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Maria Montessori and Neuroscience: The Trailblazing Insights of an Exceptional Mind

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Abstract

This comment presents Maria Montessori (1870–1952) and highlights that her child-centered method of education is based on brilliant intuitions, which were confirmed by neuroscience research many decades later, such as the distinction of three critical periods in children's psychobiological development; the importance of the environment in supporting cerebral development and in promoting learning, as well as of affective stimulation in psychological growth and maturation; the specific neural structure of humans that specifically enables the acquisition of a language; the vital role of fine object manipulation in neuropsychological development, and of the physical exercise in brain and nervous system development.

Keywords

brain development, brain plasticity, children education, psychobiological development, critical period

Maria Montessori (1870–1952), one of the most original and influential scholars of the 20th century, is best known for her revolutionary child-centred method of education, which is still used in schools throughout the world. Freud, the father of psychoanalysis, told her, "If everyone had your schools, they wouldn't need me." However, her educational philosophy—which was rooted in her lifelong observation of children—was based on a number of strikingly accurate hypotheses on child development that predated several neuroscientific discoveries by decades (Babini and Lama 2016).

Montessori was born in Chiaravalle, a village in Marche (Central Italy), to a middle-class Catholic family. In 1896, she took a medical degree at the University of Rome, becoming one of the first women in Europe to practice medicine. An early experience with children with mental disabilities living in Rome's asylums proved critical for the development of her educational philosophy and method, which she devised to teach all children. The method is based on self-education, freedom, activity, movement, and practical experience. She posited that children should be surrounded by simple objects in different shapes that can be manipulated and variously combined, in rooms with specially designed small furniture. Within 10 years of its publication, in 1909, the book where she first described her method was translated into 36 languages and printed in 58 countries.

Montessori became an international personality and an advocate for women's and children's rights (Fig. 1). In 1934, she fled to Spain to escape fascism, but in 1936 she

Figure 1. Maria Montessori (right) in Ancona in October 1950, during a meeting in her honor. MM is with the wife of the city mayor (center) and Getulia Rossi Ruggeri (left), who at that time was a teacher at an elementary school in Piticchio, Ancona. From the private collection of family Ruggeri-Censi, kindly provided by Giovanna Censi and Rita Ruggeri, grandchild and granddaughter, respectively, of Getulia Rossi.

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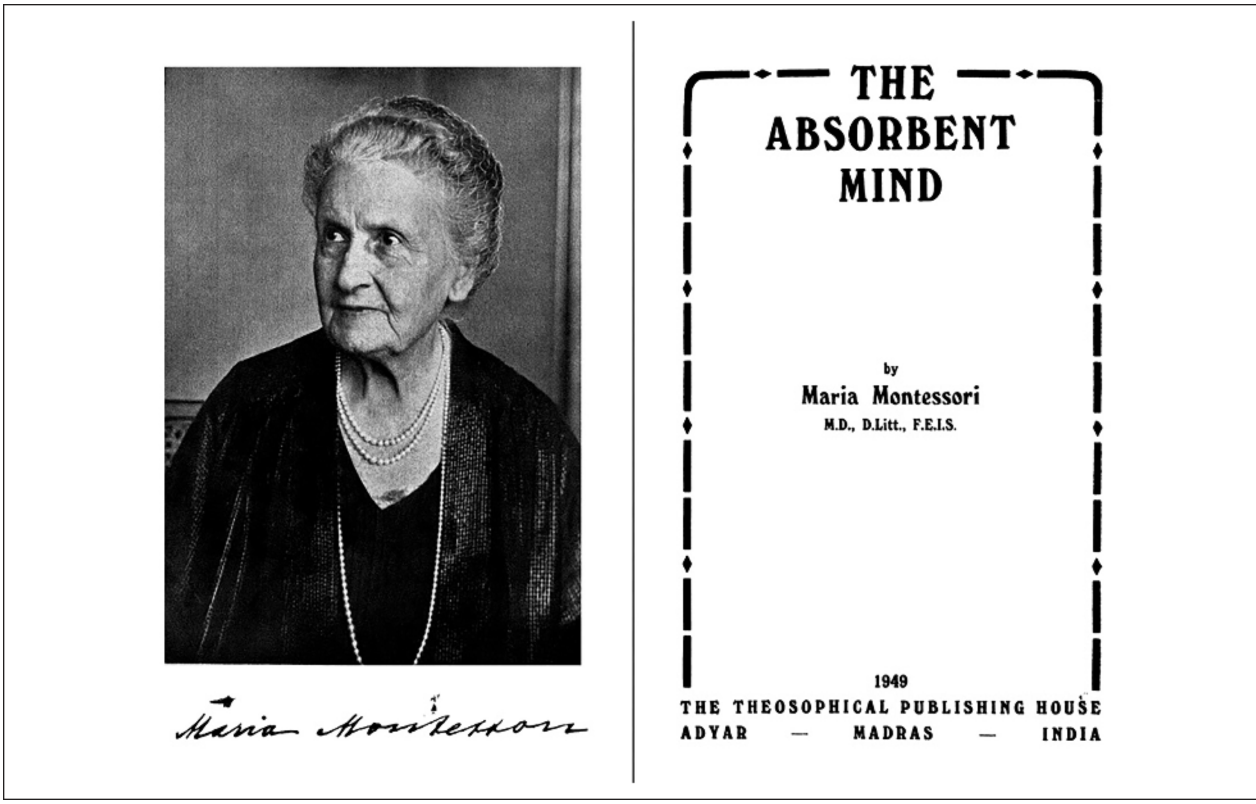

Figure 2. Picture of Maria Montessori (left) and the cover page of the original copy of her book, *The Absorbent Mind* (right), published in 1949. Reproduced from https://ia800705.us.archive.org/26/items/absorbentmind031961mbp/absorbentmind031961mbp.pdf.

had to move again due to the civil war. From 1939 to 1946, she lived in India, where she continued to study and teach. Her Indian lectures constitute the bulk of *The Absorbent Mind* (Fig. 2; Montessori 1949), the latest and most comprehensive presentation of her thinking. Her theory integrates the insights of the physician and the educator, combining biological notions with the effects of the environment. Her observations of children led her to advance a revolutionary theory of education that touched on most aspects of child development; as documented by a recent essay focusing on the relationship between Montessori's approach to the child's brain and neurosciences, her theory is still influencing the modern pedagogic methods (Regni and Fogassi 2019). Even more remarkably, several of the insights on which her child-centered educational method rests predated many major neuroscientific discoveries by decades. Some of the pioneering hypotheses on which she based her educational theory are summarized below.

Montessori identified three critical periods in children's psychobiological development. In her view, the child is a *spiritual embryo*, whose psychological development and biological growth proceed together through *sensitive periods*, in which the child is interested in and receptive to certain domains and acquires a number of specific skills and abilities (Fig. 3). These three phases go from birth to 6 years, from 7 to 11 years, and from 12 to 18 years, the latter period involving such momentous transformations as to be reminiscent of the first.

Figure 3. Picture of the first Montessori school, opened in Rome in 1907, and called "Casa dei Bambini" (Children's House). Kindly provided by Fondazione Chiaravalle Montessori, http://www.fondazionechiaravallemontessori.it/files/.thumbs/gallery/vita/1140x/gallery-26.jpg.

Neuroscientific work supporting these observations began to be published in the 1960s, showing that in

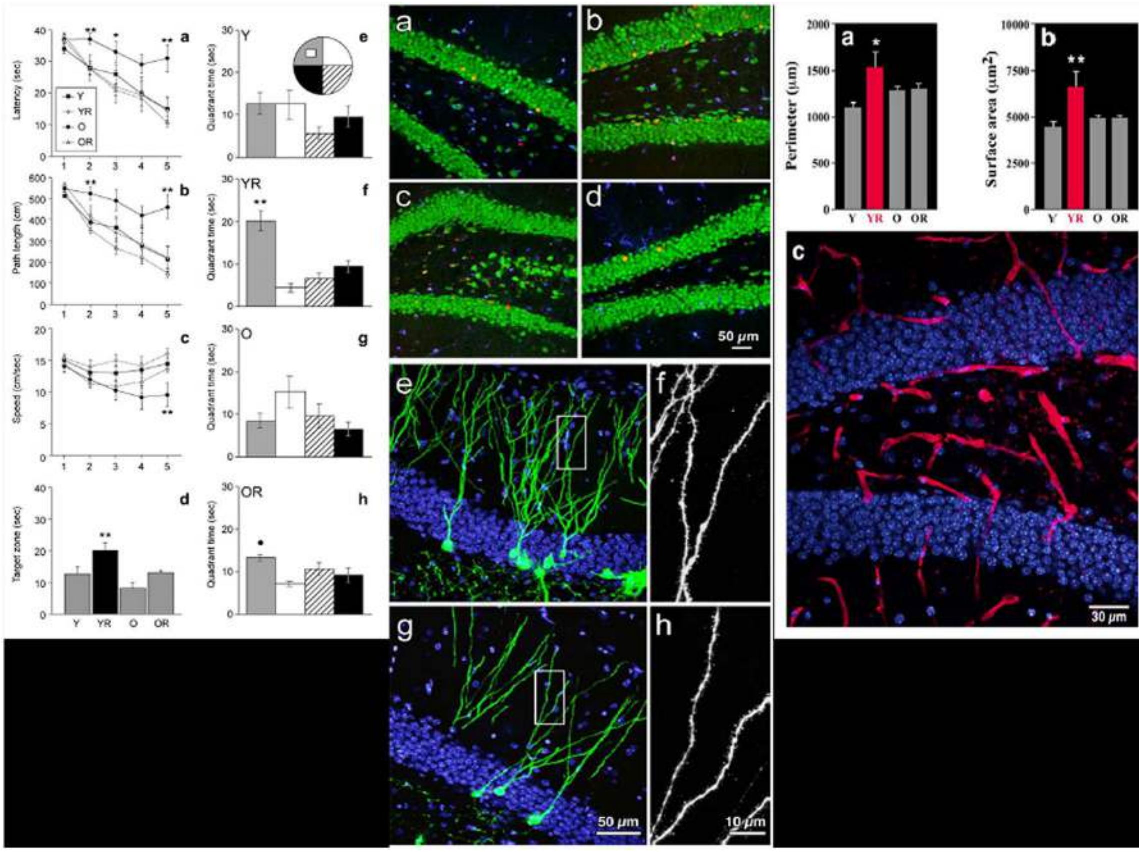

Figure 4. *Left panel*: Water maze learning in young and aged mice housed with or without running wheel access. Aged controls (O) had significantly longer latency (*a*) and swim path (*b*) to the platform than all other groups ($P < 0.01$). Swim speed (*c*) was slower in old controls than in all other groups on day 5 of training ($P < 0.03$). The probe test 4 hours after the last trial on day 5 showed that YR mice (*d, f*) and OR mice (*h*) had a significant preference for the platform quadrant but not the Y mice (*e*) and O mice (*g*). Asterisks indicate a significant difference from YR and OR mice (*) and a significant difference from all other groups/quadrants (**); the filled circle indicates a significant difference from adjacent quadrants ($P < 0.05$). Figure from Van Praag and others (2005). Copyright (2005) Society for Neuroscience. *Central panel*: Neurogenesis in the young and aged dentate gyrus. Confocal images of immunofluorescent triple-labeled sections for BrdU (red), NeuN (green), and S100β (blue) (BrdUlabeled neurons are orange [red plus green]) in young controls (*a*), old controls (*c*), young runners (*b*), and old runners (*d*) are shown, as well as photomicrographs of GFP new neurons in young (e) and aged (*g*) running mice at 4 weeks after virus injection. The boxed areas in e and *f* correspond to the enlarged images of spines in young (*f*) and aged (*h*) mice (DAPI, blue). Figure from Van Praag and others (2005). Copyright (2005) Society for Neuroscience. *Right panel*: Blood vessel size in the dentate gyrus of young and aged mice housed with or without a running wheel. (*a*) The perimeter of the vessels is larger in YR mice compared with age-matched controls (Y; $P < 0.04$) but did not differ from the aged controls (O) or aged runners (OR) ($P > 0.21$). (*b*) Vessel surface area was greater in YR mice than in all of the other groups ($P < 0.05$). (*c*) Lectin-stained vessels (red) and DAPI (blue) in the dentate gyrus. Figure from Van Praag and others (2005). Copyright (2005) Society for Neuroscience.

early childhood the cat and monkey brain is highly plastic and is strongly influenced by the environment (Hubel and Wiesel 1962, 1970; Wiesel and Hubel 1963). This line of research eventually led to the award of the 1981 Nobel Prize in Physiology or Medicine to Hubel and Wiesel. Montessori's tenet that adolescence is a period of deep transformations has also been confirmed by studies showing that the adolescent brain undergoes profound changes—more in terms of connectivity than of neural growth—until 18 to 20 years, when it reaches its adult structure and function (Giorgio and others 2008).

A groundbreaking notion in Montessori's thinking was the crucial importance of the environment in supporting neural/cerebral development and in promoting learning, also through motivation.

Scientific confirmation for it came from animal studies demonstrating that a rich and varied physical and relational

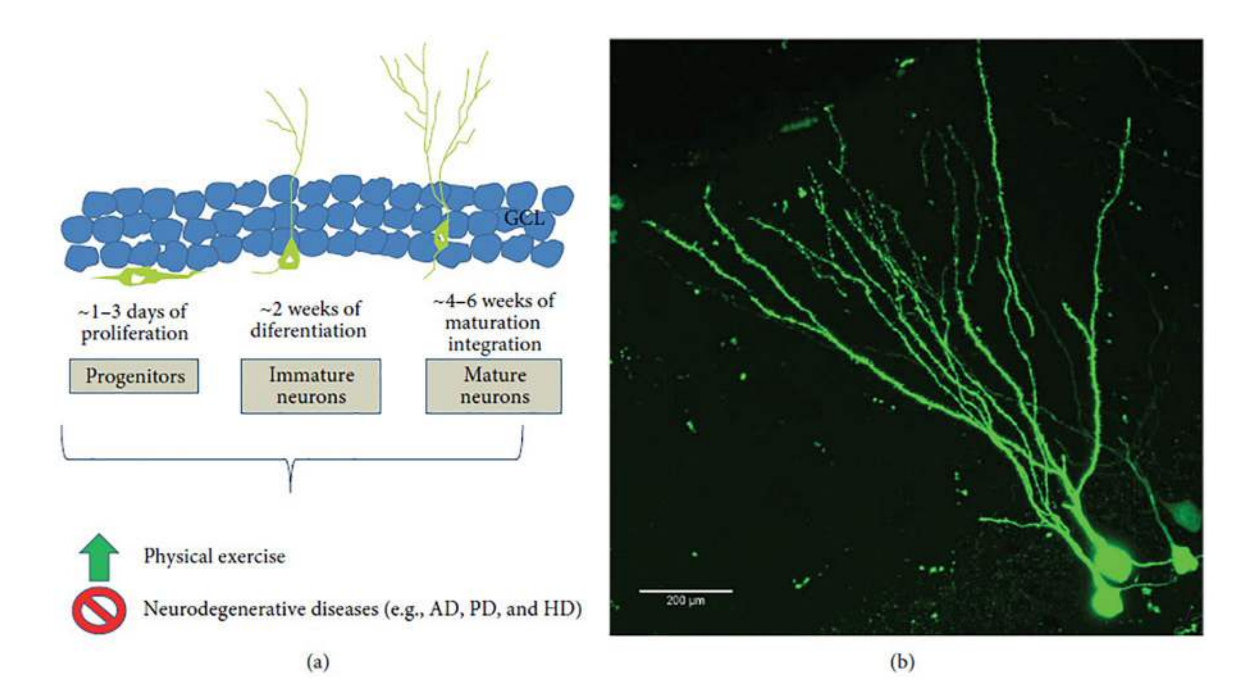

Figure 5. Development and integration of adult-born neurons in the dentate gyrus of the hippocampus. (a) The neural progenitors that are divided from neural stem cells start expressing either neuronal or glial phenotypes after just a few days of division. Newborn neurons gradually migrate from the subgranular zone (SGZ) into the granular cell layer (GCL) where they undergo maturation, followed by functional integration into the existing neural circuitry in the hippocampus. This process of hippocampal neurogenesis is known to be promoted by physical exercise and to be compromised in several neurodegenerative diseases such as Alzheimer's disease, Parkinson's disease, and Huntington's disease. (b) Confocal image of 4-week-old retroviral-labeled newborn neurons with green fluorescence protein (GFP) in the GCL (scale bar: 200 μm). Reproduced from Yau and others (2014).

environment affects the cerebral microenvironment and can even extend the critical period of brain plasticity into adulthood (Di Garbo and others 2011; Hensch 2004; Tognini and others 2012), enhancing cognitive ability and even the synaptic plasticity of the visual cortex (Sale and others 2009), and reinforcing the connections and information exchanges between cortical areas.

Another factor whose significance Montessori perceptively recognized was the powerful influence of affective stimulation on psychological growth and maturation.

Her intuition has eventually been substantiated by a wide range of studies. For instance, the description of Spitz syndrome—which is caused by sensory deprivation—in 1945 eventually led to the identification of anaclitical depression in children derived from their caregivers: all symptoms disappear when the child is reunited to the mother/caregiver. As regards the neural mechanism involved in the beneficial effects of affective stimulation on nervous system development, a seminal study showed that rat pups raised by a "good mother"—one which spends time licking and grooming them—will be healthier and more resistant to stress as adults, through a higher expression of hippocampal glucocorticoid receptor (McGowan and others 2011; Zhang and others 2010).

Montessori's observations also suggested to her that humans possess a neural structure that specifically enables the acquisition of a language, the actual language being determined by the environment.

Scientific evidence for this view came from the work, among others, of Noam Chomsky, who since 1957 developed his theory that language abilities are rooted in neural (cortical) brain structures and in a species-specific computational ability (Chomsky 1981). These skills have identifiable correlates in the brain and have not changed since the origin of language about 100,000 years ago (Berwick and others 2013). Although songbirds share with humans an ability to learn vocal imitation and a similar underlying neural organization, language is uniquely human.

Another striking insight was the vital role of fine object manipulation in neuropsychological development, which led Montessori to state that "the hand is the organ of the brain" (Montessori 1949).

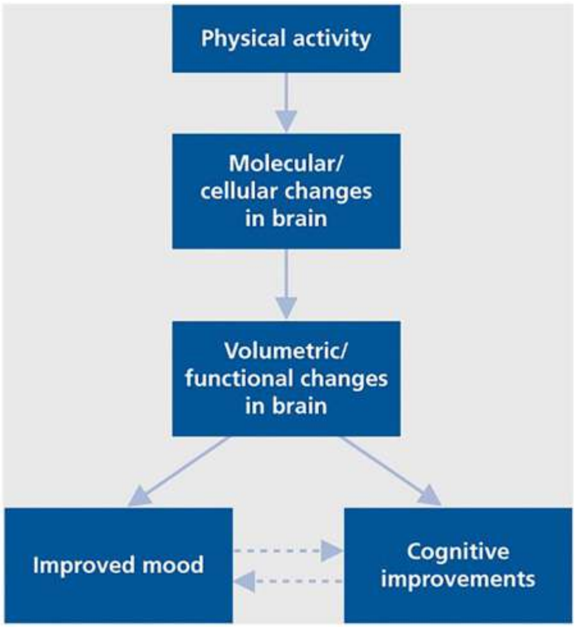

Figure 6. A schematic representation of the general path by which cognitive function and mood are improved by physical activity. It could be hypothesized that improvements in cognitive function mediate the improvements in mood or that improvements in mood mediate some of the improvements in cognitive function. The dotted lines represent these hypothesized paths. Reproduced with permission from Erickson and others (2013). Copyright Les Laboratoires Servier, 2013.

This intuition has duly been confirmed, too. Brain mapping studies have demonstrated that the size of the motor and sensory cortical regions devoted to the representation of the hand exceeds even the dimension of the hand itself, indicating that a huge number of neurons are involved in controlling its movements and in processing its sensory information. Interestingly, in string players the left hand representation is much larger than in other individuals (Elbert and others 1995), the reorganization being more pronounced in those who began playing earlier (Wilson 2010). Such high sensory resolution of the information coming from the tactile receptors of the hand makes it possible, among other things, to read Braille. Hand movements are so important that their limitation may also have dramatic effects. The finding that children who have been using a tablet since early infancy have delayed language development (https://www.repubblica.it/tecnologia/2014/05/03/news/ricerca_tablet_e_smartphone_ritardano_apprendimento_bambini-85130135/?ref=search) has led scientists to recommend avoiding touchscreen devices until 2 years of age, and to allow them sparingly afterwards (Radesky and Christakis 2016). Critically, hand motor activity may help to think and influences problem-solving, enhancing overall or systemic working memory resources if the activity is simultaneous with the intellectual task (Vallée-Tourangeau and others 2016a; Vallée-Tourangeau and others 2016b).

However, Montessori's most remarkable intuition is, in our view, the central role played by physical exercise in brain and nervous system development. Based on the trivial fact that the muscles account for about 30% of body weight, Montessori inferred that exercise must have a significance that went beyond mere body fitness and gave it a prominent role in children's daily activities.

The view that exercise is a critical factor enhancing brain development continues to receive confirmation, so much so that the motor system has come to be included in the cognitive system. Accordingly, aerobics and other types of exercise have been found to stimulate neurogenesis, also in adults and in the elderly, and to improve fiber myelination (Figs. 4-6; Erickson and others, 2013; Gons and others 2013; Pedersen 2019; Van Praag and others 2005; Yau and others 2014). Regular exercise enhances cerebral functions by increasing cognitive ability, memory, general plasticity, and gray matter volume besides improving mood. Physical activity stimulates the production of neural (brain-derived neurotrophic factor) and glial (glial-derived neurotrophic factor) growth factors by the brain (Fig. 7; Pedersen 2019); it induces faster recovery from cerebrovascular accidents (stroke); it delays the onset of neurodegenerative disorders (Alzheimer's disease, multiple sclerosis, dementia; Yau and others 2014); and can improve the control of the motor symptoms of Parkinson's disease (Pepper 2011). Notably, a 15-year-old who was diagnosed with dyspraxia at age 5 years took up sports and achieved such marked improvement in his symptoms that he went on to win athletic competitions (http://www.athletics.org.nz/News/guthrie-crofts-triple-treat). Last, but not least, physical activity seems to help prevent cancer development and enhances the effect of treatment, so that 30 minutes of exercise have been included in cancer patients' daily regimens (http://www.repubblica.it/oncologia/qualita-di-vita/2017/02/10/news/cura_dei_tumori_attivita_fisica_come_terapia-157999087).

Maria Montessori, who resolutely pursued her own education in the face of considerable difficulties and opposition and sacrificed important areas of her life to her research, was an exceptional scholar and educator whose insights predated a surprising number of crucial medical discoveries.

To celebrate the genius of this famous daughter of the Marche region, the local Medical School has named its impressive Auditorium for Maria Montessori.

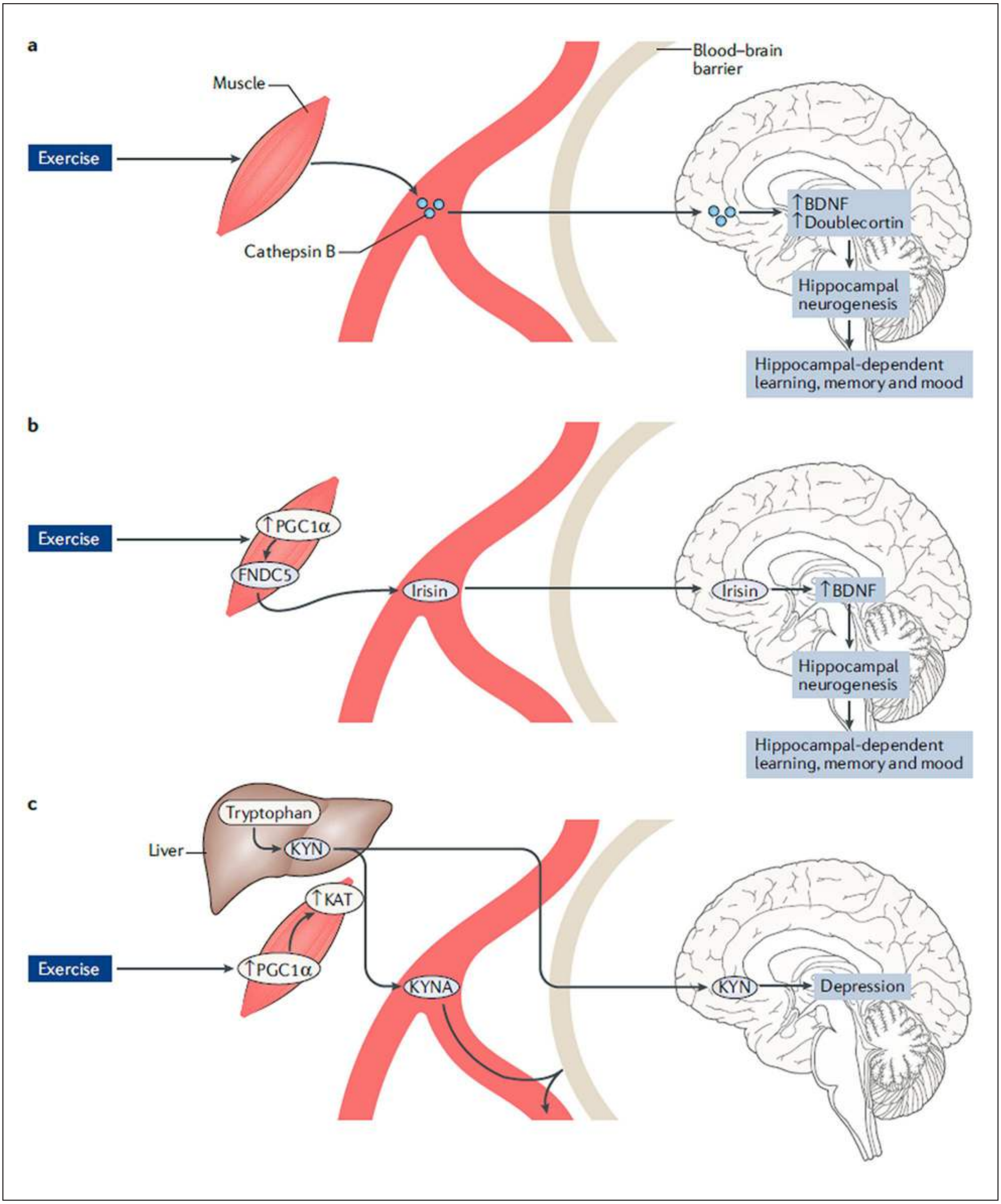

Figure 7. Ways in which exercise might beneficially affect neurogenesis, learning, memory, mood, and depression-like symptoms. (a) The myokine cathepsin B is released by skeletal muscle during exercise and might influence neurogenesis, learning, memory, and mood. AMP-activated protein kinase (AMPK) activation elicits cathepsin B secretion in skeletal muscle cells. Running increases cathepsin B levels in mouse gastrocnemius muscle, and exercise leads to an increase in

(continued)

Figure 7. (continued)

levels of the myokine cathepsin B in the plasma of mice, rhesus macaques, and humans. In vivo studies provided evidence that, in mice, peripheral cathepsin B crosses the blood-brain barrier. In vitro studies on hippocampal progenitor cells showed that cathepsin B increased both mRNA and protein levels of brain-derived neurotrophic factor (BDNF) as well as doublecortin. These factors are known to be important for neuronal migration and neurogenesis and thereby affect learning, memory, and mood. (b) FNDC5, a membrane protein that is cleaved and secreted into the circulation as the myokine irisin during exercise, might influence BDNF and influence neurogenesis, learning, memory, and mood. Exercise in mice and humans induces an upregulation of PGC1α in skeletal muscle. In mice, PGC1α expression in muscle stimulates an increase in the expression of FNDC5. Exercise also leads to a PGC1α-dependent elevation of FNDC5 in the hippocampus of mice. Peripheral delivery of FNDC5 to the liver via adenoviral vectors, resulting in elevated blood levels of irisin, induces expression of BDNF in the hippocampus, suggesting that irisin passes through the blood-brain barrier and induces BDNF expression in the brain, which will lead to enhanced learning, memory and mood. (c) High levels of the neurotoxic kynurenine (KYN) are associated with depression. Exercise enhances the PGC1α-dependent muscular expression of the enzyme kynurenine aminotransferase (KAT), which converts neurotoxic KYN into neuroprotective kynurenic acid (KYNA), thereby reducing depression-like symptoms. In contrast to KYN, KYNA is not able to pass through the blood-brain barrier. The imbalance between the neuroprotective KYNA and the neurotoxic KYN metabolites has been proposed to be critical for the development of depression. From Pedersen (2019).

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