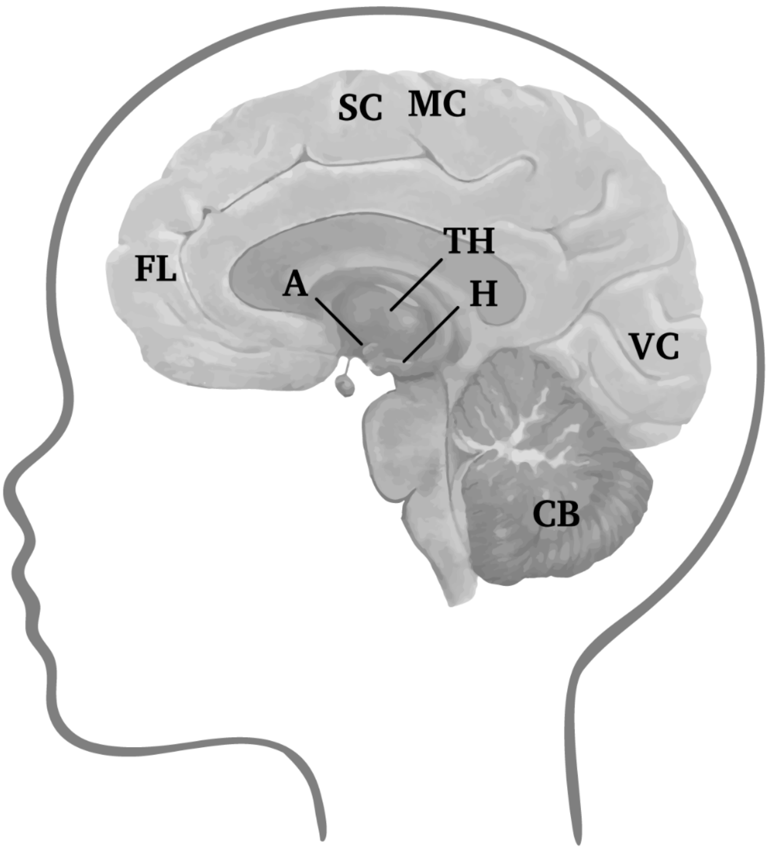

Figure 1. *A cross-sectional image of the human brain highlighting regions discussed in this paper:*
FL – Frontal lobe, important for various cognitive functions.
SC – Somatosensory cortex, involved in the perception of touch.
MC – Motor cortex, critical for controlling voluntary movements.
VC – Visual cortex, responsible for processing visual information.
TH – Thalamus, the main relay center for incoming sensory signals (except olfactory) and outgoing motor commands.
H – Hippocampus, part of the limbic system associated with learning and memory.
A – Amygdala, a component of the limbic system involved in emotional processing.
CB – Cerebellum, essential for coordinating fine muscle movements and maintaining balance.

Note: The auditory cortex is located in the temporal lobe, which is not shown in this cross-section

Emotional functions

Emotional functions relate to feelings, mood regulation, and emotional responses. They start developing during fetal life. The limbic system and its core unit, the amygdala, form early.

Emotional operations initiate in the third trimester. The limbic system tracks, processes, and stores events on an emotional scale from positive to negative, from intense to weak, and from controlled to uncontrolled. For instance, a joyful and accepting sense of well-being might be linked with endorphins and oxytocin, as well as potent emotional memories stored in the limbic system from similar situations. In contrast, frightening situations or feelings of abandonment may leave strong emotional imprints.

The mother's emotional reactions during pregnancy, especially long-term stress, which elevates cortisol levels in the body, can impact the fetus's limbic system development. Enzymes in the placenta can counter some of the cortisol, converting it to the less aggressive cortisone. However, with prolonged exposure, cortisol infiltrates the fetus's limbic system and amygdala, inducing alterations. This can influence the temperament or stress resilience of the newborn, potentially leading to various developmental and emotional disorders. (Canini et al. 2023)

Stress, adverse treatment, and neglect experienced by the infant can also result in lifelong disorders in the emotional system. The first years are vital for the development of a balanced emotional system. In a supportive environment, the baby's emotional functions mature in a balanced manner. (Sokolowski and Corbin 2012; Hambrick, Brawner, and Perry 2019; Fitzgerald, Hor, and Drake 2020; Campbell 2022)

Motor functions

Motor functions concerning movement, coordination, and physical actions are another segment of brain functions that display swift development from the newborn's very first week of life. Movement starts in the first trimester of pregnancy, the kicks are distinctly felt in the second trimester, and before birth, the fetus actively exercises its leg, arm, neck, and facial muscles. The motor cortex has already acquired many memory traces from the tactile feedback resulting from different movements before birth.

After birth, the fine-tuning functions of movements also become more active, with the cerebellum playing a significant role. The motor cortex primarily initiates voluntary movements, while the cerebellum refines and coordinates these movements. By around three years of age, the cerebellum attains its adult size, but functional refinement persists into adolescence. (Khazipov et al. 2004; Van Hooren and De Ste Croix 2020; Latash and Lestienne 2006)

Cognitive functions

Cognitive functions encompass thinking, problem-solving, decision-making, reasoning, and understanding the surrounding world.

Even before birth, the fetus reacts to external stimuli, such as sound and touch, signifying early sensory integration and cognitive processing. After birth, basic attention mechanisms develop. Newborns start recognizing faces and exhibit preferences for certain stimuli. Later, the infant begins to comprehend cause and effect and displays signs of memory retention. By the age of one, they grasp an object's permanence and solve simple problems, like finding concealed objects.

During the second and third year, they start understanding symbols, acquire a broad vocabulary, and indulge in pretend play. Also, they start grasping fundamental concepts like size and quantity and engage in more intricate problem-solving. (Sprenger 2013)

Learning functions

Learning functions include the acquisition of new knowledge and skills.

Before birth, the fetus begins to recognize and respond to sounds, especially the mother's voice, suggesting early memory formation.

After birth, they learn primarily through the senses. They begin to mimic simple actions and engage in trial-and-error learning. The adult acts as a mirror, responding to the infant's gestures and voicing. By one year old, they begin to mimic adult behaviors, learn through play, and understand simple instructions.

At two to three years old, their vocabulary grows rapidly. Rule-based learning in games and daily routines becomes familiar. Their learning is experiential and based on interaction with their environment. (Gopnik, Meltzoff, and Kuhl 1999)

Memory functions

Memory functions are related to the retention and recall of past experiences and learned information. Before birth, the fetus has the capacity to recognize familiar sounds, such as the mother's voice and a dog barking, which may suggest the formation of early memory traces. After birth, they display habituation, indicating memory of familiar stimuli. They can even recognize a lullaby sung repeatedly during pregnancy. Next, they start to show anticipatory behavior based on previous experiences and remember objects even when out of sight. (Webb et al. 2015)

By the age of 1–2 years, they can recognize familiar people, toys, and other objects and show excitement or anticipation. They also begin to understand routines and can anticipate what comes next in familiar sequences, like bedtime rituals.

Clearer long-term memory develops between 2 to 3 years of age, and they can remember words, recall past events, and follow multi-step instructions. Their memory functions evolve from basic recognition to more complex recall and retention of experiences over time. (Antunes and Biala 2012)

Active brain development and sensitive periods

Development of brain functions refers to the maturation and growth processes that the brain undergoes, allowing it to process information, regulate emotions, and control the body. This development is most rapid in early life but continues throughout adulthood.

Neurobiologically, this development occurs during prenatal development through neurogenesis by the formation of new neurons or nerve cells. Synaptogenesis also starts before birth and continues rapidly during the first few years. Pruning of synapses eliminates unused or unnecessary synapses, making neural networks more efficient. Myelination adds a myelin sheath around axons and dendrites, which speeds up the transmission of neural signals. This continues into early adulthood.

Brain development is based on neuroplasticity, which refers to the brain's ability to reorganize itself. It is most pronounced in childhood but continues throughout life.

The optimal development of the brain's various functions occurs in an environment where the infant's senses provide the brain with diverse developmental stimuli, where the baby's muscles are allowed to try and repeat different movements, and where the infant receives accepting and safe interaction with their caregivers. Thus, the brain also receives beneficial developmental stimuli for the development of emotional functions. (Johnson 2001; Fox, Levitt, and Nelson 2010; Knudsen 2004; Hensch 2004; Cisneros-Franco et al. 2020; Handryastuti and Asih 2022; Fitzgerald, Hor, and Drake 2020; Wall 2018; Tierney and Nelson 2009; Sprenger 2013; Andersen 2022)

Figure 2 illustrates the typical expected activity levels for five sensory functions—touch, hearing, smell (olfactory), taste (gustation), and vision—as well as five other brain functions: emotional, motor, cognitive, learning, and memory, from the onset of pregnancy through to three years of age.

We concentrate on evaluating the intensity of sensory and inter-neuronal activity to explain the sensitivity of sensitive periods. This approach is based on the principle that developing brain functions mature optimally in response to abundant sensory inputs and dynamic neural interactions from various brain regions.

The intensity of the color represents the level of activity and, correspondingly, the sensitivity of the development of that particular brain function during the period. White indicates ‘not yet operational’, and progressively darker shades signify increased activity and sensitivity in brain development and function.

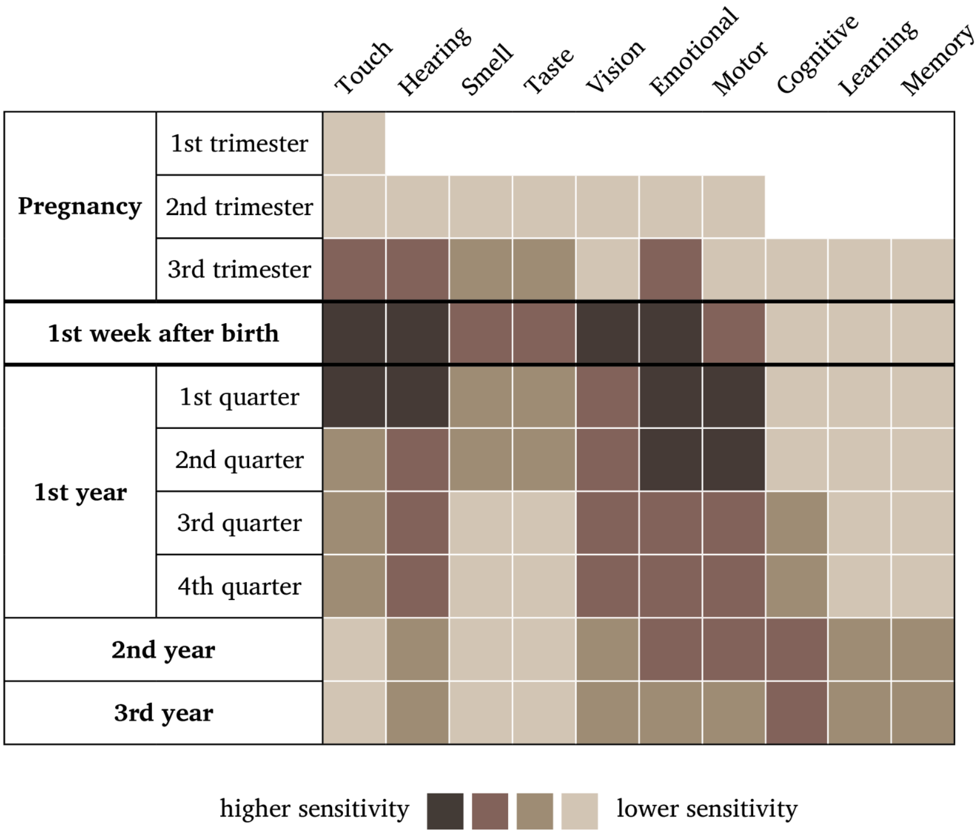

Figure 2. *A generalized depiction of the typical expected sensitivity periods of five sensory functions (touch, hearing, smell, taste, and vision), as well as five other brain functions (emotional, motor, cognitive, learning and memory) from the beginning of pregnancy to up to three years of age.*

Sensitive periods

Sensitive periods are time periods of varying length when certain brain functions develop quickly and efficiently. This development involves changes in different neural pathways and memory traces and requires plenty of developmental stimuli, like abundant sensory activation and repeated physical and emotional experiences. It's important that children receive abundant sensory stimuli and opportunities to move, explore, and interact with their environment. Extremely important is experiencing and practicing interactions with adults during these developmental periods, as the brain's programming largely occurs through practical training. (Walasek, Frankenhuis, and Panchanathan 2022; Andersen 2022)

Around birth

Also the period of pregnancy, especially its last trimester, is a sensitive phase. Factors that can disrupt development during pregnancy are: nutritional deficiencies, exposure to toxins, infections, stress and trauma. Lack of essential nutrients, like folic acid, can result in neural tube defects. Alcohol, drugs, and certain medications can lead to fetal alcohol syndrome or other developmental disorders, certain infections during pregnancy can interfere with brain development, maternal stress can affect the development of the fetal brain, leading to long-term consequences in the child's emotional and cognitive functions and physical trauma during pregnancy can potentially damage the developing brain. (Handryastuti and Asih 2022; Fitzgerald, Hor, and Drake 2020; Catale et al. 2020; Ustun, Covey, and Reissland 2023; Monfort et al. 2022; Bergman et al. 2007; Pappalardo et al. 2023; April and Erik Connor 2019; Mehl et al. 2022; Knudsen 2004; Ainiti et al. 2023)

Although significant development occurs during the fetal period, the most crucial phase for the development of brain functions begins immediately after birth. The first week, in particular, is a dynamic period for the newborn, marked by a multitude of novel sensory experiences: the sense of touch is exposed to new surfaces and temperatures, the inner ear adjusts as it clears of fluid and the auditory environment undergoes a dramatic shift, the eyes begin to process light, and the smell and taste systems encounter a variety of new stimuli. Figure 2 emphasizes this initial week as a distinct and critical phase in the newborn's life.

The first years

The first two years of life are particularly critical for the development and stabilization of brain functions.

Synapses that are consistently activated and receive frequent neural impulses are strengthened, while those that are less frequently activated undergo synaptic pruning. The fewer stimuli the brain receives, the more extensive this pruning process is. Once synapses are pruned, re-establishing them becomes a challenge. This period essentially acts as a pivotal window—a sensitive period—in development. Within this timeframe, a child's emerging personality is profoundly shaped by environmental stimuli, though it is always influenced also by genetic predispositions. (Cozolino 2014; Wall 2018; Tierney and Nelson 2009; Svanberg, Mennet, and Spieker 2010)

In Figure 2, the first years are divided into two main periods: the infant's first year, which includes four quarters, and the second and third years, which correspond to the toddler stage. It is evident that touch and hearing are the most active sensory functions during the first quarter, a time when emotional and motor functions rapidly develop. Vision develops more slowly, and cognitive functions emerge later.

Sensitive periods of sensory functions

The *sense of touch* begins to develop very early and is active during the last trimester of pregnancy, playing an essential role after birth. Upon leaving the protective environment of the womb, the newborn requires substantial skin contact to experience the comforting sensation of the mother's heartbeat and movements. The sense of touch remains significantly important throughout the first year of life as the infant learns to differentiate various surfaces and objects, initially exploring them with their mouth, where touch is particularly sensitive and taste is also present.

The *sense of hearing* is equally important during the last trimester of pregnancy and immediately after birth. The fetus is already accustomed to a variety of sounds, including the mother's heartbeat, blood circulation, breathing, speech, and everyday household noises like a dog barking. These sounds provide security and familiarity to the newborn. Moreover, throughout the early months, the infant actively employs their sense of hearing to absorb environmental sounds, caregivers' speech, and other auditory cues. The hearing develops over the first year as the child begins to comprehend sounds, words, and simple phrases. By the second year, the child's vocabulary expands as they start to remember more words. It is crucial that the child is exposed to ample speech and a variety of life's auditory experiences during both the first and second years to ensure that hearing and the associated brain functions receive adequate stimulation and practice. Other senses, such as smell, taste, and vision, also develop according to their own timelines. In particular, the sensitive periods of the sense of vision have been extensively studied, including studies of stereoscopic vision. If an infant's one eye has to be kept closed during the first few months, the ability to distinguish distances might become permanently impaired. (Davies 2021)

Sensitive periods of higher brain functions

Sensitive periods can also be identified in the development of higher brain functions. Tragic examples of this include abandoned infants whose emotional abilities remain permanently deficient. The same applies to the development of motor brain functions. If an infant is not allowed to stand during their first years of life (a sensitive period for motor development), it becomes more challenging for them to learn to walk. (Nelson, Zeanah, and Fox 2019)

Cognitive brain functions might not reach their full potential if a child is deprived of developmental opportunities during their early years. While cognitive functions, along with learning and memory functions, evolve over a more extended period compared to emotional and motor functions, they still exhibit plasticity and can be enhanced later in life. (Knudsen 2004; Feldman 2015; Malave, van Dijk, and Anacker 2022; Van Hooren and De Ste Croix 2020; Goldberg 2014; Andersen 2022)

In Figure 2, the most significant activities and developments have been compiled for the five brain functions, broken down by each period. Emotional and motor functions, being the most active, have been analyzed in greater detail. Cognitive function begins its development as the frontal cortex (FC) reaches full maturity and the myelination of neural pathways accelerates signal transmission between the central brain and the cortexes. Learning and memory functions initially rely on short-term and emotional memory until the hippocampus becomes fully operational during the third year, which is necessary for the onset of episodic memory. This delay in hippocampal maturation is why we are unable to recall events from our toddler years.

Discussion

Brains are remarkable for their flexibility; the construction instructions in the genetic code allow for the development of very different individuals from the same genetic heritage, influenced by the environment and the interactions with people (and animals) before and after birth. Sensory and other brain functions adapt based on the stimuli and interactions they receive. It is crucial, therefore, for parents and educators to understand how a baby's brain develops, how to stimulate it beneficially, and what to avoid. By recognizing specific sensitive periods, one can foster positive brain development and prevent harm. (Hakamata et al. 2022; Lönnberg et al. 2021; Shonkoff, J. P. & Phillips, D. A. 2000; Thompson 2016)

Particularly critical periods in baby care include pregnancy, the moment of birth, the week following it, and the first six months. While some sensitive periods are brief, lasting only weeks or months, others extend up to three years of age and even into adolescence.

During pregnancy, a mother's calmness and positive emotional states, along with circulating hormones, can embed emotional memories of a peaceful heartbeat and deep breathing in the fetus's limbic system. This foundation assists the newborn in establishing balanced emotional brain activity. The lullabies and friendly speech that the fetus hears, along with rhythmic movements and belly taps, reinforce these emotional memories.

Conversely, harmful substances like alcohol and drugs can cause irreversible disturbances when passed from the mother through the placenta, potentially inducing dependency in the fetus before birth. Prolonged maternal stress may also introduce stress hormones to the fetus's brain, leading to enduring alterations. (Pleil et al. 2015; Gómez-Roig et al. 2021; Ainiti et al. 2023)

The moment of birth and the subsequent week constitute a significant period of change and adaptation for the newborn. Transitioning from the warm, protective womb to the colder external world, taking the first breaths of air, encountering bright light, and hearing the loud sounds of the delivery room are drastic changes. It may be fortunate that we retain only emotional memories of this event, not episodic ones.

It is vital for the infant to connect with the mother. Kangaroo care, or extensive skin-to-skin contact, helps reinforce the emotional memories formed during pregnancy within the limbic system. This connection paves the way for the infant's ensuing life phase. (Bhamani et al. 2022; Kostilainen et al., 2021)

The first six months introduce the infant to a multitude of new situations and experiences, which contribute to a blend of positive and negative emotional memories. Novel olfactory and gustatory experiences, movements, the sight of the mother's face, new tactile sensations, and sounds inundate the infant's brain with neural impulses, shaping it to first tolerate, then anticipate, and eventually understand the environment. (Nelson, Zeanah, and

Fox 2019; Dopierala and Emberson 2023)

Familiar and safe elements are calming, while novel and unexpected ones can trigger fear in the limbic system. Consistency is key. If the environment and the caregiver's actions remain consistent, the baby's brain receives steady developmental stimuli, which is ideal training material for strengthening and accelerating its permanent programming.

Conclusion

Brain development is a periodic process, with different brain functions maturing according to their own timelines. Sensory functions develop early, providing the initial stimuli required for the advancement of higher brain functions. These training stimuli come from both caregivers and the environment. For optimal development, an abundance of sensory stimuli is necessary, alongside consistent care practices and appropriate responses to the baby's actions.

The development of the human brain during pregnancy, as well as during the newborn, infant, and toddler stages, should be thoughtfully considered in childcare planning and execution. The impact of childcare practices, both positive and negative, can lead to long-lasting changes in brain functions, particularly when they coincide with the sensitive periods of these functions. Positive interactions promote and stabilize brain development, whereas negative experiences can hinder growth or lead to instability. Consequently, a child nurtured in a supportive environment is more likely to thrive and develop a well-balanced life.

Fortunately, most families and caregivers instinctively know how to care for and treat their children. Additionally, isolated mistakes, when not repeatedly made, are generally not serious. The brain's plasticity in infants allows for corrections over time, enabling a return to normal development.

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