Neural Plasticity and Human Development

Charles A. Nelson[1]

Institute of Child Development and Department of Pediatrics, University of Minnesota, Minneapolis, Minnesota

Abstract

In this article, I argue that experience-induced changes in the brain may be a useful way of viewing the course of human development. Work from the neurosciences supports the claim that most of the behavioral phenomena of interest to psychologists (e.g., cognition, perception, language, emotion) are instantiated by the process of neural plasticity. When development is viewed in this manner, the fallaciousness of the long-standing and often contentious debate over nature versus nurture becomes apparent. Moreover, by utilizing the neuroscientific tools used to examine the effects of experience on brain and behavioral development (e.g., functional neuroimaging), we may improve how we conceptualize our notions of intervention, competence, and resilience.

Keywords

brain; plasticity; behavior

Neural plasticity can best be thought of as the subtle but orchestrated dance that occurs between the brain and the environment; specifically, it is the ability of the brain to be shaped by experience and, in turn, for this newly remolded brain to facilitate the embrace of new experiences, which leads to further neural changes, *ad infinitum*. As a rule, there are three mechanisms by which experience induces changes in the brain. An *anatomical* change might be the ability of existing synapses (i.e., connections between nerve cells) to modify their activity by sprouting new axons or by expanding the dendritic surface. A *neurochemical* change might be reflected in the ability of an existing synapse to modify its activity by increasing synthesis and release of chemicals that transmit nerve impulses (i.e., neurotransmitters). Finally, an example of a *metabolic* change might be the fluctuations in metabolic activity (e.g., use of glucose or oxygen) in the brain in response to experience.

All of these changes can occur at virtually any point in the life cycle, although to varying degrees of success. For example, some domains of behavior can be acquired only during a sensitive or critical period. Examples include song learning in the Zebra finch, social imprinting[2] in some mammals, and the development of binocular vision (for discussion, see Knudsen, 1999). Other behaviors, such as learning and memory, depend less on experience occurring at a particular point in development, and thus occur throughout the life span (see Nelson, in press). Regardless of whether there is or is not a critical period, experience is responsible for the changes that occur in the brain, which in turn determines the behavioral profile and development of the organism. Alas, this malleability is a two-edged sword, in that such changes can be both adaptive and maladaptive for the organism.

MALADAPTIVE CHANGES

Let us begin with the bad news, which is that the wrong experiences can have deleterious effects on the brain. Perhaps the clearest example concerns the effects of stress on the developing and developed brain. Rats exposed to stress pre- or postnatally show a wide range of changes in the brain's serotonin, catecholamine, and opiate systems.[3] Similarly, rats raised in social isolation make more learning errors than socially raised rats. Finally, brief maternal deprivation in the rat pup can alter the sensitivity of the hypothalamic pituitary adrenal (HPA) axis (see Black, Jones, Nelson, & Greenough, 1998, for review), thereby potentially altering the animal's ability to regulate and mount a behavioral response to threat.

Similarly, pregnant Rhesus monkeys exposed to different stressors at different points in time give birth to offspring that show seemingly permanent neurobehavioral changes. For example, at the cognitive level, the achievement of object permanence (the concept that objects out of sight continue to exist) can be delayed, and performance on tests of explicit memory[4] can be impaired. At the behavioral level, these animals display long-lasting changes in their ability to control their emotional state (see Schneider, in press).

The effects of prenatal exposure to stress are not limited to the rat or monkey. For example, Lou et al. (1994) reported that stress during pregnancy affected the head circumference of human newborns. (Head circumference is a coarse measure of brain growth.) In addition, prenatal stress was related to less than optimal outcome in the newborn period. As researchers have hypothesized for the rat and monkey, Lou et al. speculated that the effects of maternal stress on fetal brain development might be mediated by stress hormones (glucocorticoids) circulating in the bloodstream. A similar mechanism has been proposed to account for the observation that adults who have survived abuse as children show reduced volume of the hippocampus (a brain structure important for explicit memory) and, correspondingly, impairments on memory tasks. In this case, glucocorticoids act toxically on the hippocampus, which is well endowed with glucocorticoid receptors (see McEwen & Sapolsky, 1995).

Overall, there is clear evidence that early or late exposure to stress can deleteriously affect a range of brain systems, and thus a range of behaviors. In this context, one may view stress as something akin to a psychological lesion that exerts its effects to varying degrees depending on what system is targeted, the age of the organism when the stress occurred, and whether there are protective or exacerbating factors that can moderate the effects.

ADAPTIVE CHANGES

Having begun with the bad news, let us now turn to the good news, which is that being exposed to the "right" experiences can have beneficial effects on brain and behavior. Greenough and his colleagues have demonstrated that rats raised in complex environments (e.g., those filled with lots of toys and other rats) perform better than rats reared in normal laboratory cages on a variety of cognitive tasks (see Greenough & Black, 1992, for review). Correspondingly, the brains of these rats show improved synaptic contacts, and a greater number of dendritic spines. Even more impressive changes are observed in perceptual-motor tasks. For example, Black and Greenough (see Black et al., 1998) required rats to learn complex motor coordination tasks and found the rats developed more synapses within the cerebellum, a brain structure important for performance of such tasks. Kleim, Vij, Ballard, and Greenough (1997) demonstrated that these changes can be long lasting.

Reorganization of the brain based on selective experience is not limited to the rat. For example, Mühlnickel, Elbert, Taub, and Flor (1998) have reported that adults suffering from tinnitus (ringing in the ears) show a dramatic reorganization of the region of the cortex that deals with hearing. This same group (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995) has also shown that in musicians who play string instruments, the region of the somatosensory cortex (the region of the brain that subserves the sense of touch) that represents the fingers of the left hand (the hand requiring greater fine-motor learning) is larger than the area that represents the right hand (which is used to bow), and larger than the left-hand area in nonmusicians. Finally, Ramachandran, Rogers-Ramachandran, and Stewart (1992) have observed similar findings in patients who have experienced limb amputation. The region of the somatosensory cortex that sits adjacent to the region previously representing the missing limb encroaches on this area. This, in turn, may account for why patients experience sensation in the missing limb (e.g., the forearm) when this new area (e.g., that representing the cheek) is stimulated (Ramachandran et al., 1992). Collectively, this work suggests that the adult human cortex can be reorganized based on experiences that occur relatively late in life.

What of plasticity during childhood? Tallal and Merzenich (Merzenich et al., 1996; Tallal et al., 1996) have speculated that in some children, difficulty in parsing ongoing speech into sound segments leads to difficulty discriminating speech sounds. These authors have reported improvements in both speech discrimination and language comprehension when such children are given intensive training in speech processing. Although the brains of these children were not examined, presumably changes at the level of the auditory-thalamo-cortical pathway were modified by this experience.

These are but a few examples of how the brain is modified by experience; many others, in various domains of functioning, and at various points in development, could be provided. This is not to say, however, that experience-induced changes are possible in all domains of behavior at all points in time. For example, there is evidence from studies of deprivation that children not exposed to normal caretaking environments during their first few years of life may suffer long-lasting changes in their socioemotional functioning (although some individuals show sparing or recovery of function that is quite remarkable). Similarly, we have known for many years that being able to see with only one eye in the first few years of life yields intractable deficits in binocular depth perception, and that prolonged linguistic deprivation yields similarly intractable long-term deficits in language, speech perception, or both. Even these cases, however, speak to the importance of experience, as without normative experiences normal development goes awry.

IMPLICATIONS OF WORK ON NEURAL PLASTICITY FOR BEHAVIORAL DEVELOPMENT

The foregoing observations suggest that the "innate"-versus-

"learned" debate is fallacious. An example from the literature on face perception illustrates this point (some aspects of language development may be another example). Some investigators have argued that face recognition is innate, by which they (presumably) mean that it develops without benefit of experience. However, we know that infants come into contact with faces as soon as they are born. Thus, it seems just as reasonable to argue that experience drives the development of the neural tissue (perhaps selected by evolutionary pressures, given the importance of face recognition in survival) that takes on this function and that this tissue becomes specialized rather quickly. (The brain structures responsible for face recognition in the adult are in the right temporal cortex and include the fusiform gyrus.) This process would allow the ability to recognize faces to appear early in development, but this is not the same thing as saying this ability is innate *qua* innate. Conversely, to argue that face recognition is "learned" does not do justice to the fact that such learning by default necessitates changes in the brain, which in turn alter which genes are expressed (i.e., activated). Even if one argues that an ability is "genetic" (although proving such a case would seem insurmountable without benefit of being able to specify the genes), gene expression is influenced by experience, and once experience occurs, the brain is altered, which in turn alters gene expression, and so on and so forth.

What are the practical implications of the approach I am advocating? Two come to mind. The first pertains to intervention. By understanding precisely how the brain is modified by experience, we can better identify the experiences needed to bring children back on a normal developmental trajectory, or prevent them from moving off this trajectory. In addition, we can target our interventions more judiciously, rather than targeting the whole child. Finally, using the tools of the neuroscientist, we may be able to examine the brain before and after an intervention, and in so doing better determine where in the nervous system change occurred. For example, if damage to the auditory-thalamo-cortical pathway appears to be responsible for some language-learning disorders, might noninvasive procedures such as event-related potentials (electrical activity generated by the brain in response to discretely presented events) or functional magnetic resonance imaging be used to (a) confirm or disconfirm this hypothesis and (b) evaluate the effectiveness (or lack thereof) of a given intervention and its effects on brain structure and function (see Nelson & Bloom, 1997)?

A second implication of the perspective advocated in this essay pertains to our understanding of competence and resilience. As work by Masten and Garmezy (Masten et al., in press) has shown, not all children reared in suboptimal conditions (including those at significant risk for psychopathology) move off a normal trajectory. Similarly, not all children who suffer frank brain damage experience disastrous outcomes. And, in both cases, many of those who do fall off a normal trajectory show some recovery—even considerable recovery in some instances. Might we view those children who are otherwise at risk but do not show any deleterious effects as an example of neural sparing, and those who show some deficits followed by a return to a normal trajectory as an example of recovery of function? If so, can we identify how the brains of these children incorporated experience differently than the brains of children who show no sparing or recovery of function? And can we evaluate these changes using the latest tools from the neurosciences?

CONCLUSIONS

It is indisputable that some aspects of pre- and postnatal human development have their origin in the expression of genetic scripts conserved through evolution and expressed at key points in development. One example may be the prenatal expression of the genes that regulate the formation of body parts (i.e., homeotic genes); another may be the postnatal expression of genes (not yet identified) that lead to the cascade of hormonal changes that usher in puberty. Even in these cases, of course, experience may influence the outcome; for example, the presence of teratogens may corrupt the influence of the homeotic genes (e.g., thalidomide can cause limb deformities), and culture or other experiences can influence pubertal timing. These examples notwithstanding, the changes in behavior that occur over time and that are of most interest to behavioral scientists (e.g., changes in perception, cognition, social-emotional behavior) are likely mediated by experientially induced changes in the nervous system. Thus, it may serve us well to rethink how the brain develops and changes across the life span by considering the important role of experience in sculpting neural systems. In so doing, we may be able to shed some of the contentious history that has plagued our discipline for years (e.g., nature vs. nurture; innate vs. learned), and embrace new theoretical and empirical approaches to human development and brain function.

Recommended Reading

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Notes

1. Address correspondence to Charles A. Nelson, Institute of Child Development, University of Minnesota, 51 East River Rd., Minneapolis, MN 55455; e-mail: canelson@tc.umn.edu.

2. Social imprinting is the process by which an animal forms a relationship of some kind to another animal, such as the famous case of the ducklings that followed Konrad Lorenz around.

3. Serotonin and catecholamines are neurotransmitters that play a role in social and emotional behavior. The natural opiates produced by the body can induce feelings of euphoria or well-being.

4. Explicit memory is a form of memory that can be stated explicitly or declared, that can be brought to mind as an image or proposition in the absence of ongoing perceptual support, or of which one is consciously aware.

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