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PSYCHOLOGY

COURSE COMPANION

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3.1 Brain development

Inquiry questions

- How does the brain change as it grows?
- To what extent does biological development of the brain depend on life experiences?
- How good is the brain's ability to reshape itself?

What you will learn in this section

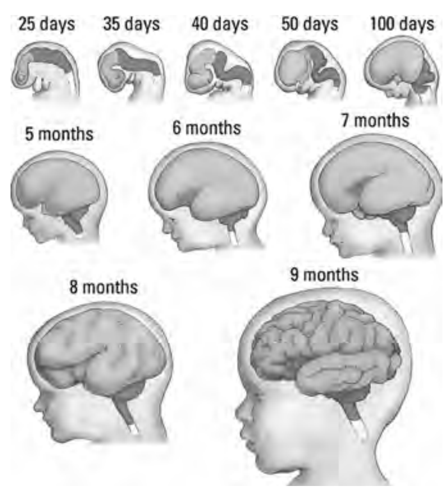
Key learning:

- Developmental neuroscience has accumulated rich knowledge about the biological process of brain maturation. This process can be viewed in terms of four stages: neurogenesis, migration of neurons, differentiation, pruning.
- Neuroplasticity is the making and breaking of synaptic connections. It is the neural mechanism of learning.
- Experience-expectant neuroplasticity works by overproducing neurons and connections and then eliminating the ones that are not used (pruning). There are critical periods of time when the brain is particularly responsive to relevant experiences.
- It is not the number of connections that determines the level of cognitive functioning, but how efficiently they are organized.
- Experience-dependent neuroplasticity has evolved to deal with experiences that are unique to the given individual. New synapses between neurons are created depending on how frequently the two neurons are activated together.
- The study of structure–function relationships in the developing brain is important, but the interaction between structure and function is complex. Developmental neuroscience should rely heavily on triangulation of evidence.
- There are important limitations associated with measurement. For example, young participants are not suitable for long brain scans, and the contrast between grey matter and white matter also changes, affecting brain imaging.

Key terms: biological maturation, neurogenesis, migration of neurons, differentiation, pruning, neuroplasticity, synaptic plasticity, cortical remapping, experience-expectant neuroplasticity, experience-dependent neuroplasticity, sensitive (critical) periods in development, discrimination paradigm, structure–function relationship, localization of function, triangulation of evidence, developmental neuroscience

In a wider context

Brain development is the biological process of the growth of neurons, the formation of new synaptic connections, and so on. This is different from cognitive development, which is the development of cognitive functions such as memory, thinking, and decision-making. Cognitive development is going to be the focus of the following sections in this unit.



▲ Figure 3.1 Prenatal development of the human brain

Biological process of brain development

The brain is a complex system of highly interrelated elements. The successful development of this system requires that each component be formed fully in a timely way and integrated correctly with other components. Broadly speaking, this process can be viewed in terms of four stages:

1. neurogenesis (the birth of neurons)
2. the migration of neurons to their correct location

Exam tip

You will not be asked any questions specifically about the structure of the brain, so there is no expectation that you will have a thorough knowledge of brain anatomy. Having said that, various examples you use to support your responses will entail knowledge of some specific parts of the brain and their functions.

For an example you know you will want to use in exams, it will help to look up any brain parts that you do not understand. There are apps available showing 3D models of the human brain. They let you see where the various parts are located, along with their functions. Carry out some research on the internet to find an app that suits you.

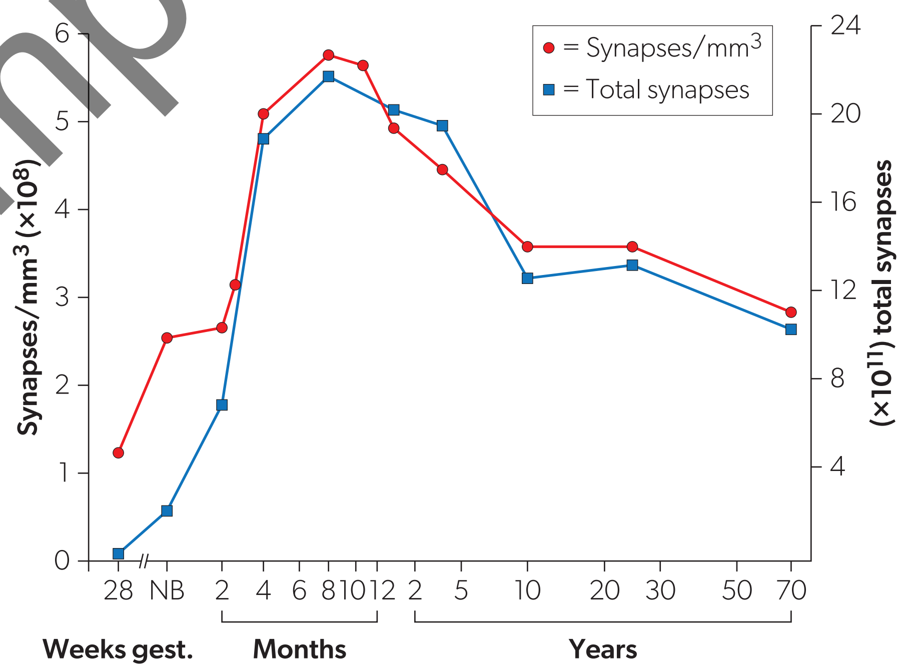
3. differentiation (the development of connections between neurons)
4. pruning (the elimination of these connections as well as neurons themselves).

Neurogenesis is the production of new nerve cells. It is mostly finished during the gestation period—that is, the neurons in your brain are all produced by the time you leave your mother's womb. Curiously, the cortex actually overproduces neurons to account for normal cell death in the future. This means you have fewer neurons now than when you were just born.

Migration occurs approximately nine weeks after conception when neurons start to migrate to their "correct" positions. They travel along special glial fibres that form very early in the foetal brain and extend from the brain's inward structures to the cortical layers. The neuron "climbs" along the fibre like a snake on a tree trunk.

It should be noted that neuronal growth in the brain cortex happens layer after layer, "inside out". That is, new neurons are formed below the previously formed layers and then travel outwards, passing the existing layers of neurons on their way. New cortical structures are added to the old ones in a complementary manner, literally "on top" of them. It would be curious to see if the development of cognitive abilities follows the same pattern (Jean Piaget would say it does. See Unit 3.2: Stage theories and continuous models of human development).

Differentiation is the growth of neural connections (synapses), and **pruning** is the elimination of these connections. Synapses start growing shortly after conception. After some critical point this growth becomes rapid (40,000 synapses per second) and continues until humans are nearly two years of age. This is followed by a plateau and then rapid reduction in the number of synapses. Elimination of synapses continues at a rate of up to 100,000 synapses per second and lasts until the end of puberty. Around 50% of synapses that are initially



▲ Figure 3.2 Synaptic density (number of synapses per mm^3) and total number of synapses in the primary visual cortex as a function of age formed are eliminated during this period. This is followed by another plateau, and then there is another drop in the number of synapses in old age.

According to Kolb and Fantie (2009), "the mechanism that controls synapse formation is one of the major mysteries of developmental neurobiology, largely because synapses are perceptible only by electron microscopy, which does not allow direct observation of their sequence of development in living tissue" (Kolb and Fantie, 2009, p. 25).

One of the puzzling observations about this process is that synapses between neurons form very rapidly and abruptly, although the two neurons may be positioned next to each other for days.

Pruning and death of neurons are perhaps the most intriguing findings of **developmental neuroscience**. Both are linked to environmental stimulation. A lack of such stimulation at a certain critical period may lead to a loss of neurons and/or connections between them (the "use it or lose it" principle). Synaptic density in the brain of an infant is larger than that in the adult brain. So, if you are using the logic "more connections = higher intelligence", then infants should be a lot smarter than adults.

SAQ Neuroplasticity

Neuroplasticity is the making and breaking of synaptic connections between neurons. During this process, neural networks in the brain literally change their shape. The reasons for such changes are both genetic (normal pre-programmed development of the brain) and environmental (e.g., injury, brain damage, or simply learning a new skill).

Neuroplasticity can be observed on different scales. On the smallest scale, at the level of a single neuron, it takes the form of **synaptic plasticity**. This is the ability of the neuron to form new synaptic connections and break old ones. On the largest scale, neuroplasticity takes the form of **cortical remapping**. This is the phenomenon when one brain area assumes the functions of another brain area—for example, due to injury.

Synaptic plasticity depends on the activity of neurons. If two nearby neurons are frequently activated at the same time, a synaptic connection between them may form. Similarly, if two neurons are rarely activated together, the existing connection may fall apart. This has been summarized like this: "neurons that fire together, wire together" (which was originally said by Carla Shatz and is quoted in Doidge, 2007) and "neurons that fire out of sync, fail to link" (Doidge, 2007, pp. 63–64).

As you will learn later in this section, in the context of brain development it is important to make a distinction between **experience-expectant neuroplasticity** and **experience-dependent neuroplasticity**. Experience-expectant neuroplasticity refers to the mechanism when the brain "anticipates" certain typical experiences and becomes particularly responsive to them at a predetermined period of time. This links closely to the idea of "critical periods" in human development. Experience-dependent neuroplasticity refers to experiences that are unique to each individual, where patterns of neuroplasticity depend entirely on the activity itself.

Pruning is also an example of neuroplasticity.

Chat with AI

If you are curious to know more about the process of **biological maturation** of the brain, use your favourite generative AI. This is a highly specialized, but well documented, field of knowledge where AI can be particularly helpful. Research papers may be too technical for you, but generative AI has a great ability to rephrase and simplify things.

You could consider the following prompt fragments and conversation starters:

- I am an introductory psychology student and have been learning about brain development (maturation). Could you tell me a bit about the process of neurogenesis—what key things do I need to know at an introductory level?
- [Ask all sorts of clarification questions, for example:] Does this mean that no new neurons are produced after birth? Is it true that neurons have a limited lifecycle and die after a certain number of years?
- Could you give me some examples of how pruning can explain cognitive growth?
- How can elimination of synaptic connections (pruning) result in better cognitive function? I don't understand this. Could you explain?

Discussion

Pruning is counterintuitive—why do cognitive processes improve when neurons are eliminated?

Discuss with a partner and share your hypotheses.

Would your commute from home to school be more efficient if there were more available routes?

ATL Communication, Social, Thinking

▲ Figure 3.3 Hindi alphabet (Devanagari script)

Experience-expectant neuroplasticity, pruning, and critical periods

Greenough, Black, and Wallace (1987) suggested that there are two types of neuroplasticity in the developing brain: experience-expectant and experience-dependent.

Experience-expectant neuroplasticity is related to the well-known idea of **sensitive (critical) periods in development**. Critical periods are brief windows of opportunity when experience can influence development. For example, there is only a relatively brief window of opportunity for language abilities to be developed in early childhood. If this opportunity is missed and the child is deprived of language and communication, it will be impossible to acquire a language ability at a later time.

Greenough, Black, and Wallace (1987) suggest that certain types of experience have been common in the evolutionary history of a species, and therefore the brain has evolved to "anticipate" them. The way this is achieved is by over-producing synaptic connections and then pruning the unnecessary ones. Specific experiences with the environment determine which synaptic connections will survive. Since these typical experiences are "expected" by the brain, they are incorporated into the unfolding genetic programme. This opens the window of opportunity exactly when the brain is ready to benefit the most from such experiences.

An example that illustrates over-production and subsequent pruning is the study of linguistic abilities of infants by Werker et al. (1981).

Werker et al. (1981) aimed to investigate the ability to discriminate between Hindi phonemes in infants (six to seven months of age), English-speaking adults, and Hindi-speaking adults. A phoneme is a sound of speech. The researchers used pairs of stimuli, such as /ta/ versus /Ta/ in Hindi. This distinction between pronounciations is not used in English, but it is meaningful in Hindi because replacing one sound with the other can sometimes change the meaning of the word.

Participants were tested in a **discrimination paradigm**:

- For infants, this procedure involves first conditioning an infant to turn their head towards the loudspeaker when there is a change in the auditory stimulus. This is reinforced for the infant with the presentation of an interesting toy animal each time they turn correctly.
- Adults press a button when they think they detect a change in stimulus.

Results of the study showed that infants (independent of nationality) were just as able to discriminate between Hindi phonemes as Hindi-speaking adults. At the same time, English-speaking adults were not able to discriminate between Hindi phonemes.

Although there is no direct measurement of synaptic connections in this study, results may be explained with the concept of pruning. In fact, the infant brain has an excess amount of neuronal connections that allows it to be responsive to speech sounds. Over time, the connections that are not involved in the infant's actual linguistic experience gradually disappear.

Activity

The idea of critical periods in brain development is also illustrated by case studies of children who were deprived of certain experiences when they were growing up. A well-known one is the case study of a girl named Genie who was severely abused, neglected, and isolated. Her father tied her to a seat and kept her locked alone in her room until the age of 13 years and 7 months. She was not exposed to any interpersonal interaction and so she did not acquire language in the critical period (Curtiss et al., 1974).

Find out more about this well-known case study. What happened after Genie was discovered by social workers? Did she ever learn how to use language? What happened after she turned 18 and returned to live with her mother?

ATL Research, Self-management

Experience-expectant learning highlights the dynamic nature of interaction between biological and environmental factors in the development of the brain. Even the genetic programme itself, due to how it has evolved, is not independent of environmental influences.

Experience-dependent neuroplasticity

By contrast, experience-dependent neuroplasticity has evolved to deal with information that is unique to a given individual. This is also quite important because in addition to typical circumstances and experiences, every organism during its lifetime deals with circumstances that are unique and unforeseen. According to Greenough, Black, and Wallace (1987), the mechanism of experience-dependent neuroplasticity is somewhat different to experience-expectant learning. There is no overproduction followed by pruning. Instead, new synapses between neurons are created depending on how frequently two neurons are activated together.

Blakemore and Cooper (1970) conducted an experiment with newborn kittens. Immediately after birth they were placed into a completely dark room. At the age of two weeks old, they were randomly allocated into one of two conditions: either a vertical or a horizontal environment. The environment was a tall cylinder, the inner walls of which were painted with black-and-white stripes (vertical or horizontal depending on the condition). The kittens also had to wear a wide black collar that did not allow them to see their own body. All they could ever see were the stripes. In this world there were no edges or corners. When they were not in the cylinder, the kittens were brought back to the dark room. This experiment lasted five months. Researchers made an interesting remark about the ethics of the study: "The kittens did not seem upset by the monotony of their surroundings and they sat for long periods inspecting the walls of the tube" (Blakemore and Cooper, 1970, p. 477).

▲ Figure 3.4 Cat in a cylinder with vertical stripes

Once the experimental manipulation ended, researchers observed the behaviour of the kittens under normal well-lit conditions, in a room furnished with tables and chairs.

All cats showed some behavioural impairments. They followed moving objects with "very clumsy, jerky head movements" (Blakemore and Cooper, 1970, p. 477).

> **TOK**
>
> Development is not always a smooth, linear process. Think about various patterns of development that may be observed in different areas of knowledge. How are these patterns different? Here are some examples.
>
> - Evolution of species: combinations of genes occur randomly. However, as certain genotypes die out because they are less adapted to environmental demands, more successful genotypes are gradually consolidated.
> - Revolution in the development of political systems: governments are overthrown and replaced, which sometimes causes dramatic changes in society.
> - Paradigm shifts in sciences: new evidence triggers the process of rethinking the very basis of a field of science.
>
> Which of these examples do you think is most similar to the development of a human child?

They tried to touch things that were far away out of their reach, on the other side of the room. As they ran around the room, they often bumped into table legs. Moreover, the cats were practically blind to shapes and contours that they had not experienced. For example, in one of the trials researchers used two cats at the same time—one from each condition. If the researcher took a long rod and shook it vertically, one of the cats (the one raised in the vertical condition) ran towards it, followed it, and played with it, while the other cat remained indifferent. If the researcher turned the rod horizontally and shook it, the cats swapped roles—now the second cat was chasing the rod and playing with it while the first one ignored it entirely.

One kitten from each group was anaesthetized and paralysed, then stripes of various spatial orientation were presented to their visual field and the activity of neurons in their visual cortex was recorded. In the cat that was raised in the horizontal environment, visual neurons fired when they were exposed to horizontal stripes and remained "silent" for the vertical stripes. The opposite was true for the other cat. Researchers concluded that the nature of visual experiences in these cats' early childhood modified the physiology of their visual cortex.

Structure–function relationship

Brain development and cognitive development have both been extensively studied. A big issue in developmental psychology is that these studies occurred in parallel but relatively independently from one another. There is a lack of research that considers brain development (structure) and cognitive development (function) in interaction.

The study of **structure–function relationships** is complicated by the fact that **localization of function** is not absolute. Some functions are distributed over large areas of the brain. For example, there is no single brain area responsible for memory or logical thinking. Moreover, localization of function in the brain of a child is not necessarily the same as that in an adult brain.

All this means that developmental neuroscience should heavily rely on the **triangulation of evidence** coming from multiple sources. An example of a research study that used this approach is Kolb and Fantie (1989). In their study, they focused on one specific cognitive ability called "categorization based on linguistic features". One popular measure of this ability is the Chicago Word Fluency Test. In this test, participants are required to write as many words as they can think of beginning with the letter "S" in five minutes. After this, the task changes and requires them to write as many four-letter words beginning with the letter "C" in another four minutes. This study tests a very specific cognitive ability that requires processing language information.

Kolb and Fantie (1989) summarized the following observations of participants' performance on the Word Fluency Test:

1. Frontal lobe regions are active when healthy adult subjects are performing the test.
2. Adult patients with confined frontal lobe lesions do very poorly on the test.
3. At the same time, the same patients perform normally on the modification of the test that requires categorization based on non-linguistic features (e.g., when asked to write the names of as many objects or animals as they can think of).

4. Children perform poorly on the Chicago Word Fluency Test when very young and gradually improve performance as they age.
5. In contrast, even very young children perform well on an adult level on the modification of the test (categorization based on non-linguistic features).

Observations 1, 2, and 3 seem to suggest that categorization based on linguistic features is localized in a specific region of the frontal lobes. Observation 4 suggests that this area gradually develops with age (note: there was no direct measurement of the activity of frontal lobes in children, so this part is an inference). Observation 5 suggests that different areas of the brain (and different cognitive abilities) mature at a different rate. The explanation for this seems to be that frontal lobes in the brain are the last to mature. Other brain areas develop faster.

As you can see, we are using data triangulation here to arrive at inferences about structure–function relationships in a developing brain.

Problems and challenges in developmental neuroscience

The invention of MRI and fMRI advanced the study of the developing brain because it became possible to study the living brain ("in vivo"). This bears the promise of bridging the gap between the study of brain development and the study of cognitive development. Obviously, the two processes should be studied together (because, in fact, it is one and the same process).

Brain imaging techniques such as MRI and fMRI are sensitive to various kinds of movement. Participants have to remain perfectly still in the scanner apparatus while their brain activity is being measured (as long as 40 minutes in some cases). Otherwise the data may get corrupted. This presents a problem with young children. Even more problematically, the comparison between older and younger children is affected. Researchers often use simple designs to minimize the time that children have to remain in the scanner, but this also means fewer variables are measured.

▲ Figure 3.5 Child in an MRI scanner

TOK

An inference is a theoretical conclusion derived from evidence. There is always a gap between evidence and inference, in that the inference is not directly given in the evidence. This gap is closed by logical reasoning. We analyse the available evidence and apply logical reasoning to it, and that is how we arrive at an inference.

Some inferences are stronger, some weaker, depending on the quality of evidence that they are based on. They also depend on the quality of logical reasoning that is applied. It is an important critical thinking ability to be able to analyse the strength of an inference.

Apart from this, the growing brain is not always well-suited for brain scans. For example, the quality of MRI and the interpretation of data from it depends on the contrast between grey matter and white matter. This contrast changes dramatically over the first years of life, and so the visual appearance of the young brain on an MRI also changes.

Conceptual analysis

Perspective and causality

From a purely biological perspective, one may think about brain development as a genetically predetermined sequence of events—maturation. With today's state of research, we know the main components and phases of this process: it is an interplay of neurogenesis, migration of neurons, differentiation, and pruning. We know which parts of the brain are expected to go through which process at approximately what time.

However, even a purely biological perspective cannot do without incorporating environmental influences. In fact, the idea of experience-expectant neuroplasticity suggests that the division of biological and environmental variables is somewhat artificial. The brain has evolved to mature in a way that considers, and makes use of, typical environmental events. Of course, environmental events in the life of a human are, to a large extent, sociocultural.

What about cognitive variables? Evidently, biological development of the brain is connected with the development of cognitive functions. However, the exact nature of this structure–function relationship remains to be fully understood. It is possible that the process of maturation pre-determines the development of cognition. However, the opposite process also takes place—engaging in acts of cognition influences the development of the brain through experience-dependent neuroplasticity.

Bias and measurement

We have considered the problem of structure–function relationships. Traditionally, research of brain development and research of cognitive development have been conducted in parallel, but there is a lack of studies that explicitly connect the two processes. We have seen that conclusions in this area are often speculative, based on incomplete evidence. Simply establishing a co-occurrence of two events in time (for example, maturation of frontal lobes and an improvement in memory performance) is not enough to make any definitive conclusions. One research study is never enough to understand the nature of structure–function relationships. We always need the triangulation of multiple sources of evidence.

We have also considered the limitations of measuring the process of brain maturation itself. For example, brain imaging technology relies on the relative distribution of white matter and grey matter in the brain, which may not be the same in a growing brain, making comparisons of brain scans across age groups somewhat challenging. Additionally, brain imaging technology cannot be fully utilized with young participants. We cannot expect them to lie still in a scanning machine for 40 minutes.