7 Brain and Behavioral Development During Childhood

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ABSTRACT This chapter summarizes what has been learned about the correspondences between brain maturation and the ontogeny of human psychological competences from birth to puberty. Significant maturational transitions occur at 2–3 months, 7–12 months, 12–24 months, 4–8 years, and puberty.

This chapter summarizes some of the temporal correspondences between the emergence of select human psychological properties and changes in brain anatomy and function across the first dozen years of human development. Although we will suggest, albeit tentatively, some theoretical bases for the correspondences, we recognize that the meaning of every conclusion must be evaluated in light of the source of evidence. The information provided by an apparatus or procedure represents only a partial picture of the whole phenomenon that scientists wish to comprehend. On many occasions, a psychological and a biological measure of a construct lead to different conclusions. For example, a majority of a group of 10-year-olds shown pictures of children they had played with 3–6 years earlier, along with pictures of unfamiliar children, failed to recognize most of the faces of their former playmates when asked to say whether they had ever seen the child in the photograph. However, many of these children, not all, produced a galvanic skin response to pictures of the children they had known earlier, but not to photographs of strangers (Newcombe and Fox, 1994). Thus, the answer to the question, "Do 10-year-olds remember their playmates after a 6-year interval?" depends on the method. This restraining principle applies to statements describing the relation between brain and psychological properties.

The conceptualization of change has been a perennial node of debate because of uncertainty over whether to treat development as continuous or as a sequence of qualitatively different stages marked by transitions. Scientists attribute a stage to an era of growth when a correlated cluster of features, displayed across a class of relevant contexts, changes its pattern of organization. However, it is usually the case that a period of time must pass before all the components assume their new organization and are displayed across a broad envelope of situations. That is why we prefer the word *phase* to *stage*, because the former term implies that the process of transformation was gradual.

The presence of temporal correlations between the maturational state of the brain and the psychological properties of children does not imply a strict determinacy, because experience is a participant in most behaviors. The brain changes that occur between 12 and 24 months are necessary for the emergence of speech, but children will not speak if they are not exposed to any language. The fundamental premise of this chapter is that brain maturation constrains the time of emergence of the psychological characteristics of our species and, although necessary, it is not sufficient for the actualization of the psychological phenomena.

Infancy

We consider first the correspondences between brain growth and psychological development during the first year, with an emphasis on the changes that occur during the transitions between 2 and 3 months and between 7 and 12 months of age. We assume that the maturational processes are occurring in infants who are exposed regularly to the objects, events, and people characteristic of all but the most depriving environments. We describe first the psychological changes, and then the brain events believed to contribute to the former.

TRANSITION AT 2–3 MONTHS The disappearance of a number of newborn reflexes, including the palmar grasp and the Babinski reflex, is a reliable sign of the first transition. Most scientists believe that this phenomenon is due to cortical inhibition of brainstem neurons (Brodal, 1981; Volpe, 1995). Projections from the supplementary motor cortex to the brainstem and spinal cord inhibit activity in the brainstem neurons (Bates and Goldman-Rakic, 1993; Galea and Darian-Smith, 1995). Although these axons reached the brainstem and spinal cord prenatally, actual synaptic contacts do not appear until 2–3 months (Kostovic, 1990; Fitzgerald, 1991). It is also relevant that GABAergic and glycinergic inhibitory interneurons in the spinal cord

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undergo enhanced growth during the first 3 months (Akert, 1994; Ralston, 1994).

This first transition is also marked by an obvious reduction in crying and an increase in social smiling (deWeerth and Geert, 2002). The former could be the result of cortical inhibition of the brainstem nuclei that mediate crying (especially the reticular formation, central gray, nucleus solitarius, and parabrachial nucleus) (Fitzgerald, 1991; Zilles and Rehkamper, 1994).

A third characteristic of the transition is the ascendance of a psychological basis for recruiting and sustaining attention to a stimulus. Duration of attention to a visual event during the first 7–8 weeks is guided primarily by its physical features, especially size, contour density, and motion. After the transition, duration of attention is modulated to a greater degree by the relation between the event and the infant's acquired schema for that event (Kagan, 1970).

A schema is the first psychological form to emerge from the brain activity evoked by an event. The psychological definition of a schema is a pattern of the event's physical features. Thus, the vocabulary that describes a schema for a visual event contains words like "contour density," "color," "shape," and "motion" and differs from the vocabulary of terms that describe the neural activity that represents the foundation of the schema. One reason why recruitment of attention to a discrepant event is not automatic before 2 months is that infants must relate the event to an acquired schema, and this process is fragile during the first 2 months of life. Further, the function relating duration of attention to discrepancy is not linear but resembles an inverted U, where moderately discrepant events recruit longer bouts of attention than very familiar or very novel events (Kagan, Kearsley, and Zelazo, 1978). For example, 4-month-olds will look longer at the face of an unfamiliar person than at a familiar face or a totally novel event (e.g., an irregularly shaped piece of polyfoam). Although there can be no absolute answer to the question, How long does an infant's schema for an event last? it is possible to estimate the duration of preservation for a particular experimental procedure and for infants of a particular age. The evidence suggests an enhancement in the duration of a schema for a new event at 2–3 months (Boller et al., 1996; Rose, Feldman, and Jankowski, 2002).

It is likely that hippocampal maturation contributes to the improved ability of 2-month-olds to recognize an event following a delay because the greatest increase in the velocity of growth of the hippocampus occurs between 2 and 3 months (Kretschman et al., 1986). Specifically, the mossy cells of the hippocampal dentate gyrus undergo a spurt of differentiation (Seress and Mrzljak, 1992). The hippocampal growth might also make it possible for 3-month-olds to establish visual expectations (Haith, 1994). Infants, lying supine, looked up at two monitors. Each monitor displayed, alternately, a chromatic picture of a face or design for 700 ms, followed by an interval of 1100 ms when both monitors were dark, after which a different stimulus appeared on the second monitor. This alternation continued for about 1.5 minutes. About one-fifth of 3½-month-olds, but no 2-month-olds, anticipated the appearance of a stimulus by moving their head to the monitor on which a picture was about to appear during the interval when both monitors were dark.

TRANSITION AT 7–12 MONTHS The transition that occurs in most healthy infants between 7 and 12 months is accompanied by the ability to retrieve schemata from past events that are no longer in the perceptual field and to hold them along with the current perception in a working memory circuit while they try to assimilate the latter to the former. Four-month-olds can recognize that an event in their perceptual field was experienced in the past, but have difficulty retrieving a schema for a past event that is no longer present and performing cognitive operations on it.

Support for this generalization comes from a longitudinal study of infants who were assessed every 2 weeks from 6 to 14 months. In one procedure the examiner hid an attractive object under one of two identical cylinders, placed an opaque screen between the infant and the cylinder for delays of either 1, 3, or 7 sec, and then removed the screen to allow the infant to reach toward one of the cylinders. There was a linear increase with age in the probability of reaching to the hidden object as the delay increased. No 7-month-old reached to the correct location with a delay of 7 sec; however, most 12-month-olds solved that problem easily (Fox, Kagan, and Weiskopf, 1979). Comparable studies of infant monkeys affirm an improvement in the ability to retrieve a hidden object following increasingly long delays at 2–3 months of age, which corresponds to 7–10 months in the human infant (Diamond and Goldman-Rakic, 1989; Diamond, 1990). The transition at 7–12 months also marks the time when schematic concepts for the phonemes of the infant's language (Kuhl, 1991), temporal sequences of syllables (Marcus et al., 1999), and spontaneous imitation following a long delay appear (Bauer, 2002).

The enhancement of working memory is accompanied by a spurt of growth and differentiation in both pyramidal and inhibitory interneurons in the prefrontal cortex between 7 and 12 months. Specifically, double bouquet interneurons in layer III show a broader distribution of dendrites and their axons display numerous ascending and descending collaterals (Mrzljak et al., 1990). This growth is accompanied by increased glucose uptake (measured by PET) in the lateral and the dorsolateral prefrontal cortex (Huttenlocher, 1979, 1990; Chugani, 1994; Kostovic, Skavic, and Strinovic, 1998). Further, changes in oxygenated and deoxygenated hemoglobin in the blood supply to the frontal lobe, based on optical scanning, affirm the role of the prefrontal cortex in working memory (Baird et al., 2002). It is also relevant that hippocampal volume approaches adult size between 10 and 12 months (Kretschman et al., 1986), due in part to the number of spines and extra large excrescences on the proximal dendrites of pyramidal cells in the CA3 region of Ammon's horn (Seress and Mrzljak, 1992). These anatomical changes are accompanied by faster alpha frequencies (6–9 Hz) between 7 and 12 months (Bell, 1998).

The integrity of the hippocampal formation, but not the prefrontal cortex, is necessary for holding a representation in a short-term memory store for periods of less than 10 sec. However, the integrity of the prefrontal cortex is necessary for successful performance on the Piagetian A not B task, even with short delays (Diamond, Zola-Morgan, and Squire, 1989). As a result, some scientists distinguish between the concept of a short-term memory store and the concept of working memory; the latter implies that some cognitive activity was imposed on the information.

THE APPEARANCE OF FEAR TO DISCREPANCY The improvement in working memory after 7 months permits infants to attempt assimilation of an event discrepant from their experience to a retrieved schema. If the discrepant event cannot be assimilated, and if the infant has no coping response, she may become fearful and cry (Bronson, 1968; Gunnar-Von Gnechten, 1978; Kagan, Kearsley, and Zelazo, 1978). The phenomenon of separation fear is illustrative. The unexpected departure of the mother, especially if the infant is in an unfamiliar place, is a discrepant event. The older infant retrieves a schema for her former presence and tries to relate it to the current perception of her absence. If the infant cannot assimilate the mother's absence to the schema for her former presence, he may become fearful and cry. The ability to hold the retrieved schema of the mother's prior presence with her current absence in a working memory circuit requires the brain maturation described earlier. Patterns of growth in the amygdala and prefrontal cortex are also likely to be relevant to both separation and stranger fear. The amygdala is activated by both unexpected and discrepant events, and projections from the amygdala to the cortex, through axons within the capsula interna, develop mature myelin between 7 and 10 months, the time when both fear of strangers and separation from a caretaker emerge (Chrousos and Gold, 1992).

The transition at 7–12 months is also accompanied by an enhanced ability to adjust sensory motor structures in the service of attaining a goal. For example, 5-month-olds use both hands to reach toward an object, whether small or large, while 8-month-olds reach with one hand toward small objects but with both hands toward large objects (Clifton et al., 1991; Rochat and Senders, 1991). The neuronal ensembles in motor cortex that mediate a class of motor action are comparable to words in the child's vocabulary. One ensemble is activated when a monkey prepares to grasp a small object with thumb and forefinger; a different ensemble is activated when the whole hand must be used to grasp larger objects (Rizzolatti, Fogassi, and Gallese, 2000).

In sum, the central feature of the behavioral changes between 7 and 12 months is the ability to retrieve schemata and hold them and the current situation in a working memory circuit for 20–30 s while comparisons are being made or additional cognitive operations are performed. We suggest that the biological foundation for these advances rests in part on growth and differentiation of neurons in the prefrontal cortex and enhanced connectivity between the prefrontal cortex and the amygdala, hippocampus, and temporal lobe. The parallels between brain and biological growth in monkeys and human infants add credibility to this view.

The second year

The second year is distinguished by four psychological competences that might depend, in part, on a particular set of changes in the brain. The new properties include (1) the ability to comprehend and to express meaningful speech, (2) the capacity to infer selected mental and feeling states in others, (3) representations of the actions that are prohibited by adults, and (4) the first signs of conscious awareness of the self's feelings and intentions.

SPEECH The brain bases for the new language competence are embedded in broad corticocortical networks that link the auditory pathway and temporal cortex to the parietal, frontal, and cerebellar regions involved in representations of temporal sequences. It may not be a coincidence that the first words emerge in most children between 12 and 15 months, the time that rapid dendritic growth occurs in the left orofacial section of Broca's area (Simonds and Scheibel, 1989). There is also an increase in the cerebellar volume, due in part to extensive lengthening of dendrites in the dentate nucleus of the cerebellum (Yamaguchi, Goto, and Yamamoto, 1989), and levels of glucose uptake attain 175% of adult values by the second birthday (Schmahmann and Pandy, 1997). Although Wernicke's area plays a greater role in the perceptual aspects of speech comprehension and Broca's area plays a greater role in the motor components of speech, both areas participate in these as well as other psychological functions (Devlin, Matthews, and Rushworth, 2003).

We suggest that the growth of neurons in cortical layer III, whose axons constitute the corpus callosum, contributes to the emergence of speech. This growth is accompanied by peak levels of glutamate binding, as well as a spurt in GABA activity in inhibitory interneurons of layer III, during the second year of life (Mrzljak et al., 1990; Slater et al., 1992; Huttenlocher and Dabholkar, 1997). Most scientists are friendly to the hypothesis that perceptual schemata representing objects and events are more fully represented in the right hemisphere, while lexical structures are more fully represented in the left (Lauder, 1983). If the layer III changes made callosal transfer more efficient, the perceptual schemata activated upon seeing a cup on a table would be integrated more rapidly with the lexical representation for the object, represented more fully in the left hemisphere, and the child might say "cup." It is of interest that a compromised ability in older adults to retrieve a name for a familiar person is accompanied by callosal thinning, suggesting the waning of a process in the elderly that is waxing in the second year (Sullivan et al., 2002).

Inference The ability to infer selected thoughts and feelings of others, a second competence of the second year, might be aided by the same aspects of brain growth. A particularly clear demonstration of this talent is observed when an adult hides a toy under one of three covers behind a barrier so that the child cannot see where the toy is hidden. If, after removing the barrier, the adult directs her gaze toward the place where the toy is located, 2-year-olds, but not 1-year-olds, will look in the direction of the adult's orientation and reach toward that place, suggesting they inferred that the adult was looking at the correct location (Kagan, 1981). When infants 8–19 months of age saw an adult turn her head toward an interesting sight, only the 18- and 19-month-olds reliably used the direction of the adult gaze to guide the direction of their orientation toward a target (Moore and Corkum, 1998; Tomasello, 1999). The ability to infer what is in the minds of others is also revealed in behavioral signs of empathy upon perceiving distress in another person (Zahn-Waxler, Robinson, and Emde, 1992; Young, Fox, and Zahn-Waxler, 1999). The growth in layer III neurons would permit the rapid integration of the schematic representations of the somatic sensations experienced when in distress, which are stored primarily in the right hemisphere, with semantic representations of the state of the other, represented primarily in the left hemisphere. As a result, empathy would occur.

Representations of Prohibited Actions Children first acquire schematic concepts for prohibited actions during the second year. Most 2-year-olds will hesitate if a parent asks them to perform an act that violates a family norm, such as pouring cranberry juice on a clean tablecloth, and will show behavioral signs of concern when they see an object whose integrity is flawed. (Kagan, 1981). Parents living on isolated atolls in the Fijian chain, who recognize this advance, believe that their children acquire *vakayala*, meaning good sense, soon after their second birthday (Kagan, 1981).

This phenomenon, too, could be facilitated by the more efficient coordination of information between the two hemispheres. Specifically, the visceral schemata that represent the feeling of uncertainty that follows parental criticism or punishment, more fully represented in the right hemisphere, will be integrated with the semantic representations for prohibited behaviors, mediated more fully in the left hemisphere.

Self-Awareness Finally, initial signs of self-awareness appear in the second year. For example, infants now recognize their reflection in the mirror, direct adults to act in particular ways, show signs of distress when they cannot imitate the behavior of another but signs of pride if they can, and describe in speech what they are doing as they are doing it (Kagan, 1981). The enhanced connectivity between the two hemispheres could contribute to these phenomena as well. The representations of the child's feeling tone, which varies from moment to moment and is an important foundation of self-awareness, is represented primarily in the right hemisphere. When this information is integrated with the semantic categories for self's name, thoughts, and intentions, represented primarily in the left, a consciousness of self's feelings and intentions could emerge.

Other Brain Events In addition to the enhanced integration of information from the two hemispheres, other maturational changes in the second year could contribute to the psychological competences of this era. For example, peak levels of glutamate binding, activity of glutamate decarboxylase, required for the synthesis of GABA, as well as a spurt in GABA activity in inhibitory interneurons of layer III occur between 1 and 2 years of age (Slater et al., 1992; Huttenlocher and Dabholkar, 1997). GABA mediates inhibitory functions, and all observers of children recognize the increased ability of 2-year-olds to regulate their behavior. In addition, the activity of choline acetyltransferase increases sharply during the second year, when pyramidal neurons begin to express acetylcholine in cell bodies and fibrillary networks (Decker and McGaugh, 1991; Court et al., 1993). Finally, there is a spurt in EEG coherence between the left parietal and left temporal areas in the middle of the second year, implying greater functional connectivity among noncontiguous cortical areas (Thatcher, 1994).

The behaviors and cognitive functions of 1-year-olds are similar to those of chimpanzees. Both species show enhanced working memory and fear to discrepant events that cannot be assimilated. However, by the end of the second year the differences between the two species become more distinct. No observer would confuse a 2-year-old child with a chimpanzee of any age because of the emergence of language, inference, awareness of prohibited acts, and self-consciousness.

Ages 2–8

The belief that a set of universal psychological properties emerges after the second birthday, accelerates between 5 and 8 years of age, and plateaus from age 8 to puberty is present in essays written centuries earlier (see White, 1996, for a review). Even nonliterate parents who are uncertain of their child's age begin to assign chores when their children reach 6 or 7 years. Parents now expect their children to be able to care for young infants, tend animals, work in the field, and conform to community mores because they have noticed that their children have become teachable, responsible, capable of understanding what others want, and able to understand rational explanations. The maturing abilities of this prolonged era include (1) active integration of past with present, (2) enhanced reliance on semantic networks, and (3) detection of shared relations between categories.

INTEGRATION OF PAST WITH PRESENT One sign of this developmental phase, usually observed by the fourth birthday, is the automatic and more reliable activation of past representations in order to interpret the present moment (Loken, Leichtman, and Kagan, 2002). This ability is the phenomenon that Jean Piaget (1950) called conservation. In a classic demonstration of this competence, an examiner shows a child two identical balls of clay and asks whether the two balls have the same amount of clay, or whether one ball has more clay than the other. All children acknowledge that the two balls have equivalent amounts of clay. The examiner then rolls one of the two balls into a sausage shape and asks the child again, "Which one has more clay?" Four-year-olds treat the question as if it were independent of the first, and, since the sausage appears to have more substance, they say that the sausage has more clay. By contrast, 7-year-olds regard the sausage as part of a temporal sequence that began when the examiner showed the child the two identical balls and asked the first conservation question. The 7-year-olds understood that after the examiner transformed one ball into the sausage the examiner intended to ask, "Given the sequence you have seen over the last minute or two, which ball has more clay?" The older child treats the second question as part of a coherent temporal sequence.

This competence motivates children to wonder about causal connections between events. The implicit question, "Why did this event occur?" provokes children to retrieve structures that might represent possible antecedents of a current situation (Povinelli et al., 1999). Thus, 7-year-olds who harm a person or damage property relate that outcome to a prior intention, or to their clumsy behavior, and, as a result, are vulnerable to a feeling of remorse. For the same reason, 7-year-old children are usually reflective on a problem following a mistake because they recognize that their error was due to a failure to consider all the alternative solutions carefully.

SEMANTIC NETWORKS A second significant feature of this era is an expanded reliance on semantic networks to categorize experience. One reason for the phenomenon called infantile amnesia is that young children do not regularly use semantic structures to code their experiences, and therefore cannot report a salient event experienced in the past (Simock and Hayne, 2002). The application of semantic categories to experience influences the way children organize and retrieve knowledge. If a list of 12 words containing two semantic categories (for example, animals and foods) is read to children 4 and 7 years old, only the older children cluster words that belong to the same semantic category in their recall. This phenomenon could only occur if older children had an automatic tendency to group words that were members of the same semantic category. The improvement in memory functioning over the years 2 through 8 is due, in part, to the use of language to structure experience (Nelson, 1996).

SHARED RELATIONS Detection of shared relations between or among categories of events is a third competence that emerges after age 4 or 5 years. Children under 6 years can detect a physical feature, function, or name that is shared by two or more events. However, younger children do not detect a shared semantic relation between events that belong to different categories (for example, the loudest of six noises shares the semantic relation of magnitude with the sweetest of six tastes). The reason for the late appearance of this competence is that the shared relation is not given immediately in perception, as is true for shape or motion, but must be inferred with a semantic form.

Seven-year-old children understand that the semantic concepts "smaller" and "bigger" are not absolute properties of any object but refer to a relation between objects. Similarly, older, but not younger, children understand that right and left refer to relations between objects and are not fixed properties of any object (Kuenne, 1946). The ability to detect relations shared by different events allows children to assign an object to a category based on multiple dimensions. For example, 7-year-olds but not 4-year-olds will sort a pile of toys that vary in size and hue into four groups (Piaget, 1950).

The psychological competences described above require the participation of many brain sites acting coordinately. One relevant fact is that the human brain attains 90% of its adult weight between 4 and 8 years (Giedd et al., 1996), with the rate of increase in cortical surface greatest between 2 and 6 years. This growth is accompanied by increased glucose uptake in both cortical and subcortical structures (Chugani, 1994, 1998).

The balance between the number of synapses formed and the number eliminated shifts after 5 or 6 years to a ratio that favors the latter. The reduction in extra synapses is assumed to reflect consolidation of the active synaptic networks that represent new learning. Synaptic density reaches its peak earlier in layer IV than in layers II and III; the latter mediate associative activity. Maximum synaptic density in the prefrontal cortex is not attained until 3–4 years of age (Huttenlocher and Dabholkar, 1997).

Dopamine concentrations, as well as the density of dopamine D_1 receptors in the monkey prefrontal cortex, approach adult values between 2 and 3 years, corresponding to 6–9 years in children. Although dopamine does not show as clear a developmental change as norepinephrine, dopaminergic fibers attain maximal extension in layer III of the monkey's prefrontal cortex at about 3 years of age, comparable to about 9–10 years in humans (Rosenberg and Lewis, 1994). Although the synthesis of serotonin peaks at 3 years, serotonin receptors do not reach maximum density in the basal ganglia, hippocampus, and cerebellum until 5 or 6 years. Finally, acetylcholinesterase-positive pyramidal neurons, believed to be restricted to apes and humans, first appear in layer III in the frontal, motor, and association cortices and the hippocampus between 4 and 5 years (Kostovic, Skavic, and Strinovic, 1988; Mesulam and Geula, 1988).

The connectivity of the brain, which is the central feature of this developmental era, is also revealed in enhanced myelination and improved EEG coherence. The axons of the anterior corpus callosum show their most rapid growth of myelin between 3 and 6 years, and the longer tracts, which link noncontiguous sites within a hemisphere, display a spurt of myelination after the third birthday. This process continues at a slower rate into adulthood (Yakovlev and Lecour, 1967; Curnes et al., 1988). As a result, the ratio of white to gray matter in layers II and III, which favored the latter during the first 3 years, is now reversed and white matter exceeds gray matter for the first time.

There is also an increase between 3 and 4 years in the magnitude of coherence of EEG frequency bands between frontal sites, on the one hand, and temporal areas, on the other (Ornitz, 2002). Finally, blood flow, which was greater in the right than in the left parietal-temporal cortex in the first 4 years, becomes greater in the left hemisphere by the fifth birthday (Takahashi et al., 1999).

The salient feature of the psychological advances observed between ages 2 and 7 is the almost automatic evocation of representations that are relevant to an incentive or context. The most fundamental brain change during this time is a massive interconnectedness involving both hemispheres, anterior and posterior cortical sites, and cortical and subcortical structures. Two facts are of special importance. The first is a shift in blood flow from the right temporal and parietal areas to homologous areas in the left hemisphere. The second is the fact that the number of synapses eliminated exceeds that of new synapses formed, first in sensory and later in frontal areas, reflecting the strengthening of circuits that have proven adaptive.

Adolescence

Although most cognitive processes are functional by 8–10 years of age, the capacity for abstract thought, logical reasoning, planning, and cognitive flexibility are enhanced after puberty and during the adolescent years (Piaget, 1950). One obvious hallmark of adolescence is the ability to detect logical contradiction or semantic inconsistency among beliefs, or between feelings and beliefs, that belong to a network. For example, recognition of disloyal thoughts about a friend ("I'm a good person, but I hope my friend fails the examination") can elicit a moment of dissonance or guilt, even if the friend is not hurt by those thoughts. The young child is less likely to recognize this inconsistency. The detection of inconsistencies in beliefs pertaining to a theme motivates youth to try to integrate their past knowledge with current experience in order to understand their present circumstances more completely. It is likely that behaviors that were issued without reflection in early childhood come under increasing control of conscious reflective processes during adolescence. For example, young children, who can distinguish among different facial expressions, often find it difficult to think about human emotions abstractly. Adolescents, by contrast, can make sophisticated inferences about a person's emotional state from that person's facial expression or posture. This may be one reason why medieval Europeans did not permit youth younger than 13 or 14 years old to take monastic vows.

The frontal cortex contributes in a major way to these cognitive capacities. Although medial temporal structures are functionally mature early in development, the frontal lobes do not reach full functional maturity until after puberty, and the anterior frontal regions mature later than posterior regions (Giedd et al., 1999; Sowell, Thompson, Holmes, Batth, et al., 1999; Sowell, Thompson, Holmes, Jernigan, et al., 1999). In addition, there is continued synaptic pruning through adolescence into the second decade (Casey et al., 2000). These advances are probably influenced by changes in neurophysiology as well (Baird et al., 1999).

The increased myelination of the anterior cingulate, which mediates emotional, attentional, and cognitive functions (Vogt, Finch, and Olson, 1992; Casey et al., 1997), should result in improved corticocortical and corticosubsortical connections. Projections from cortical and subcortical regions to the cingulate facilitate the coordination and regulation of psychological processes; unfortunately, we do not know the details of this developmental phenomenon. Research on rodent brains may shed light on this issue because projections from the rat amygdala to the cingulate appear at puberty (Amaral and Insausti, 1992). Cunningham, Battacharyya, and Benes (2002) using anterograde tracers in the amygdala, discovered a sharp increase in the density of labeled fibers originating in the amygdala and synapsing on the cingulate and medial prefrontal regions at puberty.

Finally, it is of interest that the volumes of subcortical structures in female adolescents (especially the amygdala and hippocampus) are very similar to adult volumes. By contrast, these subcortical volumes are larger in adolescent boys than in adult men, suggesting the different effects of male and female hormones on the pruning of synapses in these areas (Giedd, Snell, et al., 1996; Paus, et al., 2001).

In sum, the psychological changes that occur during the adolescent years are correlated with the pruning of synapses in prefrontal cortex, myelination of axons connecting the prefrontal cortex to the rest of the brain, and the firmer inclusion of the cingulate cortex in circuits involving the amygdala and the prefrontal cortex.

Synthesis and controversy

The evidence indicates that the times of emergence of the universal psychological features of human development are constrained by maturation of the central nervous system, even though the brain changes do not guarantee the new psychological structures. Almost all 1-year-olds, regardless of their cultural setting, are able to retrieve past representations and maintain them and their perception of the current context in a working memory circuit for intervals as long as 30 sec, in some cases longer. The fact that pyramidal neurons in frontal sites display accelerated growth from 7 to 12 months supports the suggestion that the behavioral phenomena require the biological changes.

The hidden sequence during the first 12–13 years is from (1) establishing an initial connectivity among sensory, limbic, and medial temporal structures to (2) improved integration of the two hemispheres to (3) connecting the frontal lobe to the above sites and, finally, to (4) a massive connectivity among all brain sites as the child prepares for school or, in villages without schools, for assumption of family responsibilities.

However, despite these facts, we remain frustrated in our attempt to answer three significant questions: (1) How do psychological phenomena emerge from brain activity? (2) How does experience influence brain growth? (3) Which experiences accelerate and which retard the emergence of the milestones once the brain has attained the appropriate level of growth? A wrinkled guru who knows the answers to these questions might shake her head after reading this chapter and mutter that all we have done is to describe some roughly temporal correspondences between brain and behavior and assume, with insufficient caution, a causal connection.

The Importance of Specificity The stark contrast between the specificity of brain function and the generality of many popular psychological constructs is a paradox. Almost every time a biologist posits a relation between two aspects of brain function, or between brain function and a psychological product, other scientists discover that the original claim was too general. The facts of nature force most neuroscientists to be splitters. By contrast, psychiatrists and psychologists tend to be lumpers, preferring more abstract to more constrained concepts. The profiles of change in dopamine concentration in three sites in the rat brain reveal the problem with an ambitious striving for generality. Dopamine concentrations produced by two different sweet-tasting substances were assessed in the prefrontal cortex, as well as in the shell and core of the nucleus accumbens (Bassareo, De Luca, and De Chiara, 2002). The taste of sucrose produced an increase in dopamine in the prefrontal cortex exclusively, but a combination of sucrose and chocolate, which is an unfamiliar stimulus for rats, produced a dopamine increase in all three sites. Even though both substances were "sweet," each elicited a different brain state.

Developmental psychologists are just beginning to appreciate the significance of tiny details in a procedure. For example, preschool children tested in a small room (4 × 6 feet) without any windows failed to use a landmark (a single blue wall) to find an object they saw an adult hide in the corner of the room. However, the same children used the blue wall as a landmark if they were tested in a larger room (8 × 12 feet). Simply changing the size of the room led to a different inference about the child's ability to use a landmark (Learmonth, Nadel, and Newcombe, 2002). We suggest that scientists should parse the broad constructs that dominate current psychological theory, for example, reward, fear, intelligence, and memory, into a number of more restricted concepts that are in closer accord with what is known about the brain. This suggestion is not a defense of reductionism but a plea for consistency in the level of specificity in the descriptions of brain and mind.

Localization The notion that a particular psychological process emerges from activity in a particular site remains attractive (Blanke et al., 2002). Although the ability to inhibit an inappropriate response and the ability to hold information in working memory require the integrity of the frontal lobe, neither function is localized in this site, for most psychological processes recruit structures from diverse sites. There is no single place in the brain where the memory of a past automobile accident or a feeling of vitality is recognized, even though some sites contribute more and others less to the psychological phenomenon. After a review of 275 studies that used PET or fMRI, Duncan and Miller (2002) concluded that mapping a defined cognitive process on a well-defined brain region may not be possible. The prefrontal cortex may be a general computational resource that is relied on to solve different cognitive problems.

The most significant maturational event occurring over the first dozen years is an increasing connectivity of the prefrontal cortex with the rest of the brain. The expansion of the human prefrontal cortex to one-third of the total cortical surface, compared with only one-tenth in the gorilla, appears to be a seminal reason for the display of the psychological properties that differentiate humans from all other primates. We suggest that eight distinctive human properties are (1) an expanded working memory; (2) the ability to maintain a representation of a goal, despite distractions, due to the inhibition of thoughts and responses irrelevant to the goal; (3) the ability to retrieve representations of events from the distant past, including the incentive and its temporal and spatial properties, a process called episodic memory; (4) the ability to generate representations of events that might occur in the distant future; (5) conscious awareness of self's feelings, thoughts, and properties; (6) creation of the concept of prohibited acts, understanding the semantic categories "good" and "bad," and capacities for anxiety or shame over violations of a standard; (7) the seeking of new experiences that can be understood or coped with effectively; and (8) the ability to invent relations of similarity and difference among varied classes of representations. These eight competences require participation of the prefrontal cortex and its connections to other brain sites, and therefore require coherence among brain regions.

Coda

We end by asking whether it is possible, in principle, to translate sentences describing the psychological phenomena discussed in this chapter into sentences containing only biological words. The answer is uncertain at the present time, but there are reasons to be skeptical of the possibility of a complete translation. Roald Hoffman (2001) reminds us that scientists cannot even translate a chemical description of the oxidation of iron into the vocabulary of physics without losing the central meaning of "oxidative state of a molecule."

We doubt, for example, whether scientists will be able to replace the psychological term *reward* with biological words describing only brain activity, because *preference* and *pleasure* are psychological properties of whole animals, not of neuronal circuits. One reason for the incommensurability between the languages of neuroscience and psychology is that the complete semantic network of a neurobiological term is different from the network of the same word when used to name psychological phenomena. Even the French word *douce* and the English word *sweet* have different networks (Kuhn, 2000). Although a piece of cake is called *douce* by the French and *sweet* by Americans, only the French use the word *douce* to name a bland-tasting soup and only Americans use the word *sweet* to describe a young pretty girl. Thus, *douce* and *sweet* have related but not synonymous meanings.

The semantic network for the term *fear* among neuroscientists has salient nodes for "amygdala," "freezing," "startle," and "electric shock." The salient nodes of the network for this word when used by psychologists are "worry," "uncertain," "evaluative," "vigilant," and "symptom."

The complete semantic network for a concept is analogous to the physicist's notion of a phase space, because a collection of gas molecules in a vessel can assume a very large number of states, only one of which can be measured at a given time. For example, a picture of a snake can activate many different representations, depending on the context, and no member of that family is knowable until an investigator intervenes with a probe to measure it. Therefore, the pattern of brain activation in a person lying in an fMRI scanner and looking at pictures of snakes is not the only profile these stimuli could provoke. These pictures would probably create a different brain state if the person were looking at them on a television screen at home. Every conclusion regarding the neural profile that accompanies a psychological event is valid for the class of contexts in which the measurement was made. That is why Bohr believed that scientists can never know what nature is; they only know what their measurements permit them to infer.

A behavior, thought, or feeling is the final product of a series of cascades that began with an external stimulus, thought, or spontaneous biological event. The number of cascades varies with the psychological outcome of interest. However, the biological and psychological forms that make up each cascade must be described with a distinct vocabulary. Genes, chromosomes, neurons, organisms, and species have unique functions that are linked to distinct predicates. Genes mutate, chromosomes separate, neurons depolarize, organisms mate, and species evolve.

There is an increase in order and a loss of determinism as we move from the forms and functions of one cascade to those of the next—for example, from neuronal excitation in motor cortex to a child reaching toward a rattle—because there are fewer possible ways a child can reach for an object than possible states of the relevant neuronal ensembles. Hence, it is not possible to predict the exact direction and speed of a child's arm reaching for a rattle from complete knowledge of the immediately preceding neuronal profile. As the human brain matures, the links between one stage of psychological functioning and the next become a little less predictable because of the increasing importance of the child's past experiences. Neuronal change and human experience interact to create a reciprocally influential process that recapitulates across development. This growth eventually enables most adolescents to appreciate that, like the different perceptions of a Monet painting from 1 versus 20 feet away, there is more than one way to interpret an event.

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