CHAPTER

34

The Timing of Brain Maturation, Early Experience, and the Human Social Niche

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34.1 Introduction

Descriptions of maturation of brain and behavior in human infants and children have been multiplying in spectacular fashion along with our ability to acquire a massive corpora of data, but our mechanistic understanding of the relationship of emergence of behavior wit neural maturation remains comparatively meager. Though modern imaging techniques generate increasingly more accurate renditions of the state of the brain, the translation of particular changes in brain measurements to the emergence or stepwise maturation of specific computational or behavioral capacities remains largely unrealized. Concentrating on humans and restricting coverage arbitrarily to approximately the last 5 years, we find documented the changing volume of every structural component, from brain subdivisions like cortex and brainstem (Choe et al., 2013; Ge et al., 2015; Gilmore et al., 2012; Kuklisova-Murgasova et al., 2011; Makropoulos et al., 2016; Oishi et al., 2013; Raznahan et al., 2014; Shiraishi et al., 2015; Tate et al., 2015); changing morphology, as in gyral and sulcal development (Habas et al., 2012; Rajagopalan et al., 2011; Wierenga et al., 2013; Zilles et al., 2013); the volume and arrangement of multiple cellular constituents, such as myelin, "gray" and "white" matter (Li et al., 2015; Miller et al., 2012; Raznahan et al., 2011, 2012; Simmonds et al., 2013); growth of tracts (Takahashi et al., 2012, 2014; Walker et al., 2016); and metabolism (Bluml et al., 2013); "functional networks" (Damaraju et al., 2014; Gao et al., 2015) as well as an increasing library of gene and gene product expression (Huang et al., 2013; Kang et al., 2011; Miller et al., 2014; Silbereis et al., 2016). In parallel, remarkable inventories of early infant behavior have been gathered, including instruments such as the MacArthur–Bates Communicative Development Inventory (CDI) as well as studies, particularly in the language domain (Bornstein et al., 2015; Lieven and Stoll, 2013). Some aspects of the environment of infants can now be gathered and to a degree, catalogued (Roy et al., 2015). Yet, with all these inventories, even basic questions such as "What are the features of brain maturational state necessary and sufficient to allow language learning?" remain unanswered. This is no insult to the researchers in this field, as the possibilities for experimentation in most primates, and particularly humans, is limited, but there are multiple ways to progress toward causal explanation without direct experimentation (Gu et al., 2015; Hedden et al., 2016). In the present overview, we will review the possibilities and recurring pitfalls of comparative developmental work as a solution to this central developmental question. Next, we will describe work we have performed looking at the comparative timing of brain development, focusing first on comparison of the mechanisms involved in basic neural development and brain growth. Finally, we will extend the close analysis of neural maturation to contextualize early life history events such as weaning, early locomotion, and adolescence, placing primates in the context of general mammalian development.

The central problem, universally acknowledged, is covariation of gradual change in most of the physical parameters of brain maturation, matched against mixtures of stepwise and gradual changes in behavioral capacities. Close attention to any inflections, accelerations, bumps or dips that can be detected in the rate of progress in any physical measure (synaptogenesis, myelination, gene expression, and so forth) as potential indicators of organizational changes in the physical substrate, is a first-stage approach to the covariation problem (Amunts et al., 2003; Goldman-Rakic, 1987; Scheibel, 1993). For example, making the assumption that "Broca's area" and "Wernicke's area" are the critical

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regions for language competence, researchers looked for stepwise changes in volume or bursts of synaptogenesis or myelination in those regions associated with language acquisition milestones (Brauer et al., 2011; Leroy et al., 2011; Simonds and Scheibel, 1989) or development of tracts between language-associated regions (Brauer et al., 2011), though whether language development was illuminated by such explanations was debated (for example, McMurray, 2007). Although the integration of all the comprehensive catalogues described at the outset has hardly been attempted, the search for stepwise indicators in brains or cognitive stages has not proved very fruitful. Various measures of gene expression, which might have been imagined to reveal stepwise changes underlying levels of functional maturation, show essentially uninterpretable complexity (eg, London et al., 2009). Much as the specification of a punctate location or unique structure in the body and brain typically appears to be specified by the relative expression of tens to thousands of genes (Kiecker and Lumsden, 2012; Lumsden and Krumlauf, 1996), so far, the specification of a unique maturational time point seems likely to have much the same description, an otherwise unremarkable intersection of multiple gene profiles each changing gradually over time.

Comparative approaches can unravel this knot. The possibilities for comparison are large, but three are central: individual variation, the variation produced by disease or developmental disorder, or variation between species. We will concentrate on brain evolution, the differences between species, as a key way of illuminating what differences in the timing of brain construction influence eventual brain structure and eventual behavioral capabilities. For many years, we have been amassing a database of the timing of neurodevelopmental and behavioral events in mammals, beginning in early neurogenesis, extending to as many morphological and functional developmental events as can be measured, and presently extending to perinatal and postnatal behavior, and early life history (see Relevant Websites) (Clancy et al., 2000, 2001, 2007; Darlington et al., 1999; Finlay et al., 2005; Finlay and Uchiyama, 2015; Workman et al., 2013). This research has enabled us to begin to address just how developmental events should be compared, a prerequisite to identifying which aspects of neural and behavioral development are species-general, versus species-unique.

34.1.1 "Allometrically Expected"

A traditional problem in brain allometry illustrates the problems of comparing species "fairly". If the volume of neocortex (isocortex henceforth, as the most appropriate nomenclature) is visually compared across a selection of mammalian species (Fig. 34.1, top), the fact that the human brain has a disproportionately large cortex is obvious. With this kind of comparison, cortex volume would appear to be an object of special evolutionary selection in primates, and in humans particularly. However, if either the volume or the number of neurons in the cortex is represented on a logarithmic scale, it is clear that the human isocortex is exactly the size it "should" be, following its allometric position (Fig. 34.1, bottom; from Reep et al., 2007). The entire human brain is large compared to other primates, with respect to body size, but given this large brain size, each part falls onto its "expected" position. The slope "a" representing the rate of increase of each brain component "y" with respect to whole brain volume "x" (or any index of brain volume or neuron number) is different, as given by the logarithmic transformation of the basic allometric equation ($\log y = a\log x + \log k$). The vertebrate brain itself has "negative allometry" with respect to body mass, so as the body enlarges, brains become a progressively smaller component of whole body mass (Jerison, 1973). With respect to brain mass, the isocortex has "positive allometry," so larger mammalian brains become progressively more composed of cortex, ranging from under 20% in relative volume in small shrews and rodents to over 80% in humans (Finlay and Darlington, 1995; Hofman, 1989). This point is driven home by the visual comparison of the proportion of cortex in humans versus the one-humped camel (*Camelus dromedarius*), which is roughly equivalent in mass to the human brain (Fig. 34.1, right) though camel bodies are much larger. The relative proportion of isocortex in those several brains that are absolutely larger in mass than the human brain, including some cetaceans and ungulates, continues the allometric equation, so that they have both absolutely and relatively more cortex.

Much energy has gone into a debate about whether a specific region of cortex, the prefrontal cortex, is "allometrically unexpected" in humans, which should hopefully illuminate why getting allometry right matters. Every brain region (in this case, a collection of cortical areas) has its own exponent (slope in the log-transformed equation) for its change in relative volume compared to overall isocortex volume. In mammals, the prefrontal and parietal cortex regions have an exponent that is larger than the cortex's overall exponent, or the exponent of primary sensory regions, "positive allometry" (Jerison, 1997). The question under debate is whether frontal cortex in humans is even larger still than would be expected from its already high positive allometry (Barton and Venditti, 2013; Chaplin et al., 2013; Passingham and Smaers, 2014; Semendeferi et al., 2002). But, why should anyone care about this issue? Although issues of measurement, correct statistical

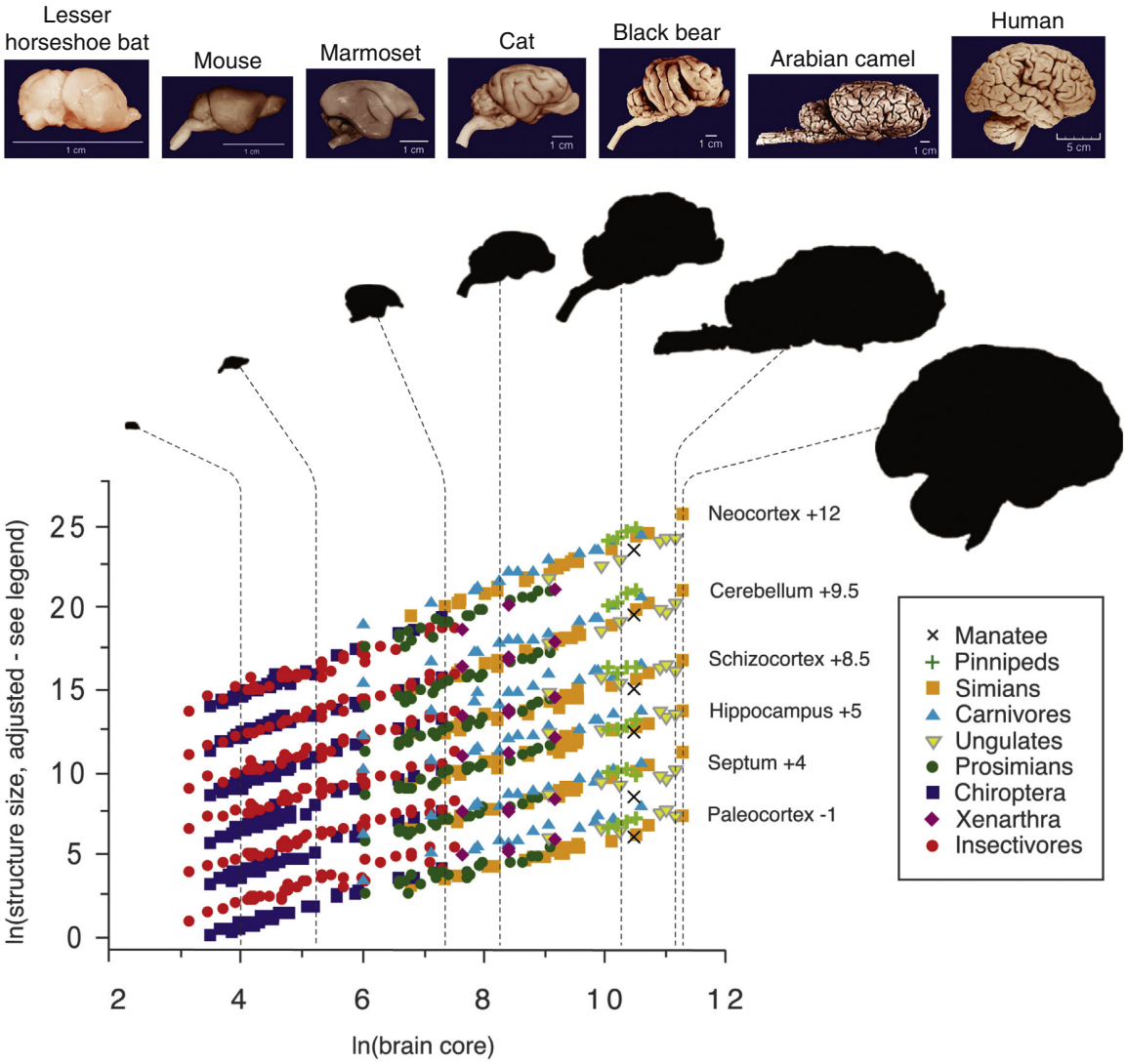

FIGURE 34.1 Comparisons of brain volume representations. Top: Brain images, normalized to show varying sizes of components. Species: Lesser horseshoe bat, (*Rhinolophus hipposideros*); mouse (*Mus musculus*); common marmoset (*Callithrix jacchus*); domestic cat (*Felis catusl*); American black bear (*Ursus americanus*); one-humped camel (*Camelus dromedaries*); human (*Homo sapiens*) Images courtesy of University of Wisconsin and Michigan State Comparative Mammalian Brain Collections (Neurosciencelibrary website (see Relevant Websites) – This site supported by the National Institutes of Health and the National Science foundation). Middle: Same images, vignetted midsagittal view above, to show absolute size. Image sources as above. Bottom: Brain component sizes from 160 mammalian species including the individual species shown above, both scales natural log scales, to demonstrate predictable scaling of brain components with respect to a brain volume index. The sizes of the 6 brain structures in the 160 species from the 9 keyed taxonomic groups are plotted relative to "brain core volume" (medulla, mesencephalon, diencephalon, and striatum). The six individual structure volumes have been adjusted by the indicated arbitrary constants to the right of each structure's name to separate the six scatterplots visually. *Data replotted from Reep, R., Darlington, R.B., Finlay, B.L., 2007. The limbic system in mammalian brain evolution. Brain Behav. Evol. 70, 57–70.*

procedure, and interpretation are all intertwined in such controversies, if researchers claim a region's volume is "allometrically unexpected" in a species of interest, they are claiming that it must have been the target of special selection, typically because of special importance of the function ascribed to that brain region in that species. Structures that change their volume according to their allometric rules, even if they seem disproportionately large on a linear scale, by contrast, require no special explanation. If the entire brain has been under special selection for larger size in any species, all of the changes in the proportionality of its parts come "for free," presumably because of the lawful extension of the developmental mechanisms that produce neuron

numbers and their associated volumes applied to every part (eg, Cahalane et al., 2014; Charvet and Finlay, 2014; Finlay and Darlington, 1995). So, the argument over allometry in the case of human prefrontal cortex is whether its developmental rules have been altered by natural selection to enhance the cognitive features associated with frontal cortex, such as cognitive control, or planning for the future, even more than they may have been enhanced by the already positive allometry of frontal cortex in mammals.

The idea of "allometrically expected" also applies to translations of developmental time from one species to another. The corpus of data is smaller, and some questions of how to compare time are rather less well worked out than the more traditional questions of energy metabolism or mass of structures, but basic allometric considerations apply. First, the appropriate coordinate system to represent time translations is a logarithmic, not a linear scale. Despite our everyday use of the 7x linear transform to represent "What is that in dog years?" such a transformation actually works poorly, overestimating the dog's relative age compared to humans in early development, and underestimating it in old age. Moreover, just as each part of the brain has its own relative rate of enlargement with respect to total brain size, each brain part has its own relative duration or rate of development with respect to the overall duration of that species' maturation (Workman et al., 2013).

To compare developmental schedules among animals, enough data must be collected to generate these allometric relationships from a number of relevant species. For example, if you wish to show that Broca's area is the subject of special selection in humans compared to a rhesus monkey, you cannot compare the relative size of a "control structure" such as primary visual cortex in the two species to "normalize" the comparison, see that the ratio of relative sizes of Broca's area is greater than that of the two primary visual cortices, and conclude that the size of Broca's area has been specially selected in humans. If Broca's area has "positive allometry" in primates, every contrast of a large and small brain will give this result. Rather, it is necessary to show that the size of Broca's area in humans exceeds its expected allometric position compared to Broca's area in other primates (Schoenemann, 2006).

Comparing relative developmental durations with an inappropriate "norming" procedure will produce the identical errors seen in comparing brain volumes inappropriately: you cannot, for example, compare the time from birth to adolescence in chimpanzees versus humans, see that the duration is longer in humans and conclude that human have been specially selected for a longer childhood, as the duration may be entirely predictable from body or brain size, or the position of birth with respect to brain and body maturation. We will discuss in more detail various issues about how to represent or normalize developmental schedules with respect to each other. In addition to the rate and slope considerations discussed so far, an additional issue in such comparisons is what date in development represents "zero," the intercept or constant "k" in the allometric equation. Although the date of birth is often chosen as a natural zero, we will argue that the choice of birth as zero is often quite misleading, given the wide range of brain maturational states at birth in mammals and primates.

34.1.2 Human Exceptionalism

Much research into comparative brain organization and comparative development is organized to answer the question "What makes humans unique?" A perusal of the literature on this subject will soon return the answer "everything." A few such claims and counterclaims have included (but are in no way limited to) the presence of Von Economo cells in the cortex as related to human sociality (Allman et al., 2010; but see Niewenhuys, 2012), the depth of layer IV in the visual cortex (Bryant et al., 2012), the size of the prefrontal cortex (cited previously), the descended larynx in relation to language (Lieberman, 1984; but see Fitch and Reby, 2001), the duration of childhood (Locke and Bogin, 2006), and so forth. On closer examination, many of these claims prove to be simply hopeful, without the appropriate comparative database. In much of this literature, a human feature of some kind is compared to that of another species, chimpanzee, rhesus, or rodent. Any disproportionate difference is accorded human uniqueness, with causal significance in human evolution usually implied. For example, the rate of cerebral growth in humans compared to chimpanzees and macaques (Sakai et al., 2013; Fig. 34.2) was described this way:

> …the rapid increase in cerebral total volume and proportional dynamic change in the cerebral tissue in humans during early infancy, when white matter volume increases dramatically, did not occur in chimpanzees. A dynamic reorganization of cerebral tissues of the brain during early infancy, driven mainly by enhancement of neuronal connectivity, is likely to have emerged in the human lineage after the split between humans and chimpanzees and to have promoted the increase in brain volume in humans.

Replotting these data in a common framework showed near perfect prediction of the human rate of brain growth from parameters determined from other primates and mammals generally, directly related to the time required to generate brains of particular mass (Finlay and Workman, 2013). The apparently exceptional "rapid increase" in early human brain volume is illusory, due to the combined effects of the linear scale and the relative placement of human birth with respect

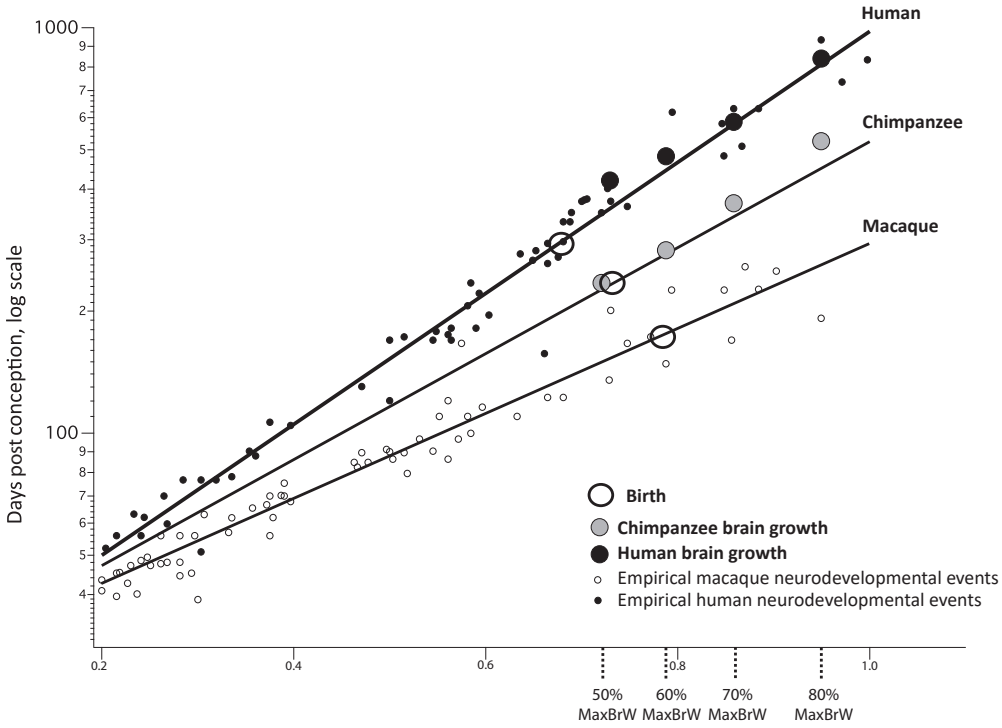

FIGURE 34.2 Comparison of postnatal and prenatal brain growth in the rhesus macaque, *Macaca mulatta*; chimpanzee (*Pan troglodytes*), and human (*Homo sapiens*). *Data replotted from Sakai, T., Matsui, M., Mikami, A., Malkova, L., Hamada, Y., Tomonaga, M., et al., 2013. Developmental patterns of chimpanzee cerebral tissues provide important clues for understanding the remarkable enlargement of the human brain. Proc. R. Soc. B Biol. Sci. 280, 753–757 to show postnatal volumetric growth of the monkey, chimpanzee and human brains on linear scales of volume (y-axis) and years (x-axis). Volume change and birth date position (*open circle*) plotted against a model overall of neural maturation in the same species from Workman, A.D., Charvet, C.J., Clancy, B., Darlington, R.B., Finlay, B.L., 2013. Modeling transformations of neurodevelopmental sequences across mammalian species. J. Neurosci. 33, 7368–7383. The "Event Scale," the x-axis, is a set of 271 normalized neural maturational events drawn from 18 species, including primates and consists of such items as neurogenesis in multiple structures, myelination, and brain growth. The Y-axis, days postconception, allows the day each species reaches each neural maturational milestone to be represented.*

to the common progress of neural maturation, a feature of human development we will return to.

There is absolutely no doubt that humans are unique in many respects, but to understand human evolution, the impulse to label every apparent deviation as singular should be resisted vigorously. Systematic determination of which human features represent the normal unfolding of a vertebrate, mammalian or primate plan, and which are actually unexpected, is the only way to understand our basic biology.

34.1.3 Life History

The comparative organization of life history has been the subject of much investigation, both for comparative physiology and anatomy, and in primatology (Stearns, 1992; Smith and Tompkins, 1995). Study of life history, as its name suggests, looks at the relative timing and organization of major life events, beginning from birth, and including such events as weaning or other parental provision of food, adolescence and reproductive maturity, dispersal, menopause, and death. Though generally allometrically predictable, life history events are much more variable than the early neurodevelopmental events, with demonstrated species differences, niche, and effects of environmental variability pervasive. In this chapter, however, we will begin to bring these two literature and types of modeling closer together, to see if any aspects of life history event prediction are better informed or predicted by using the general time representation, data, and methodology of the "translating time" project in neural development. We would like to address issues about the expectedness or unpredictability of the pattern of childbirth and weaning in humans in this framework, as well as examine claims about how neural maturation actually intersects behavioral and cognitive development in humans, and whether there is evidence of deviation of any "behavioral modules," critical periods, and the like. We will not settle these issues in this review but will begin the attempt to bring together primate life history with its neurodevelopment.

34.2 Comparative Approaches to Translating Time

34.2.1 Brief Review of Translating Time Methodology

Over the past 20 years, we initiated and then progressively expanded a database and methodology to compare the progress of neural development across species, which we call "translating time." The fundamental point of this work is to describe a mammalian "Bauplan" for neural development, and in doing so, identify deviations from this plan that might mark taxon- or species-specific alterations corresponding to evolutionary adaptations, a version of SJ Gould's heterochrony (Gould, 1977). Alternatively, the same information can be used to identify deviations related to individual differences or developmental disorders. We will briefly review the historical development of the model to highlight the changing aspects of development it revealed as taxonomic coverage expanded and the number of developmental events increased.

In the first analysis, only seven commonly employed laboratory species (including four rodents, a marsupial, cat and monkey) and peak day of neurogenesis were gathered for as many neural structures and cell groups that we could locate, from spinal cord to telencephalon (Finlay and Darlington, 1995). Quite surprisingly, the fit of a minimal two-factor model (the factors were "species" and "structure") to these empirical data was very high, and the addition of an additional term to slow the rate of marsupial development brought the fit of data to model to 0.98. We also identified systematic deviations in neurogenesis onset in limbic and olfactory structures in rodents versus the remaining species but did not yet add these terms to the model. These first observations of this set of taxonomically scattered species suggested that variations in the order of neurogenesis were relatively rare in mammals but that wholesale alterations in the rate of maturation were possible between taxonomic groups.

In further work, we added many more species, including humans and many more types of neuroembryological events. The statistical models employed continued to evolve as well. Expanding the set of noneutherian (marsupial) mammals, we confirmed the relative slowing of maturational rate in six further marsupial species and quantified deviations between them (Darlington et al., 1999). One possibility to limit the scope of the initial analysis was the hypothesis that the basic generation of neurons was predictable and clock like but that variations associated with species-specific adaptations might be abundant in subsequent organizational events, such as the initiation and elaboration of axonal and dendritic connectivity. Surprisingly again, however, addition of neuroembryological events such as axon extension, synaptogenesis, and early aspects of myelination, which extended the time frame of the model into the early neonatal period in humans, did not make the model noisier but in fact improved the fit of data to model (Clancy et al., 2001). The predictability of neurogenesis was no different from the timing of the elaboration of connectivity (the events measured occur just up to the onset of "real-world" function). The addition of new species now allowed us to add a "limbic factor" and a "cortical factor," which for primates alone, moved the predicted days of olfactory-limbic neurogenesis forward (correlated with relatively smaller size in adulthood) but protractedcortical development (the longer period of neurogenesis making the cortex relatively larger) (Clancy et al., 2007). Thus, the unusual conservation of neurodevelopmental schedules observed at first was not confined to neurogenesis but to every measured event in neurodevelopment reaching until about the time of birth in humans. One important case of "heterochrony" of neurodevelopmental events was confirmed for the limbic/isocortex factor, though these kinds of changes seemed rare.

In the most recent analysis (Workman et al., 2013), the database was considerably extended, to 18 species, and new classes of data were added, including introduction of continuous processes like changes in brain volume and myelination (by digitization), and by adding many more postnatal events, extending to approximately 3 years postnatal in humans. The increased data volume allowed us to fit a single "event scale" to all the data, the best order, and interval relationship of our now 271 distinct neurodevelopmental events (x-axis, Fig. 34.3), and describe the speed of progress of each individual species through these events as a regression equation, in days (y-axis), identifying sources of variation from both taxonomic groups and individual species. The differences in each slope may be thought of as differences in maturational rate, with steeper slopes associated with slower progress through maturational stages in absolute time: the mouse takes only about 30 days to execute the 271 events, whereas the human takes 1000 days, the human generating greater numbers of neurons and volumes of connectivity per event. The fit of model results to empirically measured results is quite close, 0.9929, including only two interaction terms, a delay in corticogenesis in primates, marsupials, and carnivores associated with a larger isocortex in these species, and a delay in neurogenesis in the retina of the nocturnal cat, associated with greater numbers of rods and rod-associated neurons. Interestingly, the timing of birth appears to be quite decoupled from neural development (Fig. 34.4). For example, cortical and cerebellar neurogenesis is ongoing at birth in some rodents but completely concluded in primates.

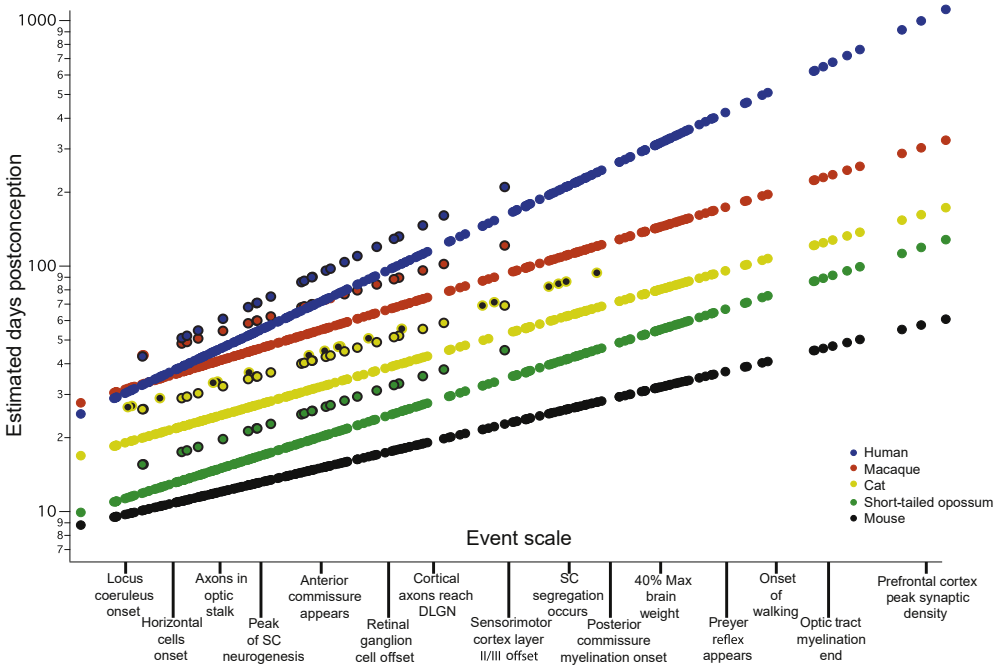

FIGURE 34.3 Translating time model. Predicted developmental schedules for human (*blue*), macaque (*red*), cat (*yellow*), short-tailed opossum (*green*), and mouse (*black*), selected from the modeled 18 species to illustrate the full range of developmental durations. The x-axis, the "Event Scale," is a common ordering of developmental events across all species and shows a subset of the 271 observed events. This scale ranges from 0 to 1, but in this case, event scale numerical values are replaced by these example events. The y-axis, log scale, is the estimated date of occurrence of each event in each species, measured from conception. Also represented on this graph are interaction terms for corticogenesis and retinogenesis, with interaction terms always associated with individual species. The *parallel lines* for a subset of events in four of the species (*black bordered circles* for human, macaque, cat, and possum) represent delays in cortical neurogenesis with respect to their time of occurrence in the rodent and rabbit. In the cat, a second *parallel line* can be seen representing the delay of retinal neurogenesis, (*yellow circle* with a *black dot*). *SC*, superior colliculus; *DLGN*, dorsal lateral geniculate nucleus. *Reproduced with permission, Figure 34.4 in Workman, A.D., Charvet, C.J., Clancy, B., Darlington, R.B., Finlay, B.L., 2013. Modeling transformations of neurodevelopmental sequences across mammalian species. J. Neurosci. 33, 7368–7383.*

Empirical support for this claim of highly conserved and predictable, but nonlinear, neurodevelopmental schedule can be found in multiple independent sources. Passingham inferred that the curves of change in brain volume across eutherian mammalian species when measured from conception were essentially superimposable, offset of growth being the only distinction (1985). Within the visual system, the timing of various developmental events could be predicted from an "anchor event," in this case, eye opening. Eye opening, which behaves as if it is a "neural event," happens at a time specified by neurodevelopmental state, whether that time occurs in utero, in an underground burrow, or even occasionally, synchronized with birth (Dreher and Robinson, 1988). Halley (2016), in a much larger and more closely measured data set of initial brain volumes, confirmed the same. More surprising still, in a study of multiple mammals ranging from laboratory rodents to antelopes, the time of the first unsupported step was similarly predictable from adult brain mass, with an additional factor for plantigrade standing position (Fig. 34.5; Garwicz et al., 2009). Therefore, precocial ungulates such as sheep and elk, who must be ready to run by birth, have accomplished this (in evolutionary time) by extending gestation and delaying birth to match conserved parameters of brain development, not by selectively advancing the general rate of brain maturation or the specific ability to walk.

The significance of a fixed neurodevelopmental program for understanding primate life history and its potential adaptations has multiple aspects. It is important to recall that in this model, only events in brain and some early behavioral capacities are included—no measures of body or organ maturation or volume, or interactional, life history events such as birth or weaning are part of the data set. In the present paper, we are outlining the first steps toward integration of somatic development and life histories with these observations.

First, recalling the idea of "allometrically expected," nothing as yet appears as yet to be unexpected about the duration, rate, or deviations from linearity in brain and behavioral development for primates in general or for humans in particular, as predicted from the brain sizes of this group. Humans have the duration and rate of neural development appropriate to produce a brain of typical human size. Therefore, though it is

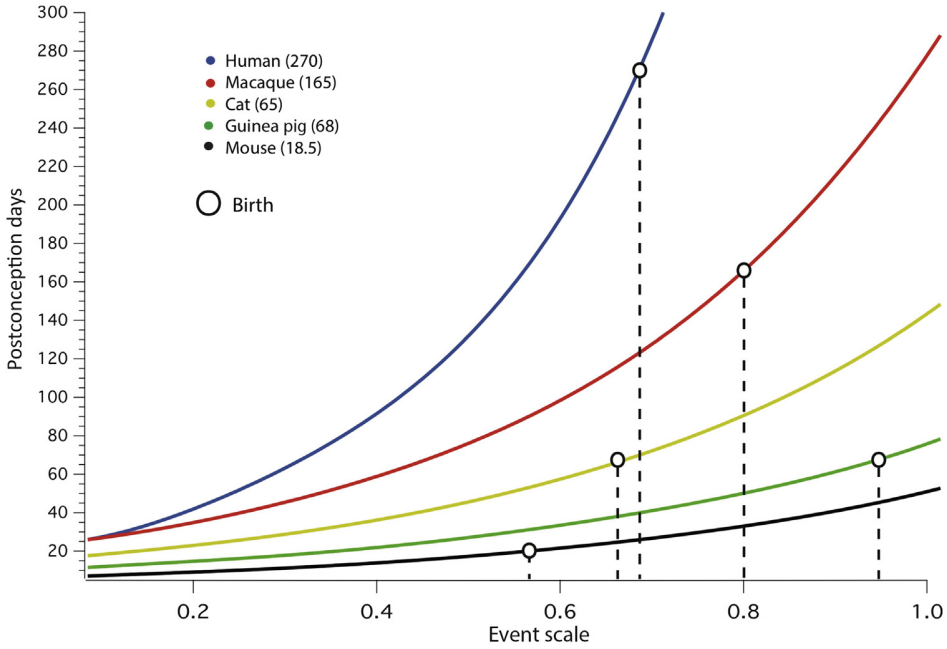

FIGURE 34.4 Variability in position of birth with respect to neural maturation. The position of birth (*open circle*, listed after each species name) for six placental mammals relative to the event scale (x-axis); the age of each mammal in PC days can be read for birth (or any event scale value) on the y-axis. The five placental mammals are chosen to represent close to the full range of the data set and include one highly precocial mammal, the guinea pig. For an example, in the mouse at birth cortical neurogenesis is still underway and synaptogenesis in the forebrain is only beginning, whereas in the guinea pig at birth, cortical neurogenesis, cortical cell migration, and basic axonogenesis are entirely complete, and the point of peak synaptic density has passed. Human, *blue*; macaque, *red*; cat, *yellow*; guinea pig, *green*; and mouse, *black*. *Reproduced with permission from Figure 34.9 in Workman, A.D., Charvet, C.J., Clancy, B., Darlington, R.B., Finlay, B.L., 2013. Modeling transformations of neurodevelopmental sequences across mammalian species. J. Neurosci. 33, 7368–7383.*

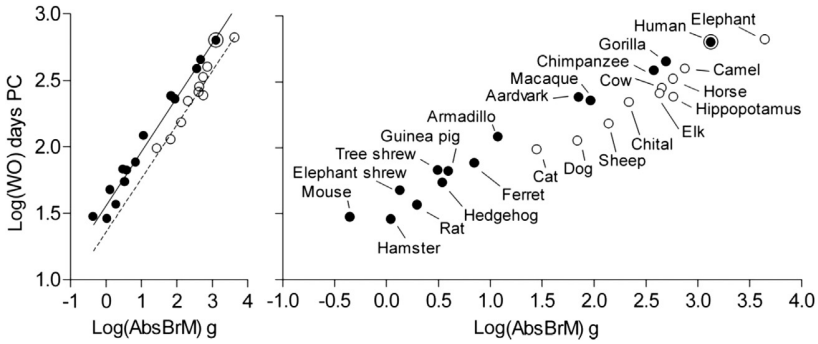

FIGURE 34.5 Absolute adult brain mass and hindlimb standing position as predictors of time to walking onset. Left, time to walking onset, log WO, as a function of absolute adult brain mass log(AbsBrM) and hindlimb standing position. *Solid symbols* and *solid regression line* represent species that can assume a plantigrade standing position and reach this milestone relatively earlier (most ungulates), *open symbols* represent those which cannot. Relative brain mass is an excellent predictor of overall maturational duration (Fig. 34.2). Right, same graph, but with x-axis expanded to allow species identification. *Reprinted with permission from Garwicz, M., Christensson, M., Psouni, E., 2009. A unifying model for timing of walking onset in humans and other mammals. Proc. Natl. Acad. Sci. 106, 21889–21893.*

entirely accurate to say that humans have the longest period of brain development of primates, as this parameter is virtually perfectly correlated with brain size (Workman et al., 2013), the claim that humans have been specially selected for a long developmental duration is unjustified—it comes "free" for selection for a large brain, or any large brain part (Barrickman et al., 2008; Charvet and Finlay, 2012). Theoretically, one could argue that a large brain is a necessary by-product of selection for extended development.

Second, the timing of birth is quite uncorrelated with neural maturation (Fig. 34.4). Some rodents (mice and rats) are born at a stage of maturation equivalent to a human of 4–5 months gestation, whereas others like the guinea pig correspond to a human of approximately 3 years postnatal. Primates, in general, are born at a middle

stage of neural maturation, not so mature as the precocial ungulates nor as immature as a number of rodents. Primates also show a fairly wide range of (neural) maturational states at birth, rhesus macaques relatively mature at birth, chimpanzees intermediate, and humans least mature (Fig. 34.2). There are a wide number of factors entering into the allocation of resources to brain versus somatic tissue, and for allowing early maturation and its nutritional source to proceed mostly in utero or mostly outside, via lactation, which we cannot discuss fully here but will list a few to illustrate the range of phenomena to consider. Depending on eventual brain size, somatic development may be delayed to prioritize energy allocation to brain (Halley, 2016); the animal may have adopted the strategy of producing a large number of embryos with short gestation, or a single one requiring a larger investment (Charnov and Downhower, 1995); the possibility of alloparenting or biparental care appears also to be a factor, allowing greater investment in brain volume (Isler and van Schaik, 2009, 2012). Finally, as has been discussed extensively for primates, the physical consideration of the size of the pelvis versus size of the cranium will be material in the timing of birth (reviewed in Trevathan, 2010). The information we have gathered on the stability of the timing of neural maturation adds a useful fixed point to this multivariate problem, as neural mass appears to be produced at a very stable rate in eutherian mammals. Any particular duration from conception to birth (if adult brain size is known) is associated with a predictable neural maturational state.

After reviewing one final aspect of the interaction of brain size and duration of development on cortical maturation, to place the state of the maturation of the cortex at birth in humans in a more general context, we will ask what is known about the significance of the particular state of the brain at birth for the types of behavioral capacities available to the animal, and particularly for learning specializations. One particular problem we will underline, and return to later, is that in most studies which compare life history events across species, time "zero" is quite naturally taken to be birth, but for many purposes, it is a very poor zero to use, as it is associated with a wide range of maturational states whose significance is sometimes assumed to be known, but often is not. Time from conception, appropriately modeled, can be a much more stable and informative way to compare neural maturational stages and aspects of life history across species.

34.2.2 Crossing Gradients in the Cortex and Their Phylogenetic Significance

We need to know what the brain is like around birth, in humans and in other primates, and in other species employed as "animal models" for research, to determine the significance of placement of birth and other early events like weaning, or establishment of early communication. For primates in general, and humans particularly, the maturational state of the isocortex has always been given particular attention, though we will argue later that this excess attention to the cortex may be misplaced for understanding species-specific adaptations in evolution. The following description of cortical development is intended to give an overview of the maturational state of the cortex around birth in terms of features of organization already formed and yet to form and mechanisms available for further maturation of the cortex. We assume the reader is familiar with the basic mechanism of the inside-out generation of the cortical layers (Rakic, 1974) within the cortical column and will focus on temporal features of this organizational feature of the cortex as it varies between species. For reasons of space, we must unfortunately neglect the rest of the brain, but the reader is directed to Workman et al. (2013) for a comprehensive catalogue of the maturational state of other brain components.

The isocortex is formed in the confluence of at least two maturational gradients, one associated with neurogenesis of the cortex itself, and the second deriving from thalamic maturation and the innervation of the cortex by the thalamus (Fig. 34.6) (reviewed in Cahalane et al., 2014; Charvet and Finlay, 2014; Finlay and Uchiyama, 2015). In all species yet described, including marsupials, rodents, carnivores, and primates, generation of neural stem cells proceeds uniformly over the cortical primordium, extending itself in surface area first, then depth, and finally in the addition of a second rank of undifferentiated cells, the subventricular zone, in the brains which will eventually be the largest (Dehay et al., 2015). The production of the first neurons (terminal neurogenesis) begins first in the rostrolateral cortex, marked by cells leaving the ventricular zone and migrating increasing distances to form the cortical plate, formed in the well-described "inside-out" relationship of neuronal "birthdate" to cortical laminar position (Rakic, 1974). Neurogenesis ceases altogether in the rostrolateral cortex first, with cessation progressing caudomedially. In the smallest brains, although the gradient can be observed, its morphological and organizational consequences are minor (Caviness et al., 1995; Charvet et al., 2014). In large brains, however, the gradient amplifies the relative time over which the anterior versus the posterior cortex is formed, giving the posterior cortex a greatly extended period of stem cell genesis and neurogenesis compared to anterior cortex (Fig. 34.7). For a within-species comparison, cortical neurogenesis begins at approximately embryonic day 38–40 throughout the isocortex in rhesus monkey (Rakic, 2002). However, neurogenesis in the anterior cortex (ie, motor or frontal

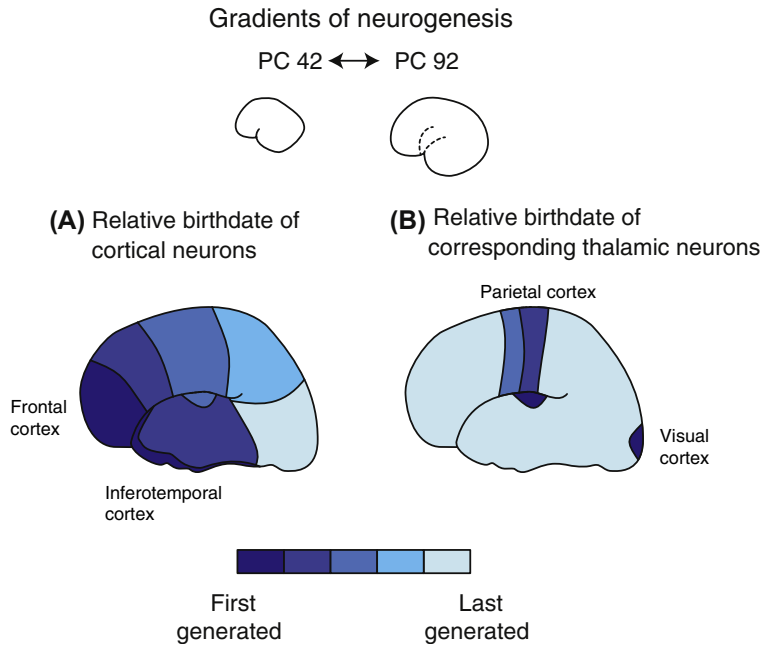

FIGURE 34.6 Contrasting gradients of neurogenesis of cortical neurogenesis of the isocortex versus thalamic innervation. Maturational gradients in early postnatal development superimposed on a lateral view of the human cortex; the relative size of the cortex during this period is represented above both diagrams. (A) Neurogenesis of cortical neurons begins at the rostrolateral margin of the cortex and proceeds posteriorly through parietal cortex to primary visual cortex, framing a period of genesis of about 50 days (PC day 42 to PC 92). (B) Neurogenesis of corresponding thalamic neurons begins with the medial geniculate body (auditory cortex), the lateral geniculate body (visual cortex), and the ventrobasal complex (somatosensory cortex), followed by neurons that innervate motor cortex. The last thalamic neurons to be produced are located in the nuclei that innervate the frontal, parietal, and inferotemporal cortex.

cortex) ends before embryonic day 80, whereas posteriorly, neurogenesis continues to embryonic day 100 in the somatosensory cortex and to embryonic day 102 in area V1 at the posterior pole of the cortex (Rakic, 2002). Note that this gradient is the opposite from the gradient usually presumed to be the case for capacities dependent on the cortex, where sensory abilities are thought to arise first in posterior occipital and parietal cortex, while frontal organizational and decision-making abilities appear later. We will resolve this apparent contradiction shortly.

This gradient becomes progressively more pronounced in the largest cortices and has large consequences (Fig. 34.8): there are many fewer neurons "per column" in frontal cortex, though the convergence of other cortical areas on frontal cortex expands the neuropil and renders the cortex approximately the same depth per column across the cortical surface(Cahalane et al., 2012). Posteriorly, cortex is neuron rich, particularly in primary sensory areas, in which additional developmental processes beyond neurogenesis allow the survival of excess neurons in layer IV, the principal thalamorecipient region (Finlay and Slattery, 1983). The gradient of neurogenesis may predispose the frontal cortex and the anterior parts of the parietal cortex to their "association" role. Neurons begin to spin out axonal processes even while migrating, and axodendritic development commences as soon as neurons are in place (Schwartz et al., 1991). As thalamic and cortical neurons have been shown to compete for sites on the same cortical neurons, the establishment of principally intracortical connectivity in frontal cortex before any thalamic input is able to arrive may predispose it to its "association" role (Windrem et al., 1988; Finlay, 1991). By contrast, the arrival of thalamic input (from the lateral geniculate nucleus) in primary visual cortex actually precedes the arrival of migrating thalamorecipient neurons in the cortical plate of the primary visual cortex, which may give thalamic axons some privilege in the competition for terminal space (Allendoerfer and Shatz, 1994).

The second gradient (Fig. 34.6, right), produced by the thalamic input to the cortex, is organized quite differently. Of all the thalamic nuclei, the primary sensory nuclei, the lateral geniculate for visual input, the medial geniculate for auditory input, and the ventrobasal (also termed ventroposteriolateral, VPL) are generated earliest, migrate to their thalamic positions, and begin to form axonal processes immediately (Bayer and Altman, 1991; Rakic, 1977). In small-brained animals whose cortices are formed over a period of days, this difference, and its interaction with the cortical gradient is not particularly striking. In larger-brained

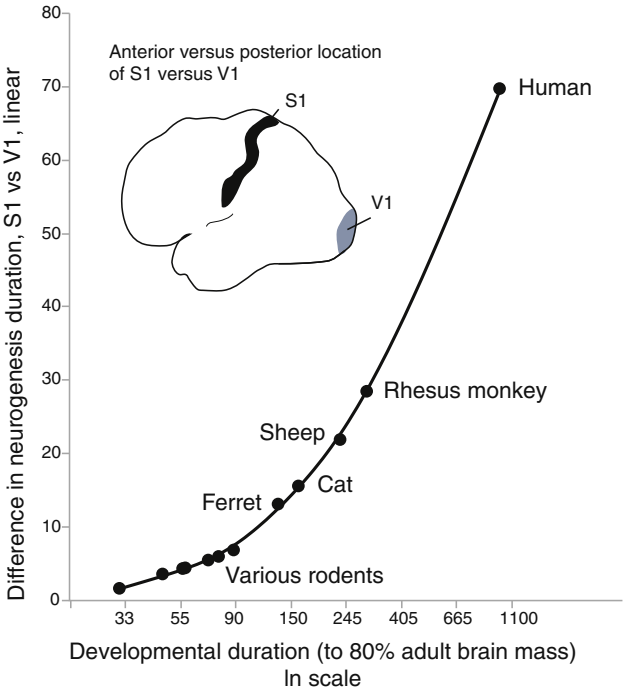

FIGURE 34.7 Difference in duration of neurogenesis of neurons contributing to anterior versus posterior regions of cortex across species. The difference in terminal neurogenesis between the anterior (ie, primary somatosensory cortex, S1) and posterior cortex (ie, primary visual cortex, V1) is plotted against the natural-logged values (ln) of developmental duration in 11 mammalian species (human, macaque, sheep, cat, ferret, rat, gerbil, hamster, mouse). This extended duration corresponds to an increasing relative number of neurons per cortical column in posterior cortex. *Replotted from Charvet, C.J., Cahalane, D.J., Finlay, B.L., 2014. Systematic, cross-cortex variation in neuron numbers in rodents and primates. Cereb. Cortex 25, 147–160.*

animals, whose cortices are formed over weeks, the thalamic input can reach the cortical plate before the migrating neuroblasts destined to become the stellate cells of layer IV arrive, and the thalamic axons remain under the cortical plate for a "waiting period" until they are signaled to enter—their target cells destined to become layer IV actually migrate through their eventual thalamic innervating axons on the way to the cortical plate. These thalamic axons exert a trophic, or perhaps a specifying, effect on these migrating neuroblasts (Oishi et al., 2016): the number of neurons in layer IV "per cortical column" is higher in primary sensory cortical areas. Across cortical areas, the differentiation of layer IV roughly matches the volume of thalamic input (Finlay, 1992). If the thalamic input is removed, by early damage to a particular thalamic nucleus, or by cytotoxic agents, the amount of early neuron death in the appropriate cortex is increased, and the relative number of neurons in layer IV is reduced (Woo and Finlay, 1996; Woo et al., 1996). Other thalamic nuclei, such as the multiple nuclei of the pulvinar, or the anterodorsal group are generated much later, and innervate their parietal and frontal targets later (Altman and Bayer, 1988a,b,c; Chalfin et al., 2007). These nuclei, however, have been studied in much less detail than the primary visual and somatosensory nuclei.

The further emergence of morphological differentiation and sensorimotor capacities follows the thalamic gradient of innervation (primary sensory areas out) rather than the original cortical gradient of cell generation (anterior to posterior) (Bates et al., 2002; Finlay and Uchiyama, 2015). It is important to realize, however, that "sensorimotor capacities" reflecting real-world information and action, versus the electrical activity (as realized in action potentials in axons, field potentials, and somewhat later, active connections arising from neuron-to-neuron junctions and synapses) are not the same. Self-organizational activity, as has been described systematically in the case of "retinal waves," which segregate projections by eye-of-origin in the lateral geniculate body, and perhaps in the cortex as well, begins before photoreceptors are generated or the eyes are open (Wong, 1999). Similar self-organization begins in the somatosensory system, for example, as the number and topology of vibrissae are established in their central representations (Senft and Woolsey, 1991; Brown et al., 1995). Regular, periodic bouts of motor activity begin soon after motoneuron synaptic connections are made, one of the earlier events in central nervous system development (Robertson et al., 1982). This self-organization, subcortical and cortical, generally begins as soon as neurons have differentiated and in time, merges with externally generated organizational activity. For example, the noncorresponding activity in the two eyes produced independent by "retinal waves" in the two retinas, which initially serves to segregate the projections from the two eyes in the thalamus and cortex, falls away just before the time when the eyes first regard the visual world and are replaced by real-world correlations which reintegrate information from places in the two retinas representing corresponding places in the external world (Wong, 1999). However, all of the events in neurogenesis and establishment of initial connectivity that have been described so far are early embryonic events, and in humans occur well before establishment of ex utero viability, graded over 3–5 months postconception. In rats, mice and hamsters, however, birth, the end of corticogenesis and the beginning of thalamocortical innervation occur at approximately the same time.

By the time of 6 months postconception, many basic somatomotor functions are established (though we make no assumption such functions would depend on the cortex), such as responsiveness to somatosensory stimulation, basic motor programs such as alternating limb movements and suckling. Interestingly, multiple

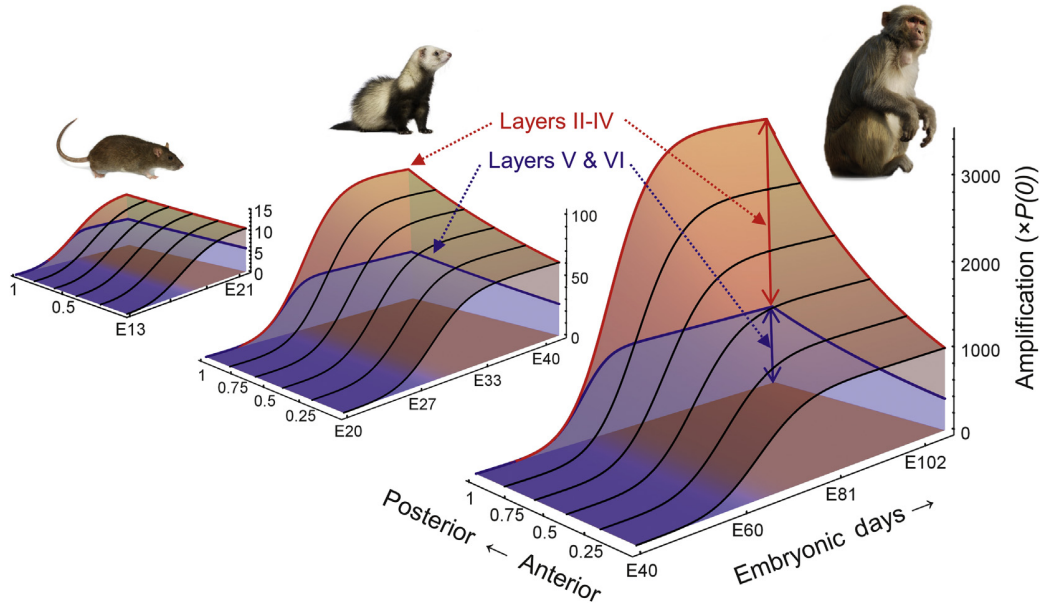

FIGURE 34.8 Model-predicted interspecies and intracortex differences in the timing, extent, and layer assignment of cortical neuron output. Shown are the predicted amounts of neuronal output (in terms of amplification of a unit precursor pool) across the anterior–posterior (spatial) axis of the cortex over the course of embryonic neurogenesis (time axis) for three different cortex adult volume values (1.0, similar to a rat; 1.75, similar to a ferret; 2.5, similar o a macaque monkey). The larger cortices have a longer developmental interval, produce orders of magnitude more neurons in total, and, in particular, have a greater complement of upper layer neurons. The anterior–posterior gradient in neuron number becomes more pronounced in larger cortices, and it is the upper layers that accommodate the greater proportion of the increasing quantities of neurons. *Rat and ferret images courtesy of iStockphoto/GlobalP; Macaque image courtesy of iStockphoto/JackF; From unpublished doctoral dissertation Cahalane, D.J., Charvet, C.J., Finlay, B.L., 2014. Modeling local and cross-species neuron number variations in the cerebral cortex as arising from a common mechanism. Proc. Natl. Acad. Sci. 111, 17642–17647.*

kinds of learning have been shown to occur in the prenatal period in humans, other primates and laboratory rodents, including habituation, associative learning, and reinforcement learning, including preferences for particular chemosensory and language prosody patterns (Alberts and Ronca, 1993; Beauchemin et al., 2011). Most interesting for the present discussion is that preference for mother's voice, and for the prosody of the infant's native language can be established in this prenatal period, which if not represented in the isocortex directly must surely interact with the later cortical representation of these features (Jusczyk et al., 1993; Mahmoudzadeh et al., 2013; Werker and Tees, 1992).

The immediate postnatal (but eyes closed, in burrow) period in rodents, up until the time of eye opening and first exit from the nest has been extensively studied and often used as a "model system" for the effects of early stress on attachment and later learning ((Sanchez et al., 2001; reviewed in Moriceau et al., 2010; Gunnar and Quevedo, 2006)). It is instructive to contrast just how different this maturational state is from the human immediate postnatal period (Fig. 34.4). Birth in rodents is roughly coincident with the end of cortical neurogenesis, which happens at about 70 days, a little over 2 months postconception in humans. Rodents at this age are capable of suckling, and rather uncoordinated motion to reach the teat, which improves progressively up to eye opening, which happens two to two and a half weeks after birth (about a month postconception), somewhat before coordinated, unsupported walking (Fig. 34.5). As mentioned earlier, from birth until eye opening, several kinds of learning have been demonstrated including learning of olfactory preferences in rodents and the establishment of some chemosensory preferences. From birth to unsupported walking in rat pups ranges from PC day 15–20 to PC 30 (about 2 weeks postnatal). The corresponding period for humans from birth to unsupported walking begins 6 months prior to birth and extends to about 1 year postnatal. The same neural maturational state can bracket wildly different birth-related states. These rodent pups use learning to apply environmental information for immediate functional purposes (the "olfactory tether") at neural maturational states far earlier than humans do, though they are quite helpless sensorily and motorically for the most part (Blass, 1987). The capacity for in utero learning has been demonstrated in humans during roughly similar maturational states, and though no immediate functional purpose is attached to it, it has been implicated in channeling the future course of attachment and language learning (Mampe et al., 2009; Moon et al., 2013).

We have laid out the progress of morphological and functional development, focusing on the cortex, to get an idea of what stage of neural development the human infant presents to the world at birth and how that might relate to critical periods and perinatal behavior and learning in other species. The ultimate goal is to see if there is evidence of special junctures or states in the progress of neural maturation that might inform us about the significance of the peri- and postnatal period for learning in general and social learning in particular. So, to review, by about 3 months postconception, the human infant has generated almost all of its cortical plate as described in Fig. 34.8, including its richly detailed anterior to posterior organization, and thalamic innervation in primary sensory and motor areas is established. As we have argued elsewhere, those two features carry the seeds of hierarchically organized information extraction and prediction, progressively more powerful in larger brains (Finlay and Uchiyama, 2015). Intracortical connectivity is also being established, well along in frontal cortex at 3 months, but just beginning in occipital cortex.

In the second trimester, self-organizational activity is much in evidence, with the onset of retinal waves coincident both with establishment of retinal and thalamocortical connectivity, phasic motor activity, as well as locally correlated activity within structures (Wong, 1999). In addition to cell-to-cell genetic recognition mechanisms, this endogenous activity serves to separate axonal and dendritic projections with uncorrelated activity and helps refine topographic maps in projections between brain regions, based on correlated activity.

A first phase of "exuberance" of numbers of neurons, connections, and neurotransmitter and receptor expression peaks during this period, related to the first establishment of excitatory connectivity between regions, both synaptic and nonsynaptic (Innocenti and Price, 2005; O'Leary and Koester, 1993). A corresponding regressive event, normally occurring neuron loss is at its peak (Janowsky and Finlay, 1983, 1986). Neurotransmitters and neuromodulators are overexpressed in neurons at this time; that is, neurons of the type that will express a single neurotransmitter at adulthood may express several (reviewed in Finlay et al., 1991). One particularly interesting feature of this organizational period is the method by which inhibitory synapses are incorporated into circuitry: inhibitory neurons typically express excitatory transmitters first, which allows them to be integrated by excitatory Hebbian mechanisms into local circuitry. After they are thus inserted into topographically appropriate circuitry, their excitatory synaptic machinery is lost, and they begin to express GABA-ergic mechanisms or other neuromodulators (Ben-Ari, 2002; Cancedda et al., 2007). The first synaptic specializations appear, but in much reduced numbers compared to the eventual perinatal and adult states, to be discussed at length in the next section. During this period of first organization of connectivity, altricial rodents and carnivores such as the ferret have already been born; cats are born somewhat later, just before eye opening, corresponding to the end of the second trimester in humans. In cats and ferrets at this point, the self-organizational feature of retinal waves drops out, to be replaced by real-world, visually driven activity (Wong et al., 1995). Primates remain securely in utero, though their eyes have opened, and the status of retinal waves is largely unknown.

Thus, by the end of the period corresponding to the end of the second trimester in humans, all neurons in the isocortex have been generated and deployed, and normal neuronal death has been completed in this population. The fundamental pattern of neuron density and laminar organization seen in adults is established. Gross patterns of axonal connectivity, including aspects of nearest-neighbor topology and self-segregation of neurons with uncorrelated activity is laid down both by cell-to-cell recognition and activity-driven processes. Basic distinctions of excitatory and inhibitory connections are expressed. At this point, however, differences in the position of birth and in the consequent "real-world" environmental stimulation cause divergence in maturation: animals born at early-to-middle stages of neural maturation will begin to embark on activity-driven critical periods such as the segregation of ocular dominance columns, whereas animals that are largely precocial, such as primates and ungulates, apparently remain "on hold."

34.2.3 The Case of the Synaptic Surge

One component of neural maturation dissociates itself from the rest of the highly integrated schedule of neural maturation and associates with birth, a surge of synaptogenesis raising synaptic density in the cortical neuropil nearly two orders of magnitude. The number of species forming the basis for this claim is limited, involving necessarily partial data from humans (Huttenlocher and Dabholkar, 1997; Huttenlocher et al., 1982), extensive data from the rhesus macaque (Bourgeois et al., 1994, 1989; Bourgeois and Rakic, 1993; Rakic et al., 1994, 1986; Zecevic et al., 1989; Zecevic and Rakic, 1991) and complete data sets from marmosets (Missler et al., 1993) and rodents (Blue and Parnevelas, 1983). Within and across species, the patterns are consistent.

Although the corpus of data collected by Huttenlocher (1997, 1982) on the development of human synaptic density is typically cited to show a sequential series of changes in synaptic density across cortical areas, contrasting with the "synchronous" macaque, the overall picture is quite similar to the macaque and marmoset when they are placed in corresponding time frames

(Fig. 34.9, top and bottom right; Bates et al., 2002). As the claims of sequential maturation of cortical areas are often supported by only one or two data points per area in the human work, with a methodology not employing important stereological corrections to capture relative synaptic and neuron densities (see extended discussion in Bates et al., 2002), the data collected from experimental animals are empirically better sources for this claim. All cited studies, including those from human material, show a burst of synaptogenesis at birth, of the "Type 1" morphology associated with excitatory neurotransmission. In the macaque, all isocortical areas show a burst of synaptogenesis around the time of birth, in every area simultaneously (Rakic et al., 1986), as well as in various noncortical targets, including the basal ganglia and cerebellum (Brand and Rakic, 1979; Eckenhoff and Rakic, 1991). Interestingly, the rat shows a similar surge, though its surge is not timed to the animal's birth, but rather to eye opening, the time when rat pups begin to first exit the nest (Blue and Parnevelas, 1983).

A major point of interest is the cause of the synaptic surge, whether it might be initiated by the onslaught of experience surrounding birth or entrance into the light directly, or whether it is initiated endogenously in anticipation of birth. While it is apparent an upswing

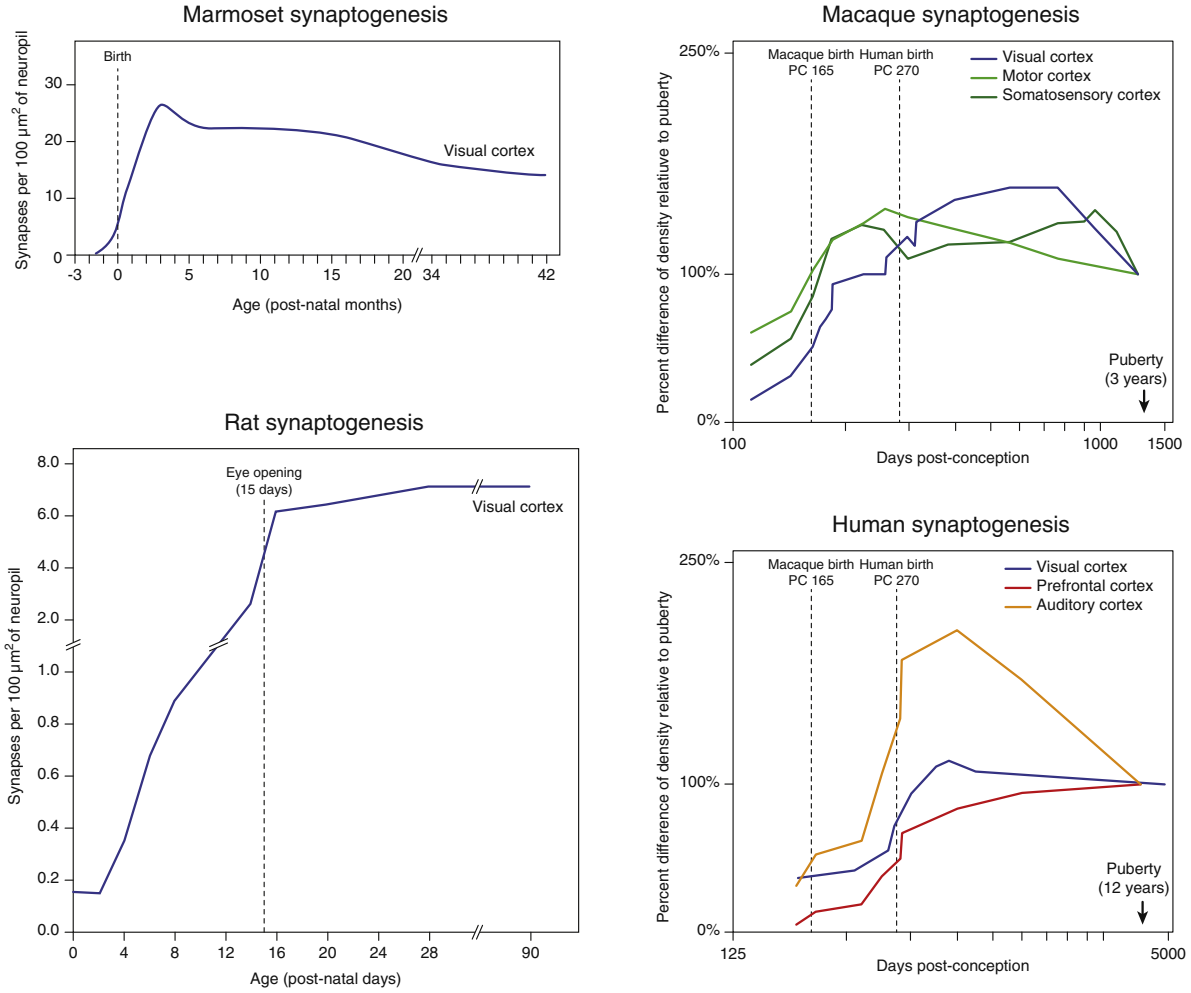

FIGURE 34.9 A surge in excitatory synaptic numbers in the isocortex occurs at birth or at exit from nest. Top left: changing density of synapses in the primary visual cortex of the marmoset; birth indicated by the dotted line. Redrawn from data of Figure 34.4 in Missler, M., Eins, S., Merker, H.J., Rothe, H., Wolff, J.R., 1993. Prenatal and postnatal development of the primary visual cortex of the common marmoset. 1. a changing space for synaptogenesis. J. Comp. Neurol. 333, 41–52. Bottom left: Densities of axodendritic synapses for the total number (type 1 plus type 2) in the visual cortex of rats of various postnatal ages. Rat eye opening and nest exit occurs between postnatal days 16–20. Redrawn from data of Figure 34.1, Blue, M.E., Parnevelas, J.G., 1983. The formation and maturation of synapses in the visual cortex of the rat: quantitatve analysis. J. Neurocytol. 12, 697–712. Top and bottom right: Synaptogenesis in macaque and human showing coordinated perinatal increases in three cortical regions. The corresponding neural maturational state for both species is shown on both graphs, to show that the surge in synaptic density relates to birth, not a particular state of neural maturation determined by the translating time models. Top right: macaques Bottom right) Human (model version, Finlay and Darlington, 1995).

begins before birth, the question was addressed directly in macaques by delivering the macaque infants several weeks prematurely, prior to the onset of the synaptic surge, to determine whether the onset of visual (and other) stimulation would initiate synaptogenesis (Bourgeois et al., 1989). While small changes in the proportion of excitatory and inhibitory synapses were observed immediately following this Caesarian delivery, the burst of synaptogenesis still occurred when the animal would have been born, not when it was born artificially. As it is the case that the fetus initiates birth (Nathanielscz, 1998), it is quite plausible that a maturational signal originating in the fetus prior to birth also initiates the coordinated synaptic surge across structures, though the nature of the signal is not known. A likely reason for the sudden addition of a massive number of synapses, whose state of activity is unknown, is that synaptic sorting and stabilization can then involve the addition, stabilization, and the subtraction of synapses rather than synapse addition alone, employing various empirically demonstrated additive and subtractive mechanisms (Bear, 2003; Bi and Poo, 2001).

A second important feature is that the surge of synaptogenesis is dissociated from the lockstep of neural maturation so dominant up until this point. As can be seen in the comparison of human and macaque synaptogenesis with their births (Parallel vertical lines; right top and bottom graphs for macaque versus human; Fig. 34.9), the surge occurs at quite different maturational points. Both of these points occur well after the organizational events occurring in the human second trimester we have just described but are still quite separated in maturational time. This observation, and several others we will discuss, all point at a long plateau beginning around birth and continuing well through infancy to early childhood, where events termed "critical periods" or "cortical plasticity" may be both initiated or delayed, and where the neural substrate of the cortex appears to undergo rather few known self-initiated organizational changes. This plateau stands in marked contrast to the rapid, time-locked sequence of organizational changes seen in the second trimester.

Finally, as described earlier, learning has been shown to occur in utero in humans, particularly in the language domain, for both descriptive studies demonstrating prenatal or immediate postnatal preference for mother's voice and accent, and experimental studies demonstrating evidence of postnatal recognition for text or music repeatedly presented before birth (Jusczyk et al., 1993; Mahmoudzadeh et al., 2013; Werker and Tees, 1992). It is interesting to speculate how such learning survives the perinatal synaptic onslaught; perhaps there are "tunable" subcortical structures not affected by the synaptic burst, which later serve to channel isocortex-based language learning, in the manner described in models both for avian imprinting and for face recognition (Johnson, 2005). Alternatively, in several systems, "reference" topographic maps have been described which remain stable in the case of induced sensory conflict, such as between visual and auditory topographic maps in the owl, where the auditory map is accommodated to the visual map, independent of their relative volume, or which one has been altered from its normal state (Konishi, 2003).

34.2.4 Early and Late Processes in Myelination

The developmental study of myelination has two aspects. The first is the initial production of myelin sheaths, beginning not long after axonogenesis in long pathways, and time-locked in the way typical of most other early neural events (reviewed in Workman et al., 2013). The proximate stimulus for myelogenesis has been studied most extensively in the early development of motor neurons, and the optic nerve (Sherman and Brophy, 2005), and is initiated when axon diameter reaches a critical value (Foster et al., 1982). Therefore, in typical development, the highly predictable nature of this event is not initiated by an independent genetic signal directly derived in some fashion from fetal age, but by local signaling of a relevant maturational state. This mechanism, however, allows large deviations to occur in myelination should a developmental challenge of some kind occur. For example, after a bout of perinatal hypoxia, if the corpus callosum is inspected for gross morphology, its appearance in gross morphology and size is unchanged, but the number of axons comprising it is much larger than normal, with thinner axon diameters and less myelin sheathing (Miller et al., 1993). In macaques, the immediate perinatal period is the peak of callosal (and probably intracortical) axon loss (LaMantia and Rakic, 1990). As the reduction in number of callosal axons is unaccompanied by neuron loss in the relevant populations, neuron survival is most likely allowed by maintenance of branches in either long-range or short-range connections (Ivy and Killackey, 1981).

Initial interest in myelination initiation or surges in early development as markers of sensitive periods in sensory or cognitive capacities (eg, Pulvermüller and Schumann, 1994) has not generated much follow-up work. Complementing difficult developmental fMRI studies of the development of functional connectivity (Geerligs et al., 2015), experience-dependent axon organization or myelination, or some correlate of it, however, has become a staple of neuroimaging experiments in development and adulthood, principally using diffusion tensor imaging (Greene et al., 2014; Ingalhalikar et al., 2015; May, 2011; Pandit et al., 2014). This technique examines the vibration or diffusion of water molecules resulting from the

presence of extended, "anisotropic" membranes characteristic of both axons and myelin sheathing to infer axon presence. Large tracts can be detected with this method, though branching and crossing tracts cause interpretative problems when it is used to infer details of connectivity. Precise comparisons of connection details of this technique with results obtained by traditional tract-tracing in both monkeys and macaques have produced rather disappointing results (Azadbakht et al., 2015; Jbabdi et al., 2015; Donahue et al., 2016). Nevertheless, plausible features of gross aspects of normal growth can be demonstrated, such as the first appearance of long tracts, growth, and changing within-tract organization. In addition to volume differences, a decrease in "fractional anisotropy" of identified tracts has been shown repeatedly, both in normal development and consequent to particular learning regimes (such as juggling or piano playing) from early childhood to middle adulthood (Dick et al., 2011; May, 2011; Zatorre et al., 2012). In these cases, the signal from identified tracts increases, as if axon bundles are becoming more orderly and aligned as the result of either growth or organizing experience (Fields, 2015). Just what feature of normal axon topology in tracts would become better "aligned" by piano playing or reading is not obvious, though one unintuitive feature of axon growth might be considered. For axons, the process of "growth" should be distinguished from addition of "length" as very little of total axon length is produced by growth by extension at axon terminal regions, as might reasonably be assumed (Pfister et al., 2004). Rather, neuron cell bodies act as if they are essentially fixed, as are their terminal zones, and as the brain otherwise grows through addition of mass of all kinds (other neural processes, glia; vasculature), tension thus exerted on axons causes new membrane to be interpolated into existing axon length. This traction has other consequences for brain growth and function and has been shown to warp the dimensions of receptive fields in the retina conforming to the directions of force and expansion (Schall and Leventhal, 1987; Wong, 1990) and has been proposed as one cause of the development of gyri and sulci in the cortex (Van Essen, 1997). Normal traction, interacting with neural activity in some as yet unknown manner, might contribute to the decreasing anisotropy of long tracts, as the order in a collection of overlaid textile fibers might emerge as any two points of the mass are put under tension.

The extensive use of neuroimaging to describe human development (the extent of this literature prevents a completely comprehensive review) has led to measurement of multiple morphological features whose physiological or functional interpretation is unclear but which are reliably associated with maturation. The relative volume of "grey matter volume," "cortical thickness," or "gray matter density" in the cortex is such a phenomenon, where grey matter corresponds to the cell-dense layers of the cerebral cortex, contrasted with "white matter", the myelinated tracts located under the cortex or interposed between cortical areas in gyri. Typically, gray matter is measured to increase in total volume or, more typically, relative depth throughout early development and then regresses by a small amount, depending on cortical region (a selection of such surveys, in several species, emphasizing cortex (Aggarwal et al., 2015; Conrad et al., 2012; Croteau-Chonka et al., 2016; Giedd et al., 1999, 1997, 1996; Giedd and Rapoport, 2010; Gogtay et al., 2004; Hammelrath et al., 2016; Li et al., 2015; Makropoulos et al., 2016; Raznahan et al., 2012; Shaw et al., 2006; Shiraishi et al., 2015; Silbereis et al., 2016). The contributions to growth and loss of volume include any change in the volume (but not number) of neuronal cell bodies and their processes, including axonal and dendritic arbors, and the numbers and associated volumes of glia and vasculature. Excluding the perinatal "synaptic surge" discussed earlier, synapse number and density in cortical areas roughly follows the same pattern of small early increase, then decrease. In addition, simple segregation of cell and axonal processes, causing changes in delineation of borders, and the geometrical consequence of the expanding "sphere" of the cortex on the measured depth of its outer shell will also impact relative sizes of these zones. Additive and regressive changes should be assumed to cooccur, resulting in the repeatedly described small net increase in total volume in early development, and a small net negative near the end. The increase and then regression of gray matter depth changes progressively throughout childhood and occurs earlier in primary sensory areas than in posterior parietal and frontal cortex (Gogtay et al., 2004). Precocity as measured by IQ in childhood changes this measure: the peak grey matter depth in parietal and frontal cortex and its following regression occurs later in high-IQ children (Shaw et al., 2006).

Changes in gray matter thickness or total volume parallel some preconceptions about the nature of brain plasticity in some ways and contradict others. The early stabilization of primary sensory areas and the general back-to-front progression of the rate of maturation is in accord with well-known earlier neurodevelopmental features discussed earlier, but well more than half of the cortex is essentially asymptotic in depth and volume change well before adolescence, frontal cortex the exception in its tardiness (Petanjek et al., 2011). Consider also that the very definition of high IQ in childhood is precocity, while cortical measures show delay. Such a "paradoxical" effect is not hard to interpret as an extended period of plasticity, but it also indicated that a particular level of ability (in this case a precocious one) can be decoupled from gray matter thickness: the same brain thickness could be thus associated with quite different vocabulary

attainment depending upon the overall trajectory of an individual's growth. Overall, an overarching structural and mechanistic similarity of the process of cortical maturation from the early postnatal period to adolescence emerges from this literature, given that the morphological changes described are produced by multiple components. Gradients across the cortical surface are often the focus of these papers, while mosaic, area-by-area distinctions are seldom, if ever, noted (eg, statements to the effect that "many investigators note the precocious emergence of adult white matter thickness specific to frontal area xyz"). Nor is there any particular pattern of genetic expression, nor description of a special subclass of synaptic plasticity, for example, associated only with early, middle, or late phases of cortical maturation. As always, "absence of evidence is not evidence of absence," but the vast amount of descriptive material now available to us begins to require at least an attempt at appreciating its message. Few signals of part-by-part maturation of the isocortex either idiosyncratic by species or general over species have emerged.

34.2.5 What Are "Critical Periods" in Morphological Terms?

In adults, the computational structures supporting "learning" are quite diverse, varying in organization in different brain locations. Associative or "statistical" learning is distributed widely throughout the nervous system, with a slow form in the isocortex contrasted with much more rapid association in the hippocampus (McClelland et al., 1995). Reinforcement and habit learning are best linked to the basal ganglia and associated structures (Doya, 2001; Graybiel, 2008) and are known to be gated by social and other specific reward systems by neuromodulators (Young and Wang, 2004; Goodson and Thompson, 2010). For the cerebellum, numerous models of circuitry optimizing error correction and prediction exist (Bastian, 2006; Doya, 2001). By contrast, for the mechanisms of early learning in humans, and in initial "animal model" work, researchers have focused almost exclusively on associative, Hebbian and anti-Hebbian learning (Berardi et al., 2000). No reason exists, however, to believe that associative learning is in any sense primary, or that reinforcement and error-driven learning do not participate in the early organization of behavior. The initial research focus on synapse stabilization at the neuromuscular junction (Sanes and Lichtman, 1999) and ocular dominance columns (Bi and Poo, 2001; Katz and Crowley, 2002) was reinforced by the early prominence of connectionist modeling (Elman et al., 1996) and demonstrations of statistical learning (Saffran et al., 1996), later resolving into "deep learning" of statistical and contingent structure in complex input (Schmidhuber, 2015). All of these research threads highlight mechanisms that discover by fundamentally associative mechanisms correlated structure in input, and represent it efficiently, compared to, for example, selective stabilization of input according to behavioral or motivational importance, or efficiency in executing behavioral goals. Since the following brief review will compound the error of this idiosyncratic focus on a single mechanism, we point out at the outset the formal similarities of "habit learning" in the reinforcement literature to "critical period" and "sensitive period" effects, even though the latter studied almost entirely in the context of associative mechanisms.

34.2.5.1 *Initial Parameter Setting: One-To-One Connections, Topographic Maps, and Brain–Body Alignment*

The first work on learning in the mammalian nervous system began with two model systems: the formation of the "ocular dominance columns" of the primary visual cortex, integrating and segregating like and unlike input from the two eyes (Katz and Crowley, 2002; Wiesel, 1999) and the establishment of one-to-one neuron-to-muscle fiber connections at the neuromuscular junction (Sanes and Lichtman, 1999). Research in several other domains followed from these. The study of ocular dominance columns became naturally associated with the more general issue of topographic map formation in the visual system (Udin and Fawcett, 1988). Multimodal map registration, particularly between visuomotor and auditory maps, concentrated on midbrain representation (Stein and Stanford, 2008). Work in somatosensory system, particularly the rodent vibrissal system, addressed the question of how to match the number and arrangement of peripheral elements, the whiskers, onto a central cortical representation (Van der Loos and Welker, 1985). Every one of these domains depends on mechanisms involving Hebbian "fire-together, wire-together" mechanisms that bring like-responding elements together, increases efficiency and the sparseness of representations, and generate (in combination with other mechanisms) the ubiquitous mapping of nearest-neighbor to nearest-neighbor topological arrays in the nervous system (Kaas, 1997). Numerous interesting generalities emerged from this work. First, they all show continuity between endogenous and exogenous ordered activity. Like early neuron death (Oppenheim, 1991), the initiation of organization in these networks often depends on some increase in synaptic activity and is delayed or might not begin in the absence of activity, self-initiated and self-terminating. Thus the onset is not time-locked to an endogenous maturational signal but rather to meaningful stimulation (one exception being changes associated with metamorphosis (Hoskins,

1990)). The organizational processes are competitive, and imbalance in inputs can reduce the unfavored input, such as a closed eye in competition with an open eye for cortical synaptic space (Wiesel and Hubel, 1965). These processes are "critical periods" or "sensitive periods," because while they are somewhat plastic in timing, they are not infinitely so, and a loss of input due to imbalanced completion, after an early period of development, cannot be recovered (Berardi et al., 2000). Similarly, early misregistration of maps cannot be wholly undone. Much current research is focused on genetic, pharmacological, or situational factors that can extend or reinstate plasticity (Hübener and Bonhoeffer, 2014). This thorough description of early organization and critical periods was the great focus and accomplishment of initial work on developing neural systems.

Though the temptation to give these established mechanisms much credit for the basic organization of the nervous system is strong, it is important to remember what remains unexplained. To begin with the most elaborated case, the complex interlocking maps of dimensions of ocular dominance, orientation, motion, and visuotopic location are laid down in the visual cortex in the first several years of human life, and if this process is disturbed, irrecoverable amblyopia can result (Levi et al., 2015). The establishment of these patterns has been described almost exclusively in terms of associative networks, with excitatory and inhibitory components that serve to reduce redundancy in central representations and sharpen intrinsic topographic representations. Interestingly, however, real-world function may impinge on the ongoing success and functionality of such projections (Rodger and Dunlop, 2015). In later development, however, the visual cortex continues to participate in learning-related changes, both long and short term, assembling environmental statistics, and even altering topographic projections if part of an input is silenced (Gilbert and Li, 2012, 2013). The cortical regions corresponding to inactive or lost locations in the retina or inactive digits on the hand will become responsive to adjacent regions of the sensorium in short intervals (Florence et al., 1997). Across the lifespan, the brain is constantly amassing and updating the information that makes Bayesian prediction feasible, from details of early sensory processing to higher-order organization, in both long-term assemblies such as the statistics of images to short-term priming (Burr and Cicchini, 2014). In an extreme case, after only 2 or so weeks of visual deprivation and Braille-learning in adulthood, the visual cortex will become both active in Braille reading and essential in its execution (Burton et al., 2002; Merabet and Pascual-Leone, 2010). Activation of so-called "visual" cortex in multiple nonvisual tasks is commonplace in imaging studies (Anderson et al., 2013). Are the elaborate topographies of retinal topography, interocular alignment, wavelength calculation, and orientation selectivity established in early development employed in some useful fashion in the distributed activation demonstrated in adulthood, or are they circumvented? How does apparent reuse and reassignment dissociate itself from the "critical period" nature of early morphological organization (Anderson, 2014)?

34.2.5.2 *Genes, Species-Typical Behaviors, and Cortical Areas*

Another possible source of information about the nature of sensitive or critical periods might be found in gene expression networks (Hensch, 2004). The genes expressed in early development across the cortex have now been mapped in some detail, though their "meaning" has hardly begun to be understood. The features that stand out in these examinations are first, the rostral-to-caudal pattern of maturation of gene expression described earlier in relation to the generation and early termination of neurogenesis from rostral to caudal (Miller et al., 2014; Pletikos et al., 2014; Silbereis et al., 2016), and second, the separate status of the primary sensory cortices, in terms of early maturation superimposed upon the early maturational gradient, genes involved in axon-target recognition presumably important for the unique trophic and topographic dependence of thalamus-to-cortex in those areas, and associated neurotransmitter systems (Hamasaki et al., 2004; Yamamori, 2011). Notably absent, at this admittedly early point in the understanding of developmental genetic networks, is any signature of genes associated with a sensitive period, or early or other individuated maturation of a nonprimary cortical area (Pletikos et al., 2014). From the behavioral end, evidence exists for genetic loading of face recognition ability (Shakeshaft and Plomin, 2015) and aspects of language learning (Newbury and Monaco, 2010). Working backward from plasticity-relevant mechanisms such as synapse stabilization, particular genes involved with such mechanisms have been described for some time, as described by Hensch (2004); what is absent is a signature of coordination of the multiple mechanisms required for a temporally specified critical period. Conceivably, we might expect something of this kind if the special circuitry which must be present (somewhere in the brain) for the reliably elicited infant preference for faces was found in or around cortical regions related to face recognition in adults, but nothing as yet has been described. This question has been examined in bird song learning, in particular, where readiness for song learning can be partially decoupled from the bird's age (London et al., 2009; Clayton, 2013). So far, however, it has been difficult to recognize any genetic state associated with a "sensitive period" using a variety of assays of gene expression. So far, a very large number of genes can be identified

with this state, so many as to be uninformative about particular mechanistic questions. Similar excess of genes in flux at any point has also been described for the cortex, where the link to a singular change in perceptual or behavioral competence is even less clear.

Parallel examination of the functional properties of the cortex, however, has made it increasingly unlikely that special genetic mechanisms defining the computational properties of a defined location in cortex could be the way a species-specific sensitive period is produced. The best-researched example is human infant's special competence in "recognizing" faces and preferring to look at them (Pascalis and Kelly, 2009). Ignoring at this point whether adult face-sensitive cortex is best described by localized activity in a particular region or a network of regions (Haxby et al., 2000), we may simply ask if the infant pattern of activation resembles the adult configuration, for example, showing an early nucleus of activation in a region also indexed in adults, perhaps later spreading to other linked regions. Nothing of this kind is seen but rather a qualitatively different pattern of activation than the adult, which takes close to 10 years of experience to approximate the adult configuration (Cohen Kadosh et al., 2011; de Haan et al., 2002). Similarly, considering language organization, the immediate and largest deficits and delays in language acquisition result from damage to the right side of the cortex, not the left, opposite to the adult pattern (Bates and Roe, 2001). Early infant preferences for faces and speech must of course have some neural correlate, but the origin of such early preferences may quite likely be found outside of the neocortex, though adult processing competence will later require the cortex.

34.2.5.3 *Gradients of Activation, Activity, or Cessation of Activity*

Another way of the developing cortex might organize incoming information is by coming "on line" area by area, seeded by initial activity in primary sensory and motor areas, and then entering into computation in a rough caudal-to-rostral hierarchy (Finlay and Uchiyama, 2015). This hypothesis is in line with information on "feed-forward" and "feed-back" cortical projections, and what we know about the gross morphology of the sequence of maturation in cortical areas (Gogtay et al., 2004). The idea of "self-initiating, self-terminating" circuitry for sensitive periods would be consistent with progressive entry of regions, cortical or otherwise, into synaptic integration. A critical problem in the development of learning in distributed systems was identified by Elman (1993) that makes this possibility particularly attractive: if a network is to learn a number of tasks, a critical requirement is to have a way of releasing computational resources gradually, so that old tasks are not routinely overwritten by new tasks. Is there evidence for any version of this possibility?

With the now often-mentioned exception of primary sensory areas, the evidence for sequential activation of cortical areas is poor (though explicit examination of specified regions in a plausible hierarchy has not actually been examined with this question in mind). By "activation," we might mean the idea that regions of cortex far forward in the hierarchy are simply inactive in early development, or their level of activity is lower by some metric. The most impressive evidence contrary to this argument is the presence of robust activity in the frontal cortex quite early in development while performing "cognitive control" tasks, far before those abilities dependent on frontal cortex have stabilized in adolescence and adulthood (Casey et al., 2005). Overall, the general pattern of learning in development recapitulates what is typically seen in individual bouts of learning in specified tasks: the initial pattern of activation is widespread, and often bilateral, settling down into a more localized pattern of "crystallized" or "mature" activation after extensive learning tasks. Therefore, whatever organizes the roughly hierarchical organization of maturation in the cortex is not expressed in activity by itself, but some consequence of that activity, or the cessation of some kind of activity. One quite interesting hint has emerged in a recent study of ocular dominance plasticity in mice, which argued that the maturation of silent glutaminergic synapses into active synapses on principal neurons marked the end of the critical period (Huang et al., 2015). This maturation, which involved the conversion of as many as 50% of synaptic profiles, could be prevented with the animal's visual responsivity, both behavioral and electrophysiological, essentially normal, although ocular dominance profiles remained malleable.

34.2.5.4 *Summary: Deploy With Military Precision, Then (Eagerly) Sit and Wait*

In the first section, we reviewed "translating time" research, in which a multitude of developmental events in the basic construction of the brain occurred in precise sequence over numerous species, appropriately scaled to the developmental duration for each species. Though echoes of this scheduling persist, for example, in changes across the cortex in grey and white matter volumes, once constructed, the brain appears to tolerate a great amount of deviation in the onset and the organization of experience. These changes appear as broad gradients in achievement of maximum volume, and the small decrement in volume associated with the end of some sensitive periods. Birth can occur at a variety of times with respect to neural maturation, and the "synaptic surge," an apparent morphological index of the onset of significant experience, is also decoupled from an exact

point in neural maturation and may also be decoupled from birth. Most organizational sensory events that have been investigated in detail, such as the formation of ocular dominance columns, do not begin at a specified maturational state independent of experience but are initiated by the experience itself. Over a wide range, the isocortex is as yet embarrassingly free of any gene, activity, or morphological indication of cortical area–specific sensitive periods, in onset or offset. The entire cortex, however, presents an organized processing device to incoming input, privileging primary sensory and motor areas, with those embedded in a generally hierarchically arranged sequence of areas. Perplexingly, it is not the relative onset or any progressive change in amount of activity that is best associated with a cortical area's hierarchical position, but perhaps when its uncommitted synaptic elements are depleted (Huang et al., 2015). The following discussion of social learning and the lesser predictability of life history events will give further rationale for what might appear a perplexing contrast in the lockstep of initial neural development compared with the initiation of learning in the world.

Before turning to that subject, however, we suggest that associative networks and the isocortex have been given unwarranted prominence in understanding the emergence of early behavior. To be sure, a great deal of the initial representation of the body in the brain, such as understanding nearest-neighbor relationships in sensory surfaces, the number of sensors on the face, the size and positioning of the eyes, the length of the limbs, and the patterns of coactivation of muscles are directly dependent on associative learning and are well understood in that context. All of those features of brain–body organization, however, are notably free of any motivational, or even motor context in the sense of directed movement. Attending to any cue, such as the preference to look at simple contrast over blur, or for the mother's voice, a face-like configuration, or beginning the babbling and attention to response necessary for language intrinsically involves a component of motivation and some action by the infant, if only an eye movement (Syal and Finlay, 2011). Circuitry attached to motivation, movement, and reward does not lie in the cortex but in the basal ganglia and basal forebrain and is the more likely place to look for the sources of sequential organization of behavior involving any motor decisions. These regions are also known to have circuitry reflecting the continually changing behavioral disposition of the animals, from suckling, to dispersal, to attending to new infants. These preferences can be manifest in multiple ways, from the innate predispositions to approach, avoid, or learn from certain stimulus configurations that we have just described. However, these preferences may be quite more complex, minimally containing the circuitry to adapt responses to contexts (Graybiel, 1998). They may also change the weighting and linkage of rewards, for example, the adolescent emphasis on positive and discounting of negative outcomes (Cohen et al., 2016), or obligatory linkages, such as the requirement of a particular individual for social reward in monogamous animals (Young and Wang, 2004).

34.3 Life History

34.3.1 Construction of Individual Brains Versus Life History Transactions

"Translating time", as we have described it, is well described by a single goal: to construct the brain in the specific duration allowed for a mammal, appropriately scaled for a particular brain size. The events of "life history", by contrast—birth, weaning, adolescence, dispersal, first parenthood, and so forth—are transactional and social, defined by competing interests and multiple goals. These two contrasting organizational features of maturing systems are not entirely mutually exclusive, of course. We described one tradeoff in one organ system against another within brain development, whether to allocate tissue preferentially to olfactory-limbic structures or to isocortex. Conversely, the timing of life history events will have necessary constraints from neural and somatic maturation. Overall, however, the timing of life history events such as birth or weaning depends not only on the maturational state of the child but also the competing and aligning interests of the child and mother both, in both in individual variation and cross-species contexts (Royle et al., 2012). For another example, the timing of dispersal from a home range is unlikely to depend on a single maturational signal from the nervous system of an individual reaching a criterion age but will more likely also involve seasonality, competition for resources prior to leaving and likely competition consequent to leaving (Royle et al., 2012). In the general context of evo-devo, we will present some preliminary evidence and arguments here that brains have evolved in the context of such contingency and variability and thus possess the circuitry that demonstrates the evolutionary prevalence of such transactions.

34.3.2 Human Birth in Its Primate and Mammalian Contexts

We will discuss here some general considerations involving the timing of birth, and the specific timing of human birth in the context of other primates, and mammals in general. Overall, a long gestation requires more investment of resources from the mother than does a short one. This investment involves not only the transfer of nutrients to the fetus but also a lengthening of the

interval to the next conception, and hence a decrease of maternal reproductive rate. However, there are several reasons why it might be adaptive for a mother to invest in a long gestation and produce precocial offspring; these might include the need to avoid predators and the need to move around safely shortly after birth, the latter including the need to avoid drowning in the case of aquatic mammals (Pagel and Harvey, 1988). Because brain mass is a power-law function of developmental duration during the early phases of development that include gestation (Passingham, 1985; Workman et al., 2013; Halley, 2015), gestation length is also tightly coupled to the degree of brain maturation. This means that for species of equal brain size, the later born species will necessarily be neurologically more mature at birth.

Humans are usually viewed as an altricial species among the great apes, often with reference to the large proportion of brain growth that occurs after birth. This is frequently interpreted as a prolongation of a fetal rate of development far beyond birth (Coqueugniot et al., 2004), but this interpretation is based on the erroneous assumption that birth occurs at the same stage in fetal development across different species, and any changes that are observed in development after birth are the result of evolutionary modifications of the developmental schedule itself. The same assumption governs statements about behavioral development such as, "it takes the human newborn a year to reach the stage of motor development equivalent to that of a newborn great ape" (Smith and Tompkins, 1995: p. 269). However, such manifestations of "secondary altriciality" do not necessarily reflect an evolutionary reshaping of the developmental schedule; it could simply be that the position of birth is being moved to an earlier time with respect to a developmental schedule that is conserved across species and elongation of human development that is "allometrically expected." With regard to development of the nervous system, our analysis shows that this is likely to be the case. Humans are born in a neurologically more altricial state than other apes, but this does not mean that humans are an evolutionary anomaly; to the contrary: human altriciality is well within general mammalian norms.

The classic explanation for human altriciality has been the "obstetrical dilemma": In this scenario, the transition to bipedal locomotion in human evolution led to a narrowing of the skeletal structure of the birth canal, conflicting with selection pressure toward larger brains that make passage through the birth canal more difficult, and thus necessitating early birth so that a substantial portion of cranial expansion could take place outside the womb (Schultz, 1949; Rosenberg and Trevathan, 1995). Another explanation is that it may be maternal metabolic constraints rather than cephalopelvic proportion that determine the timing of birth in humans (Dunsworth et al., 2012). In either interpretation, both reinforce the idea that birth timing is a negotiation between the requirements of the fetus and the mother, not linked to a precise degree of neural development. Evolution can then act as a filter, with surviving individuals possessing overall organizational properties robust to commonly occurring variation. The comparative record shows that variation in the timing of birth with respect to neural maturation is very broad, both in widely separated taxonomic groups, but also in relatively closely related species, such as current chimpanzees and humans. Therefore, we may ask, what features of developmental patterns for neural maturation versus environmental learning will be most robust to this challenge?

34.3.3 Human Weaning in Its Primate and Mammalian Contexts

The transition from suckling to independent feeding constitutes a major shift in the behavioral and cognitive capacities required for survival (Lee, 1996). Knowing the stage of brain maturity at which weaning takes place is therefore of clear benefit for understanding the relationship between development of the nervous system and life history adaptations. And by situating weaning in a developmental plan that is normalized across species, we can make principled comparisons between species or taxa.

Our analysis shows that weaning, such as birth, is an event that is variable and uncoupled from the highly coordinated schedule of brain development (Fig. 34.10). An animal that can no longer depend on its mother for energetic input must be able to supplement its diet with other sources of nutrition, and this requires a degree of cognitive and behavioral competence that allows for the independent acquisition and ingestion of foods. And because many of these forms of competence, particularly the early-developing ones, will be synchronized with brain development, any variability in the timing of weaning for a species is likely to be associated with the duration of developmental time over which a young individual of that species is able to get support from its social group.

In a cross-cultural survey of weaning practices, the median age of weaning across 133 nonindustrial societies was reported to be 29 months postbirth, with a standard deviation of 10 months (Sellen, 2001). In traditional societies, earlier weaning is associated with shorter interbirth intervals. Early weaning should be conducive to higher reproductive output, all other things being held equal. As an illustration of how late weaning can be when initiated by the child, it has been reported in a large sample of US mothers that the average age of child-led weaning is 4.4 years, or 53 months (Dettwyler, 2004), which is much later than

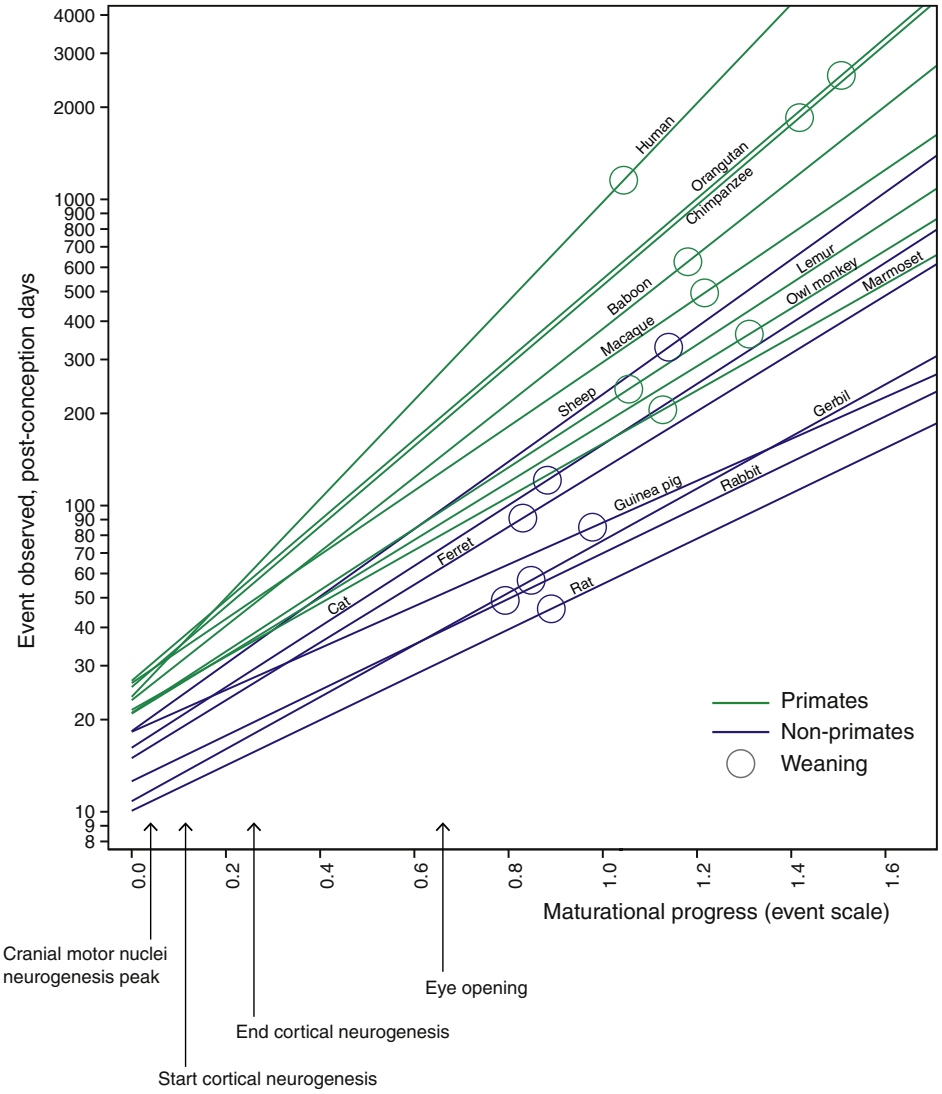

FIGURE 34.10 Variability in weaning compared to neural maturational state. Predicted developmental schedules for eight primate and seven nonprimate species, with observed timing of weaning indicated for each. The event scale on the x-axis has been extended beyond its original range of 0–1, to allow for extrapolation of developmental trajectories into the range in which weaning occurs. Examples of events included in the model are displayed at their respective positions on the event scale, on the x-axis. The y-axis indicates the estimated date of the occurrence of each event in each species. Plotted species include those whose developmental schedules are directly predicted by the model as well as those that are not. The latter consists of all of the primates except for the human and rhesus macaque, which are the two primates included in the current version of model. For the unmodeled primate species, we used adult brain weight to estimate slope and gestation length to estimate intercept, as these variables have been shown to predict the timing of events with reasonable accuracy. Timing of weaning in postconception days and associated references for each species are as follows: baboon (*Papio cynocephalus*), 625.5, Jones et al. (2009); cat (*Felis catus*), 121, Tacutu et al. (2013); chimpanzee (*Pan troglodytes*), 1849, Robson and Wood (2008); ferret (*Mustela putorius*), 91, Isler and van Schaik (2012); gerbil (*Meriones unguiculatus*), 49, Tacutu et al. (2013); guinea pig (*Cavia porcellus*), 85, Jones et al. (2009); hamster (*Mesocricetus auratus*), 34, Jones et al. (2009); human (*Homo sapiens*), 1140, Sellen (2001); lemur (*Lemur catta*), 240, Rowe (1996); macaque (*Macaca mulatta*), 495, Promislow (1991); marmoset (*Callithrix jacchus*), 205.5, Tacutu et al. (2013); Orangutan (*Pongo pygmaeus pygmaeus*), 2540, Barrickman (2008); owl monkey (*Aotus azarae*), 363, Jones et al. (2009); rabbit (*Oryctolagus cuniculus*), 57, Jones et al. (2009); rat (*Rattus norvegicus*), 46, Tacutu et al. (2013); sheep (*Ovis aries*), 329, Tacutu et al. (2013).

the nonindustrial average noted earlier, and significantly later than the median weaning age for US mothers, which is around 7 months (CDC).

If we compare any of these measures, even the latest reported, to reported weaning ages for other apes, such as the Western gorilla at around 3 years and the chimpanzee at 4–5 years, we see that weaning is earlier in humans, as has been emphasized by many researchers studying human life history evolution (Kennedy, 2005; Promislow, 1991; Reichard and Barelli, 2008). But this observation is based on absolute duration. If we examine allometric predictions for these species compared to brain maturation,

we see that humans are weaned even earlier than the linear projection would suggest. So, it is the case that humans are weaned significantly earlier than other primates. Considering all mammals, and not only primates, however, humans are weaned at a maturational point well within general mammalian variability (Figs. 34.3 and 34.10).

34.3.4 The Serial Litter and the Social World

One popular anthropological writer went so far as to characterize human reproduction, compared to other primates, as a "serial litter" (Morris, 2012). Having one offspring maturing at a time, with the long duration of development that a big brain seems to absolutely require, as we discussed in the earlier sections, with an 8–9 year interbirth interval is a low-output reproductive strategy that seems risky at best. So, humans have made two alterations in reproduction associated with the "serial litter" strategy, not only the early weaning observed by anthropologists, but also the relatively shortened gestation with respect to neural maturation we describe. Both of these are methods of reducing unique maternal investment to tractable levels, depending on either biparental care, or other alloparenting in the early postnatal period and progressively more as childhood progresses (Hrdy, 2011). One particularly attractive idea about a reliable source of alloparental care is the "grandmother hypothesis," which links late aspects of maternal life history to human altriciality and early weaning together (Hawkes et al., 1998). Female fertility ends at the same (absolute) age in humans as it does in other great apes (Robson et al., 2006; Robbins et al., 2006). Unlike other great ape females, however, women remain productive for decades longer: great apes become frail and rarely survive to menopause, while even in hunter-gatherer populations (where mortality is relatively high) about a third of the women are past the child-bearing years (Blurton Jones et al., 2002; Blurton Jones, 2016; Hawkes, 2003, 2010). The linkage of postmenopausal longevity is combined with weaning ages early compared to other primates may be the critical source of the markedly increased reproductive productivity in humans.

In contrast to this essentially economic rationale, an alternate interpretation of relatively early birth combined with a long developmental duration is that extended development is critical for some aspect of learning or cognition, with language learning the most obvious candidate (Bjorklund, 1997; Locke and Bogin, 2006). While it is possible that this is the case, several arguments can be martialed against any such single-factor causal scenario. Language experience can be quite variable: cross-culturally, while infant-directed speech has several hallmark similarities (Broesch and Bryant, 2015), aspects like the total amount of speech can be widely variable (Bornstein et al., 2015), and the rate of acquisition of markers of language maturity can vary widely by socioeconomic status (Fernald et al., 2013). Finally, large brains and long development are indissociable (Charvet and Finlay, 2012), and language is a necessary outcome of neither.

One of the most profound differences in human development, however, we suggest, is the changed social environment produced by early weaning. A long period of development results, with the brain positioned during the entire time for maximum learning, from early childhood to adolescence, where the infant and child is not being solely provisioned by the mother, but most typically by a larger group, from grandmothers, to the minimal "nuclear family" to much more extended related and nonrelated groups. Humans have an extended childhood where language, custom, and allegiance are being defined by an extended social group, not by the immediate parents. This allegiance to a peer group is often made over the complaints of the parents (Locke and Bogin, 2006). So it may be that an essentially economic decision, to limit maternal investment to a viable amount, may be one foundation of our extensive and very unusual sociality.

This economic decision thrusts the human child, unlike other primates, in the early parts of its "sensitive period" of development of any number of sensory, cognitive, motor, and social abilities out of the small society of mother and child, and into the village of age peers, other relatives, and any number of unrelated others. While much evidence suggests relatively greater attunement of the human child for social interaction, imitation, and cooperation (examples from a large literature: Bullinger et al., 2011; Haun et al., 2014; Tomasello, 1999), it is not only the motivations and preferences of the child that differ from its primate ancestors. Possessed of an exceptionally large brain constructed in a primate-typical schedule, with an allometrically predictable extended period of maturation filtered by evolution to be permissive of variability, the human child exercises those motivations and preferences in social environments more variable in every respect than those of any immediate primate relative. The developmental niche we inhabit is thus a curious mixture of a conserved neurodevelopmental schedule and a specially adapted life history.

References

Aggarwal, M., Gobius, I., Richards, L.J., Mori, S., 2015. Diffusion MR microscopy of cortical development in the mouse embryo. Cereb. Cortex 25, 1970–1980.

Alberts, J.R., Ronca, A.E., 1993. Fetal experience revealed by rats - psychobiological insights. Early Hum. Dev. 35, 153–166.

Allendoerfer, K.L., Shatz, C.J., 1994. The subplate, a transient neocortical structure. Annu. Rev. Neurosci. 17, 185–218.

Allman, J.M., Tetreault, N.A., Hakeem, A.Y., Manaye, K.F., Semendeferi, K., Erwin, J.M., et al., 2010. The von Economo neurons in frontoinsular and anterior cingulate cortex in great apes and humans. Brain Struct. Funct. 214, 495–517.

Altman, J., Bayer, S.A., 1988. Development of the rat thalamus. I. Mosaic organization of the thalamic neuroepithelium. J. Comp. Neurol. 275, 346–377.

Altman, J., Bayer, S.A., 1988. Development of the rat thalamus. II. Time of origin and settling pattern of neurons derived from the anterior lobule of the thalamic neuroepithelium. J. Comp. Neurol. 275, 378–405.

Altman, J., Bayer, S.A., 1988. Development of the rat thalamus. III. Time of origin and settling pattern of neurons of the reticular nucleus. J. Comp. Neurol. 275, 406–428.

Amunts, K., Schleicher, A., Ditterich, A., Zilles, K., 2003. Broca's region: cytoarchitectonic asymmetry and developmental changes. J. Comp. Neurol. 465, 72–89.

Anderson, M.L., 2014. After Phrenology: neural reuse and the interactive brain. MIT Press, Cambridge.

Anderson, M.L., Kinnison, J., Pessoa, L., 2013. Describing functional diversity of brain regions and brain networks. Neuroimage 73, 50–58.

Azadbakht, H., Parkes, L.M., Haroon, H.A., Augath, M., Logothetis, N.K., de Crespigny, A., et al., 2015. Validation of high-resolution tractography against in vivo tracing in the macaque visual cortex. Cereb. Cortex 25, 4299–4309.

Barrickman, N.L., 2008. Evolutionary relationship between life history and brain growth in anthropoid primates. PhD Dissertation. Duke University.

Barrickman, N.L., Bastian, M.L., Isler, K., van Schaik, C.P., 2008. Life history costs and benefits of encephalization: a comparative test using data from long-term studies of primates in the wild. J. Hum. Evol. 54, 568–590.

Barton, R.A., Venditti, C., 2013. Human frontal lobes are not relatively large. Proc. Natl. Acad. Sci. 110, 9001–9006.

Bastian, A.J., 2006. Learning to predict the future: the cerebellum adapts feedforward movement control. Curr. Opin. Neurobiol. 16, 645–649.

Bates, E., Roe, K., 2001. Language Development in Children with Unilateral Brain Injury. In: Nelson, C.A., Luciana, M. (Eds.), Handbook of Developmental Cognitive Neuroscience. MIT Press, Cambridge, MA, pp. 281–307.

Bates, E., Thal, D., Finlay, B.L., Clancy, B., 2002. Early language development and its neural correlates. In: Segalowitz, S.J., Rapin, I. (Eds.), Child Neurology, vol. 8. Elsevier Science B.V., Amsterdam, pp. 109–1076.

Bayer, S.A., Altman, J., 1991. Neocortical Development. Raven Press, New York.

Bear, M.F., 2003. Bidirectional synaptic plasticity: from theory to reality. Philos. Trans. R. Soc. Lond. B Biol. Sci. 358, 649–655.

Beauchemin, M., Gonzalez-Frankenberger, B., Tremblay, J., Vannasing, P., Martinez-Montes, E., Belin, P., et al., 2011. Mother and stranger: an electrophysiological study of voice processing in newborns. Cereb. Cortex 21, 1705–1711.

Ben-Ari, Y., 2002. Excitatory actions of gaba during development: the nature of the nurture. Nat. Rev. Neurosci. 3, 728–739.

Berardi, N., Pizzorusso, T., Maffei, L., 2000. Critical periods during sensory development. Curr. Opin. Neurobiol. 10, 138–145.

Bi, G.-Q., Poo, M.-M., 2001. Synaptic modification by correlated activity: Hebb's postulate revisited. Annu. Rev. Neurosci. 24, 139–166.

Bjorklund, D.F., 1997. The role of immaturity in human development. Psychol. Bull. 122, 153.

Blass, E.M., 1987. Critical events during sensitive periods of social development in rats. In: Bornstein, M.H. (Ed.), Sensitive Periods in Development: Interdisciplinary Perspectives. Psychology Press, New York, pp. 81–91.

Blue, M.E., Parnevelas, J.G., 1983. The formation and maturation of synapses in the visual cortex of the rat: quantitatve analysis. J. Neurocytol. 12, 697–712.

Bluml, S., Wisnowski, J.L., Nelson, M.D., Paquette, L., Gilles, F.H., Kinney, H.C., et al., 2013. Metabolic maturation of the human brain from birth through adolescence: insights from in vivo magnetic resonance spectroscopy. Cereb. Cortex 23, 2944–2955.

Blurton Jones, N.G., 2016. Demography and Evolutionary Ecology of Hadza Hunter-Gatherers. Cambridge University Press, Cambridge.

Blurton Jones, N.G., Hawkes, K., O'Connell, J.F., 2002. Antiquity of post-reproductive life: are there modern impacts on hunter-gatherer post-reproductive life spans? Am. J. Hum. Biol. 14 (2), 184–205.

Bornstein, M.H., Putnick, D.L., Cote, L.R., Haynes, O.M., Suwalsky, J.T.D., 2015. Mother-infant contingent vocalizations in 11 countries. Psychol. Sci. 28, 1272–1284.

Bourgeois, J.P., Goldman-Rakic, P.S., Rakic, P., 1994. Synaptogenesis in the prefrontal cortex of rhesus monkeys. Cereb. Cortex 4, 78–96.

Bourgeois, J.P., Jastreboff, P.J., Rakic, P., 1989. Synaptogenesis in visual cortex of normal and preterm monkey: evidence for intrinsic regulation of synaptic overproduction. Proc. Natl. Acad. Sci. U.S.A. 86, 4297–4301.

Bourgeois, J.P., Rakic, P., 1993. Changes of synaptic density in the primary visual cortex of the macaque monkey from fetal to adult stage. J. Neurosci. 13, 2801–2820.

Brand, S., Rakic, P., 1979. Cytodifferentiation and synaptogenesis in the neostriatum of fetal and neonatal rhesus monkeys. Anat. Embryol. 169, 21–34.

Brauer, J., Anwander, A., Friederici, A.D., 2011. Neuroanatomical prerequisites for language functions in the maturing brain. Cereb. Cortex 21, 459–466.

Broesch, T.L., Bryant, G.A., 2015. Prosody in infant-directed speech is similar across western and traditional cultures. J. Cognition Dev. 16, 31–43.

Brown, K.E., Arends, J.J.A., Wasserstrom, S.P., Zantua, J.B., Jacquin, M.F., Woolsey, T.A., 1995. Developmental transformation of dendritic arbors in mouse whisker thalamus. Dev. Brain Res. 86, 335–339.

Bryant, K.L., Suwyn, C., Reding, K.M., Smiley, J.F., Hackett, T.A., Preuss, T.M., 2012. Evidence for ape and human specializations in geniculostriate projections from VGLUT2 immunohistochemistry. Brain Behav. Evol. 80, 210–221.

Bullinger, A.F., Zimmermann, F., Kaminski, J., Tomasello, M., 2011. Different social motives in the gestural communication of chimpanzees and human children. Dev. Sci. 14, 58–68.

Burr, D., Cicchini, G.M., 2014. Vision: efficient adaptive coding. Curr. Biol. 24, R1096–R1098.

Burton, H., Snyder, A.Z., Conturo, T.E., Akbudak, E., Ollinger, J.M., Raichle, M.E., 2002. Adaptive changes in early and late blind: a fMRI study of Braille reading. J. Neurophysiol 87, 589–607.

Cahalane, D.J., Charvet, C.J., Finlay, B.L., 2012. Systematic, balancing gradients in neuron density and number across the primate isocortex. Front Neuroanat 6, 28.

Cahalane, D.J., Charvet, C.J., Finlay, B.L., 2014. Modeling local and cross-species neuron number variations in the cerebral cortex as arising from a common mechanism. Proc. Natl. Acad. Sci. 111, 17642–17647.

Cancedda, L., Fiumelli, H., Chen, K., Poo, M.M., 2007. Excitatory GABA action Is essential for morphological maturation of cortical neurons in vivo. J. Neurosci. 27, 5224–5235.

Casey, B.J., Tottenham, N., Liston, C., Durston, S., 2005. Imaging the developing brain: what have we learned about cognitive development? Trends Cognit. Sci. 9, 104–110.

Caviness, V.S., Takahashi, T., Nowakowski, R.S., 1995. Numbers, time and neocortical neuronogenesis: a general developmental and evolutionary model. Trends Neurosci. 18, 379–383.

Chalfin, B.P., Cheung, D.T., Muniz, J.A.P.C., Silveira, L.C.L., Finlay, B.L., 2007. Scaling of neuron number and volume of the pulvinar complex in New World primates: comparisons with humans, other primates and mammals. J. Comp. Neurol. 504, 265–274.

Chaplin, T.A., Yu, H.-H., Soares, J.G.M., Gattass, R., Rosa, M.G.P., 2013. A conserved pattern of differential expansion of cortical areas in simian primates. J. Neurosci. 33, 15120–15125.

Charnov, E.L., Downhower, J.F., 1995. A trade-off-invariant life-history rule for optimal offspring size. Nature 376, 418–419.

Charvet, C.J., Cahalane, D.J., Finlay, B.L., 2014. Systematic, cross-cortex variation in neuron numbers in rodents and primates. Cereb. Cortex 25, 147–160.

Charvet, C.J., Finlay, B.L., 2012. Embracing covariation in brain evolution: large brains, extended development, and flexible primate social systems. In: Michel, A.H., Dean, F. (Eds.), Progress in Brain Research, vol. 195. Elsevier, pp. 71–87.

Charvet, C.J., Finlay, B.L., 2014. Evo-Devo and the primate isocortex: the central organizing role of intrinsic gradients of neurogenesis. Brain. Behav. Evol. 84, 81–92.

Choe, M.-S., Ortiz-Mantilla, S., Makris, N., Gregas, M., Bacic, J., Haehn, D., et al., 2013. Regional infant brain development: an MRI-based morphometric analysis in 3 to 13 month olds. Cereb. Cortex 23, 2100–2117.

Clancy, B., Darlington, R.B., Finlay, B.L., 2000. The course of human events: predicting the timing of primate neural development. Dev. Sci. 3, 57–66.

Clancy, B., Darlington, R.B., Finlay, B.L., 2001. Translating developmental time across mammalian species. Neuroscience 105, 7–17.

Clancy, B., Kersh, B., Hyde, J., Anand, K.J.S., Darlington, R.B., Finlay, B.L., 2007. Web-based method for translating neurodevelopment from laboratory species to humans. Neuroinformatics 5, 79–94.

Clayton, D.F., 2013. The genomics of memory and learning in songbirds. Annu. Rev. Genomics Hum. Genet. 14, 45–65.

Cohen, A.O., Breiner, K., Steinberg, L., Bonnie, R.J., Scott, E.S., Taylor-Thompson, K.A., et al., 2016. When is an adolescent an adult? Assessing cognitive control in emotional and nonemotional contexts. Psychol. Sci. 27 (4) (Online).

Cohen Kadosh, K., Cohen Kadosh, R., Dick, F., Johnson, M.H., 2011. Developmental changes in effective connectivity in the emerging core face network. Cereb. Cortex 21, 1389–1394.

Conrad, M.S., Dilger, R.N., Johnson, R.W., 2012. Brain growth of the domestic pig(*sus scrofa*) from 2 to 24 weeks of age: a longitudinal MRI study. Dev. Neurosci. 34, 291–298.

Coqueugniot, H., Hublin, J.-J., Veillon, F., Houët, F., Jacob, T., 2004. Early brain growth in Homo erectus and implications for cognitive ability. Nature 431, 299–302.

Croteau-Chonka, E.C., Dean, D.C., Remer, J., Dirks, H., O'Muircheartaigh, J., Deoni, S.C.L., 2016. Examining the relationships between cortical maturation and white matter myelination throughout early childhood. Neuroimage 125, 413–421.

Damaraju, E., Caprihan, A., Lowe, J.R., Allen, E.A., Calhoun, V.D., Phillips, J.P., 2014. Functional connectivity in the developing brain: a longitudinal study from 4 to 90 months of age. Neuroimage 84, 169–180.

Darlington, R.B., Dunlop, S.A., Finlay, B.L., 1999. Neural development in metatherian and eutherian mammals: variation and constraint. J. Comp. Neurol. 411, 359–368.

de Haan, M., Humphreys, K., Johnson, M.H., 2002. Developing a brain specialized for face perception: a converging methods approach. Dev. Psychobiol. 40, 200–212.

Dehay, C., Kennedy, H., Kosik, K.S., 2015. The outer subventricular zone and primate-specific cortical complexification. Neuron 85, 683–694.

Dettwyler, K.A., 2004. When to wean: biological versus cultural perspectives. Clin. Obstetr. Gynecol 47, 712–723.

Dick, F., Lee, H.L., Nusbaum, H., Price, C.J., 2011. Auditory-motor expertise alters "speech selectivity" in professional musicians and actors. Cereb. Cortex 21, 938–948.

Donahue, C.J., Sotiropoulos, S.N., Jbabdi, S., Hernandez-Fernandez, M., Behrens, T.E., Dyrby, T.B., Coalson, T., Kennedy, H., Knoblauch, K., Van Essen, D.C., Glasser, M.F., 2016. Using diffusion tractography to predict cortical connection strength and distance: a quantitative comparison with tracers in the monkey. J. Neurosci. 36, 6758–6770.

Doya, K., 2001. Complementary roles of basal ganglia and cerebellum in learning and motor control. Curr. Opin. Neurobiol. 10, 20–58.

Dreher, B., Robinson, S.R., 1988. Development of the retinofugal pathway in birds and mammals: evidence for a common timetable. Brain. Behav. Evol. 31, 369–390.

Dunsworth, H.M., Warrener, A.G., Deacon, T., Ellison, P.T., Pontzer, H., 2012. Metabolic hypothesis for human altriciality. Proc. Natl. Acad. Sci. 109, 15212–15216.

Eckenhoff, M.F., Rakic, P., 1991. A quantitative analysis of synaptogenesis in the molecular layer of the dentate gyrus in the rhesus monkey. Dev. Brain Res. 64, 129–135.

Elman, J.L., 1993. Learning and development in neural networks: the importance of starting small. Cognition 48, 71–99.

Elman, J.L., Bates, E.A., Johnson, M.H., Karmiloff-Smith, A., Parisi, D., Plunkett, K., 1996. Rethinking Innateness: a connectionist perspective on development. MIT Press, Cambridge, MA.

Fernald, A., Marchman, V.A., Weisleder, A., 2013. SES differences in language processing skill and vocabulary are evident at 18 months. Dev. Sci. 16, 234–248.

Fields, R.D., 2015. A new mechanism of nervous system plasticity: activity-dependent myelination. Nat. Rev. Neurosci. 16, 756–767.

Finlay, B.L., 1991. Control of cell number and type in the developing and evolving neocortex. In: Finlay, B.L., Innocenti, G., Scheich, H. (Eds.), The Neocortex: Ontogeny and Phylogeny NATO ASI Series. Plenum Press, New York, pp. 33–41.

Finlay, B.L., 1992. Cell death and the creation of regional differences in neuronal numbers. J. Neurobiol. 23, 1159–1171.

Finlay, B.L., Darlington, R.B., 1995. Linked regularities in the development and evolution of mammalian brains. Science 268, 1578–1584.

Finlay, B.L., Innocenti, G., Scheich, H., 1991. The neocortex: ontogeny and phylogeny. Plenum Press, New York.

Finlay, B.L., Silveira, L.C.L., Reichenbach, A., 2005. Comparative Aspects of Visual System Development. In: Kremers, J. (Ed.), The Structure, Function and Evolution of the Primate Visual System. John Wiley and Sons, New York, pp. 37–72.

Finlay, B.L., Slattery, M., 1983. Local differences in amount of early cell death in neocortex predict adult local specializations. Science 219, 1349–1351.

Finlay, B.L., Uchiyama, R., 2015. Developmental mechanisms channeling cortical evolution. Trends Neurosci. 38, 69–76.

Finlay, B.L., Workman, A.D., 2013. Human exceptionalism. Trends Cognit. Sci. 17, 199–201.

Fitch, W.T., Reby, D., 2001. The descended larynx is not uniquely human. Proc. R. Soc. Lond. B 268, 1669–1675.

Florence, S.L., Jain, N., Kaas, J.H., 1997. Plasticity of somatosensory cortex in primates. Semin. Neurosci. 9, 3–12.

Foster, R.E., Connors, B.W., Waxman, S.G., 1982. Rat optic nerve: electrophysiological, pharmacological and anatomical studies during development. Dev. Brain Res. 3, 371–386.

Gao, W., Alcauter, S., Elton, A., Hernandez-Castillo, C.R., Smith, J.K., Ramirez, J., et al., 2015. Functional network development during the first year: relative sequence and socioeconomic correlations. Cereb. Cortex 25, 2919–2928.

Garwicz, M., Christensson, M., Psouni, E., 2009. A unifying model for timing of walking onset in humans and other mammals. Proc. Natl. Acad. Sci. 106, 21889–21893.

Ge, X., Shi, Y., Li, J., Zhang, Z., Lin, X., Zhan, J., et al., 2015. Development of the human fetal hippocampal formation during early second trimester. Neuroimage 119, 33–43.

Geerligs, L., Renken, R.J., Saliasi, E., Maurits, N.M., Lorist, M.M., 2015. A brain-wide study of age-related changes in functional connectivity. Cereb. Cortex 25, 1987–1999.

Giedd, J.N., Blumenthal, J., Jeffries, N.O., Castellanos, F.X., Liu, H., Zijdenbos, A., et al., 1999. Brain development during childhood and adolescence: a longitudinal MRI study. Nat. Neurosci. 2, 861–863.

Giedd, J.N., Castellanos, F.X., Rajapakse, J.C., Vaituzis, A.C., Rapoport, J.L., 1997. Sexual dimorphism of the developing human brain. Prog. Neuro Psychopharmacol. Biol. Psychiatry 21, 1185–1201.

Giedd, J.N., Rapoport, J.L., 2010. Structural MRI of pediatric brain development: what have we learned and where are we going? Neuron 67, 728–734.

Giedd, J.N., Snell, J.W., Lange, N., Rajapakse, J.C., Casey, B.J., Kozuch, P.L., et al., 1996. Quantitative magnetic resonance imaging of human brain development: ages 4-18. Cereb. Cortex 6, 551–560.

Gilbert, C.D., Li, W., 2012. Adult visual cortical plasticity. Neuron 75, 250–264.

Gilbert, C.D., Li, W., 2013. Top-down influences on visual processing. Nat. Rev. Neurosci. 14, 350–363.

Gilmore, J.H., Shi, F., Woolson, S.L., Knickmeyer, R.C., Short, S.J., Lin, W., et al., 2012. Longitudinal development of cortical and subcortical gray matter from birth to 2 years. Cereb. Cortex 22, 2478–2485.

Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., et al., 2004. Dynamic mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. U.S.A. 101, 8174–8179.

Goldman-Rakic, P.S., 1987. Development of cortical circuitry and cognitive function. Child Dev. 58, 601–622.

Goodson, J.L., Thompson, R.R., 2010. Nonapeptide mechanisms of social cognition, behavior and species-specific social systems. Curr. Opin. Neurobiol. 20, 784–794.

Gould, S.J., 1977. Ontogeny and Phylogeny. Harvard University Press, Cambridge, Massachusetts.

Graybiel, A.M., 2008. Habits, rituals, and the evaluative brain. Annu. Rev. Neurosci. 31, 359–387.

Graybiel, A.N., 1998. The basal ganglia and chunking of action repertoires. Neurobiol. Learn. Mem. 70, 119–136.

Greene, D.J., Laumann, T.O., Dubis, J.W., Ihnen, S.K., Neta, M., Power, J.D., et al., 2014. Developmental changes in the organization of functional connections between the basal ganglia and cerebral cortex. J. Neurosci. 34, 5842–5854.

Gu, S., Satterthwaite, T.D., Medaglia, J.D., Yang, M., Gur, R.E., Gur, R.C., et al., 2015. Emergence of system roles in normative neurodevelopment. Proc. Natl. Acad. Sci. 112, 13681–13686.

Gunnar, M., Quevedo, K., 2006. The neurobiology of stress and development. Annu. Rev. Psychol. 58, 145–173.

Habas, P.A., Scott, J.A., Roosta, A., Rajagopalan, V., Kim, K., Rousseau, F., et al., 2012. Early folding patterns and asymmetries of the normal human brain detected from in utero MRI. Cereb. Cortex 22, 13–25.

Halley, A.C., 2015. Meta-analysis of ontogenetic brain/body allometry across mammals: implications for primate encephalization and fetal growth theories of relative brain size. Brain Behav. Evol. 85, 287–293.

Halley, A.C., 2016. Prenatal brain-body allometry in mammals. Brain Behav. Evol. 88 (1), 14–24.

Hamasaki, T., Leingärtner, A., Ringstedt, T., O'Leary, D.D., 2004. EMX2 regulates sizes and positioning of the primary sensory and motor areas in neocortex by direct specification of cortical progenitors. Neuron 43, 359–372.

Hammelrath, L., Škokić, S., Khmelinskii, A., Hess, A., van der Knaap, N., Staring, M., et al., 2016. Morphological maturation of the mouse brain: an in vivo MRI and histology investigation. Neuroimage 125, 144–152.

Haun, D.B.M., Rekers, Y., Tomasello, M., 2014. Children conform to the behavior of peers; Other great apes stick with what they know. Psychol. Sci. 25, 2160–2167.

Hawkes, K., 2003. Grandmothers and the evolution of human longevity. Am. J. Hum. Biol. 15, 380–400.

Hawkes, K., 2010. How grandmother effects plus individual variation in frailty shape fertility and mortality: guidance from human–chimpanzee comparisons. Proc. Nat. Acad. Sci. U.S.A. 107 (Suppl. 2), 8977–8984.

Hawkes, K., O'Connell, J.F., Jones, N.B., Alvarez, H., Charnov, E.L., 1998. Grandmothering, menopause, and the evolution of human life histories. Proc. Natl. Acad. Sci. 95, 1336–1339.

Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2000. The distributed human neural system for face perception. Trends Cognit. Sci. 4, 223–233.

Hedden, T., Schultz, A.P., Rieckmann, A., Mormino, E.C., Johnson, K.A., Sperling, R.A., et al., 2016. Multiple brain markers are linked to age-related variation in cognition. Cereb. Cortex 26, 1388–1400.

Hensch, T.K., 2004. Critical period regulation. Annu. Rev. Neurosci. 27, 549–579.

Hofman, M.A., 1989. On the evolution and geometry of the brain in mammals. Prog. Neurobiol. 32, 137–158.

Hoskins, S.G., 1990. The metamorphosis of the amphibian eye. J. Neurobiol. 21, 970–989.

Hrdy, S.B., 2011. Mothers and others: the evolutionary origins of mutual understanding. Harvard University Press, Massachusetts.

Huang, H., Jeon, T., Sedmak, G., Pletikos, M., Vasung, L., Xu, X., et al., 2013. Coupling diffusion imaging with histological and gene expression analysis to examine the dynamics of cortical areas across the fetal period of human brain development. Cereb. Cortex 23, 2620–2631.

Huang, X., Stodieck, S.K., Goetze, B., Cui, L., Wong, M.H., Wenzel, C., Hosan, L., Dong, Y., Lowel, S., Schlüter, O.M., 2015. Progressive maturation of silent synapses governs the duration of a critical period. Proc. Natl. Acad. Sci. 112, E3131–E3140.

Hübener, M., Bonhoeffer, T., 2014. Neuronal plasticity: beyond the critical period. Cell 159, 727–737.

Huttenlocher, P.R., Dabholkar, A.S., 1997. Regional differences in synaptogenesis in human cerebral cortex. J. Comp. Neurol. 387, 167–178.

Huttenlocher, P.R., de Courten, C., Garey, L.J., Van der Loos, H., 1982. Synaptogenesis in human visual cortex – evidence for synapse elimination during normal development. Neurosci. Lett. 33, 247–252.

Ingalhalikar, M., Parker, D., Ghanbari, Y., Smith, A., Hua, K., Mori, S., et al., 2015. Connectome and maturation profiles of the developing mouse brain using diffusion tensor imaging. Cereb. Cortex 25, 2696–2706.

Innocenti, G.M., Price, D.J., 2005. Exuberance in the development of cortical networks. Nat. Rev. Neurosci. 6, 955–965.

Isler, K., van Schaik, C.P., 2009. Why are there so few smart mammals (but so many smart birds)? Biol. Lett. 5, 125–129.

Isler, K., van Schaik, C.P., 2012. Allomaternal care, life history and brain size evolution in mammals. J. Hum. Evol. 63, 52–63.

Ivy, G.O., Killackey, H.P., 1981. The ontogeny of the distribution of callosal projection neurons in the rat parietal cortex. J. Comp. Neurol. 195, 367–389.

Janowsky, J.S., Finlay, B.L., 1983. Cell degeneration in the early development of forebrain and cerebellum. Anat. Embryol. 167, 439–447.

Janowsky, J.S., Finlay, B.L., 1986. Normal neuron loss and axon retraction in early development: their significance for the outcome of perinatal brain damage. Dev. Med. Child Neurol. 28, 375–389.

Jbabdi, S., Sotiropoulos, S.N., Haber, S.N., Van Essen, D.C., Behrens, T.E., 2015. Measuring macroscopic brain connections in vivo. Nat. Neurosci. 18, 1546–1555.

Jerison, H.J., 1973. Evolution of the Brain and Intelligence. Academic Press, New York.
Jerison, H.J., 1997. Evolution of prefrontal cortex. In: Krasnegor, N.A., Lyon, G.R., Goldman-Rakic, P.S. (Eds.), Development of the Prefrontal Cortex: Evolution, Neurobiolgy and Behavior. Pall H. Brooks Publishing Co., Baltimore, pp. 9–26.
Johnson, M.H., 2005. Subcortical face processing. Nat. Rev. Neurosci. 6, 766–774.
Jones, K.E., Orme, K.E., Safi, K., Sechrest, W., Boakes, E.H., et al., 2009. PanTHERIA: a species-level database of life history, ecology, and geography of extant and recently extinct mammals. Ecology 90, 2648–2700.
Jusczyk, P.W., Friederici, A.D., Wessels, J.M.I., Svenkerud, V., Jusczyk, A.M., 1993. Infants' sensitivity to the sound pattern of native-language words. J. Mem. Lang. 32, 402–420.
Kaas, J.H., 1997. Topographic maps are fundamental to sensory processing. Brain Res. Bull. 44, 107–112.
Kang, H.J., Kawasawa, Y.I., Cheng, F., Zhu, Y., Xu, X., Li, M., et al., 2011. Spatio-temporal transcriptome of the human brain. Nature 478, 483–489.
Katz, L.C., Crowley, J.C., 2002. Development of cortical circuits: lessons from ocular dominance columns. Nat. Rev. Neurosci. 3, 34–42.
Kennedy, G.E., 2005. From the ape's dilemma to the weanling's dilemma: early weaning and its evolutionary context. J. Hum. Evol. 48, 123–145.
Kiecker, C., Lumsden, A., 2012. The role of organizers in patterning the nervous system. Annu. Rev. Neurosci. 35, 347–367.
Konishi, M., 2003. Coding of auditory space. Annu. Rev. Neurosci. 26, 31–55.
Kuklisova-Murgasova, M., Aljabar, P., Srinivasan, L., Counsell, S.J., Doria, V., Serag, A., et al., 2011. A dynamic 4D probabilistic atlas of the developing brain. Neuroimage 54, 2750–2763.
LaMantia, A.-S., Rakic, P., 1990. Axon overproduction and elimination in the corpus callosum of the developing rhesus monkey. J. Neurosci. 10, 2156–2175.
Lee, P.C., 1996. The meanings of weaning: growth, lactation, and life history. Evol. Anthropol. Issues News Rev. 5, 87–98.
Leroy, F., Glasel, H., Dubois, J., Hertz-Pannier, L., Thirion, B., Mangin, J.-F., et al., 2011. Early maturation of the linguistic dorsal pathway in human infants. J. Neurosci. 31, 1500–1506.
Levi, D.M., Knill, D.C., Bavelier, D., 2015. Stereopsis and amblyopia: a mini-review. Vis. Res. 114, 17–30.
Li, G., Lin, W., Gilmore, J.H., Shen, D., 2015. Spatial patterns, longitudinal development, and hemispheric asymmetries of cortical thickness in infants from birth to 2 years of age. J. Neurosci. 35, 9150–9162.
Lieberman, P., 1984. The Biology and Evolution of Language. Harvard University Press, Cambridge, MA.
Lieven, E., Stoll, S., 2013. Early communicative development in two cultures: a comparison of the communicative environments of children from two cultures. Hum. Dev. 56, 178–206.
Locke, J.L., Bogin, B., 2006. Language and life history: a new perspective on the development and evolution of human language. Behav. Brain Sci. 29, 259–325.
London, S.E., Dong, S., Replogle, K., Clayton, D.F., 2009. Developmental shifts in gene expression in the auditory forebrain during the sensitive period for song learning. Dev. Neurobiol. 69, 437–450.
Lumsden, A., Krumlauf, R., 1996. Patterning the vertebrate neuraxis. Science 274, 1109–1115.
Mahmoudzadeh, M., Dehaene-Lambertz, G., Fournier, M., Kongolo, G., Goudjil, S., Dubois, J., et al., 2013. Syllabic discrimination in premature human infants prior to complete formation of cortical layers. Proc. Natl. Acad. Sci. 110, 4846–4851.
Makropoulos, A., Aljabar, P., Wright, R., Hüning, B., Merchant, N., Arichi, T., et al., 2016. Regional growth and atlasing of the developing human brain. Neuroimage 125, 456–478.
Mampe, B., Friederici, A.D., Christophe, A., Wermke, K., 2009. Newborns' cry melody is shaped by their native language. Curr. Biol. 19, 1994–1997.
May, A., 2011. Experience-dependent structural plasticity in the adult human brain. Trends Cognit. Sci. 15, 475–482.
McClelland, J.L., McNaughton, B.L., O'Reilly, R.C., 1995. Why there are complementary learning systems in the hippocampus and neocortex: insights from successes and failures of connectionist models of learning and memory. Psychol. Bull. 102, 419–457.
McMurray, B., 2007. Defusing the childhood vocabulary explosion. Science 317, 631.
Merabet, L.B., Pascual-Leone, A., 2010. Neural reorganization following sensory loss: the opportunity of change. Nat. Rev. Neurosci. 11, 44–52.
Miller, B., Nagy, D., Finlay, B.L., Chance, B., Kobayashi, A., Nioka, S., 1993. Consequences of reduced cerebral blood flow in brain development: I. Gross morphology, histology, and callosal connectivity. Exp. Neurol. 124, 326–342.
Miller, D.J., Duka, T., Stimpson, C.D., Schapiro, S.J., Baze, W.B., McArthur, M.J., et al., 2012. Prolonged myelination in human neocortical evolution. Proc. Natl. Acad. Sci. 109, 16480–16485.
Miller, J.A., Ding, S.-L., Sunkin, S.M., Smith, K.A., Ng, L., Szafer, A., et al., 2014. Transcriptional landscape of the prenatal human brain. Nature 508, 199–206.
Missler, M., Eins, S., Merker, H.J., Rothe, H., Wolff, J.R., 1993. Prenatal and postnatal development of the primary visual cortex of the common marmoset .1. a changing space for synaptogenesis. J. Comp. Neurol. 333, 41–52.
Moon, C., Lagercrantz, H., Kuhl, P.K., 2013. Language experienced in utero affects vowel perception after birth: a two-country study. Acta Paediatr. 102, 156–160.
Moriceau, S., Roth, T.L., Sullivan, R.M., 2010. Rodent model of infant attachment learning and stress. Dev. Psychobiol. 52, 651–660.
Morris, D., 2012. The Naked Man: A Study of the Male Body. Random House, New York.
Nathanielscz, P.W., 1998. Comparative studies on the initiation of labor. Eur. J. Obstetr. Gynecol. Reprod. Biol. 78, 127–132.
Newbury, D.F., Monaco, A.P., 2010. Genetic advances in the study of speech and language disorders. Neuron 68, 309–320.
Niewenhuys, R., 2012. The insular cortex: a review. In: Hofman, M.A., Falk, D. (Eds.), Evolution of the Primate Brain: From Neuron to Behavior, vol. 195. Elsevier, pp. 123–153.
O'Leary, D.D.M., Koester, S.E., 1993. Development of projection neuron types, axon pathways, and patterned connections of the mammalian cortex. Neuron 10, 991–1006.
Oishi, K., Faria, A.V., Yoshida, S., Chang, L., Mori, S., 2013. Quantitative evaluation of brain development using anatomical MRI and diffusion tensor imaging. Int. J. Dev. Neurosci. 31, 512–524.
Oishi, K., Nakagawa, N., Tachikawa, K., Sasaki, S., Aramaki, M., Hirano, S., et al., 2016. Identity of neocortical layer 4 neurons is specified through correct positioning into the cortex. eLife 5, e10907.
Oppenheim, R.W., 1991. Cell death during development of the nervous system. Annu. Rev. Neurosci. 14, 453–502.
Pagel, M.D., Harvey, P.H., 1988. How mammals produce large-brained offspring. Evolution 101, 948–957.
Pandit, A.S., Robinson, E., Aljabar, P., Ball, G., Gousias, I.S., Wang, Z., et al., 2014. Whole-brain mapping of structural connectivity in infants reveals altered connection strength associated with growth and preterm birth. Cereb. Cortex 24, 2324–2333.
Pascalis, O., Kelly, D.J., 2009. The origins of face processing in humans: phylogeny and ontogeny. Perspect. Psychol. Sci. 4, 200–209.
Passingham, R.E., 1985. Rates of brain development in mammals including man. Brain Behav. Evol. 26, 167–175.
Passingham, R.E., Smaers, J.B., 2014. Is the prefrontal cortex especially enlarged in the human brain allometric relations and remapping factors. Brain Behav. Evol. 84, 156–166.

Petanjek, Z., Judas, M., Simic, G., Rasin, M.R., Uylings, H.B.M., Rakic, P., et al., 2011. Extraordinary neoteny of synaptic spines in the human prefrontal cortex. Proc. Natl. Acad. Sci. 108, 13281–13286.

Pfister, B.J., Iwata, A., Meaney, D.F., Smith, D.H., 2004. Extreme stretch growth of integrated axons. J. Neurosci. 24, 7978–7983.

Pletikos, M., Sousa, A.M.M., Sedmak, G., Meyer, K., Zhu, Y., Cheng, F., et al., 2014. Temporal specification and bilaterality of human neocortical topographic gene expression. Neuron 81, 321–332.

Promislow, D.E., 1991. Senescence in natural populations of mammals: a comparative study. Evolution 1010, 1869–1887.

Pulvermüller, F., Schumann, J.H., 1994. Neurobiological mechanisms of language acquisition. Lang. Learn. 44, 681–734.

Rajagopalan, V., Scott, J., Habas, P.A., Kim, K., Corbett-Detig, J., Rousseau, F., et al., 2011. Local tissue growth patterns underlying normal fetal human brain gyrification quantified in utero. J. Neurosci. 31, 2878–2887.

Rakic, P., 1974. Neurons in the rhesus monkey visual cortex: systematic relation between time of origin and eventual disposition. Science 183, 425–427.

Rakic, P., 1977. Genesis of the dorsal lateral geniculate nucleus in the rhesus monkey: site and time of origin, kinetics of proliferation, routes of migration and pattern of distribution of neurons. J. Comp. Neurol. 176, 23–52.

Rakic, P., 2002. Neurogenesis in adult primate neocortex: an evaluation of the evidence. Nat. Rev. Neurosci. 3, 65–71.

Rakic, P., Bourgeois, J.P., Goldman-Rakic, P.S., 1994. Synaptic development of the cerebral cortex: implications for learning, memory, and mental illness. Self Organ. Brain 102, 227–243.

Rakic, P., Bourgeouis, J.-P., Eckenhoff, M., Zecevic, N., Goldman-Rakic, P.S., 1986. Concurrent overproduction of synapses in diverse regions of the primate cerebral cortex. Science 232, 232–235.

Raznahan, A., Greenstein, D., Lee, N.R., Clasen, L.S., Giedd, J.N., 2012. Prenatal growth in humans and postnatal brain maturation into late adolescence. Proc. Natl. Acad. Sci. 109, 11366–11371.

Raznahan, A., Shaw, P., Lalonde, F., Stockman, M., Wallace, G.L., Greenstein, D., et al., 2011. How does your cortex grow? J. Neurosci. 31, 7174–7177.

Raznahan, A., Shaw, P.W., Lerch, J.P., Clasen, L.S., Greenstein, D., Berman, R., et al., 2014. Longitudinal four-dimensional mapping of subcortical anatomy in human development. Proc. Natl. Acad. Sci. 111, 1592–1597.

Reep, R., Darlington, R.B., Finlay, B.L., 2007. The limbic system in mammalian brain evolution. Brain Behav. Evol. 70, 57–70.

Reichard, U.H., Barelli, C., 2008. Life history and reproductive strategies of Khao Yai Hylobates lar: implications for social evolution in apes. Int. J. Primatol. 29, 823–844.

Robbins, A.M., Robbins, M.M., Gerald-Steklis, N., Steklis, H.D., 2006. Age-related patterns of reproductive success among female mountain gorillas. Am. J. Phys. Anthropol. 131, 511–521.

Robertson, S., Dierker, L., Sorokin, Y., Rosen, M., 1982. Human fetal movement: spontaneous oscillations near one cycle per minute. Science 218, 1327–1330.

Robson, S.L., Wood, B., 2008. Hominin life history: reconstruction and evolution. J. Anat. 212, 394–425.

Robson, S.L., van Schaik, C.P., Hawkes, K., 2006. The Derived Features of Human Life History. In: Hawkes, K., Paine, R.R. (Eds.), The Evolution of Human Life History. SAR Press, Santa Fe, USA, pp. 17–44.

Rodger, J., Dunlop, S.A., 2015. Central nerve regeneration in reptiles. Neural Regen 43, 1–24.

Rosenberg, K., Trevathan, W., 1995. Bipedalism and human birth: the obstetrical dilemma revisited. Evol. Anthropol. Issues News Rev. 4, 161–168.

Rowe, N., 1996. The Pictorial Guide to the Living Primates. Pogonias Press, New York.

Roy, B.C., Frank, M.C., DeCamp, P., Miller, M., Roy, D., 2015. Predicting the birth of a spoken word. Proc. Natl. Acad. Sci. 112, 12663–12668.

Royle, N.J., Smiseth, P.T., Kölliker, M., 2012. The Evolution of Parental Care. Oxford University Press, Oxford.

Saffran, J.R., Aslin, R.N., Newport, E.L., 1996. Statistical learning by 8-month-old infants. Science 274, 1926–1928.

Sakai, T., Matsui, M., Mikami, A., Malkova, L., Hamada, Y., Tomonaga, M., et al., 2013. Developmental patterns of chimpanzee cerebral tissues provide important clues for understanding the remarkable enlargement of the human brain. Proc. R. Soc. Biol. Sci. 280, 753–757.

Sanchez, M.M., Ladd, C.O., Plotsky, P., 2001. Early adverse experience as a developmental risk factor for later psychopathology: evidence from rodent and primate models. Dev. Psychopathol. 13, 419–449.

Sanes, J.R., Lichtman, J.W., 1999. Development of the vertebrate neuromuscular junction. Annu. Rev. Neurosci. 22, 389–442.

Schall, J.D., Leventhal, A.G., 1987. Relationships between ganglion cell dendritic structure and retinal topography in the cat. J. Comp. Neurol. 257, 149–159.

Scheibel, A.B., 1993. Dendritic Structure and Language Development. In: Boysson-Bardies, B., Schonen, S., Jusczyk, P., McNeilage, P., Morton, J. (Eds.), Developmental Neurocognition: Speech and Face Processing in the First Year of Life. Springer, Dordrecht, Netherlands, pp. 51–62.

Schmidhuber, J., 2015. Deep learning in neural networks: an overview. Neural Netw. 61, 85–117.

Schoenemann, P.T., 2006. Evolution of the size and functional areas of the human brain. Annu. Rev. Anthropol. 35, 379–406.

Schultz, A.H., 1949. Sex differences in the pelves of primates. Am. J. Phys. Anthropol. 7, 401–424.

Schwartz, M.L., Rakic, P., Goldman-Rakic, P.S., 1991. Early phenotype expression of cortical neurons: evidence that a subclass of migrating neurons have callosal axons. Proc. Natl. Acad. Sci. 88, 1354–1358.

Sellen, D.W., 2001. Comparison of infant feeding patterns reported for nonindustrial populations with current recommendations. J. Nutr. 131, 2707–2715.

Semendeferi, K., Lu, A., Schenker, N., Damasio, H., 2002. Humans and great apes share a large frontal cortex. Nat. Neurosci. 5, 272–276.

Senft, S.L., Woolsey, T.A., 1991. Growth of thalamic afferents into mouse barrel cortex. Cereb. Cortex 1, 308–336.

Shakeshaft, N.G., Plomin, R., 2015. Genetic specificity of face recognition. Proc. Natl. Acad. Sci. 112, 12887–12892.

Shaw, P., Greenstein, D., Lerch, J., Clasen, L., Lenroot, R., Gogtay, N., et al., 2006. Intellectual ability and cortical development in children and adolescents. Nature 440, 676–679.

Sherman, D.L., Brophy, P.J., 2005. Mechanisms of axon ensheathment and myelin growth. Nat. Rev. Neurosci. 6, 683–690.

Shiraishi, N., Katayama, A., Nakashima, T., Yamada, S., Uwabe, C., Kose, K., et al., 2015. Morphology and morphometry of the human embryonic brain: a three-dimensional analysis. Neuroimage 115, 96–103.

Silbereis, J.C., Pochareddy, S., Zhu, Y., Li, M., Sestan, N., 2016. The cellular and molecular landscapes of the developing human central nervous system. Neuron 89, 248–268.

Simmonds, D., Hallquist, M.N., Asato, M., Luna, B., 2013. Developmental stages and sex differences of white matter and behavioral development through adolescence: a longitudinal diffusion tensor imaging (DTI) study. Neuroimage 92, 356–368.

Simonds, R.J., Scheibel, A.B., 1989. The postnatal development of the motor speech area: a preliminary study. Brain Lang. 37, 42–58.

Smith, B.H., Tompkins, R.L., 1995. Toward a life history of the. Hominidae. Annu. Rev. Anthropol 20, 257–279.

Stearns, S.C., 1992. The Evolution of Life Histories. Oxford University Press, Oxford.

Stein, B.E., Stanford, T.R., 2008. Multisensory integration: current issues from the perspective of the single neuron. Nat. Rev. Neurosci. 9, 255–266.
Syal, S., Finlay, B.L., 2011. Thinking outside the cortex: social motivation in the evolution and development of language. Dev. Sci. 14, 417–430.
Tacutu, R., Craig, T., Budovsky, A., Wuttke, D., Lehmann, G., et al., 2013. Human ageing genomic resources: integrated databases and tools for the biology and genetics of ageing. Nucleic Acids Res. 41, D1027–D1033.
Takahashi, E., Folkerth, R.D., Galaburda, A.M., Grant, P.E., 2012. Emerging cerebral connectivity in the human fetal brain: an MR tractography study. Cereb. Cortex 22, 455–464.
Takahashi, E., Hayashi, E., Schmahmann, J.D., Ellen Grant, P., 2014. Development of cerebellar connectivity in human fetal brains revealed by high angular resolution diffusion tractography. Neuroimage 96, 326–333.
Tate, M.C., Lindquist, R.A., Nguyen, T., Sanai, N., Barkovich, A.J., Huang, E.J., et al., 2015. Postnatal growth of the human pons: a morphometric and immunohistochemical analysis. J. Comp. Neurol. 523, 449–462.
Tomasello, M., 1999. The Cultural Origins of Human Cognition. Harvard University Press, Harvard.
Trevathan, W., 2010. Ancient Bodies, Modern Lives. Oxford University Press, Oxford.
Udin, S.B., Fawcett, J.W., 1988. The formation of topographic maps. Annu. Rev. Neurosci. 11, 289–327.
Van der Loos, H., Welker, E., 1985. Development and plasticity of somatosensory brain maps. In: Rowe, M., Willis, J.W.D. (Eds.), Development, Organization, and Processing in Somatosensory Pathways; Neurology and Neurobiology, vol. 14. Alan R. Liss, New York, pp. 53–67.
Van Essen, D., 1997. A tension-based theory of morphogenesis and compact wiring in the central nervous system. Nature 385, 313–318.
Walker, L., Chang, L.-C., Nayak, A., Irfanoglu, M.O., Botteron, K.N., McCracken, J., et al., 2016. The diffusion tensor imaging (DTI) component of the NIH MRI study of normal brain development. Neuroimage 124, 1125–1130.
Werker, J.F., Tees, R.C., 1992. The organization and reorganization of human speech perception. Annu. Rev. Neurosci. 15, 377–402.
Wierenga, L.M., Langen, M., Oranje, B., Durston, S., 2013. Unique developmental trajectories of cortical thickness and surface area. NeuroImage 87.
Wiesel, T.N., 1999. Early explorations of the development and plasticity of the visual cortex: a personal view. J. Neurobiol. 41, 7–9.
Wiesel, T.N., Hubel, D.H., 1965. Comparison of the effects of unilateral and bilateral eye closure on cortical unit responses in kittens. J. Neurophysiol 28, 1029–1040.
Windrem, M.S., Jan de Beur, S., Finlay, B.L., 1988. Control of cell number in the developing neocortex: II. Effects of corpus callosum transection. Dev. Brain Res. 43, 13–22.
Wong, R.O.L., 1990. Differential growth and remodelling of ganglion cell dendrites in the postnatal rabbit retina. J. Comp. Neurol. 294, 109–132.
Wong, R.O.L., 1999. Retinal waves and visual system development. Annu. Rev. Neurosci. 22, 29–47.
Wong, R.O.L., Chernjavsky, A., Smith, S.J., Shatz, C.J., 1995. Early functional neural networks in the developing retina. Nature 374, 716–718.
Woo, T.U., Finlay, B.L., 1996. Cortical target depletion and ingrowth of geniculocortical axons: implications for cortical specification. Cereb. Cortex 6, 457–469.
Woo, T.U., Niederer, J.K., Finlay, B.L., 1996. Cortical target depletion and the developing lateral geniculate nucleus: implications for trophic dependence. Cereb. Cortex 6, 446–456.
Workman, A.D., Charvet, C.J., Clancy, B., Darlington, R.B., Finlay, B.L., 2013. Modeling transformations of neurodevelopmental sequences across mammalian species. J. Neurosci. 33, 7368–7383.
Yamamori, T., 2011. Selective gene expression in regions of primate neocortex: implications for cortical specialization. Prog. Neurobiol. 94, 201–222.
Young, L.J., Wang, Z., 2004. The neurobiology of pair bonding. Nat. Neurosci 7, 1048–1054.
Zatorre, R.J., Fields, R.D., Johansen-Berg, H., 2012. Plasticity in gray and white: neuroimaging changes in brain structure during learning. Nat. Neurosci. 15, 528–536.
Zecevic, N., Bourgeois, J.-P., Rakic, P., 1989. Changes in synaptic density in motor cortex of rhesus monkey during fetal and postnatal life. Dev. Brain Res. 50, 11–32.
Zecevic, N., Rakic, P., 1991. Synaptogenesis in monkey somatosensory cortex. Cereb. Cortex 1, 510–523.
Zilles, K., Palomero-Gallagher, N., Amunts, K., 2013. Development of cortical folding during evolution and ontogeny. Trends Neurosci. 36, 275–284.

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http://neurosciencelibrary.org/ – Brain Museum Source.
www.translatingtime.net – Home Page for Translating Time Utility and Model.