To what extent can cognitive development be understood in terms of the specialization of function in specific structures of the brain ?

by Patricia Karsten

The analysis of children's early cognitive development is concerned with how children develop the mental abilities they need to make sense of the world, how they begin to understand and use language, and the development of higher cognitive functions like planning and adaptation of behaviour to the situational context. Cognitive development goes along with development of specialized functional structures in the brain, specifically in the cerebral cortex. The following discussion begins by illustrating the modularity of cognitive functions referring to Fodor's 'Modularity of mind', and then presents two opposing views regarding the process by which modularity and functional specialization of brain structures are achieved: innateness (genetical predisposition) vs. epigenesis (interaction between genes an environment). The notion of plasticity, understood as the brain's ability to adapt to changing environments, is further explored as it provides key evidence to support an epigenetic view of the developmental process. It will be shown that cognitive development and the functional specialization of brain structures are inextricably linked, introducing the notion of domain-specificity to Piaget's modelling of successive developmental stages.

The human mind works in a highly modular way, and its functional units, the so-called cognitive modules, can in many cases be mapped to structural units of the cerebral cortex. For example, language is typically processed on the temporal lobe, sideways on the left hemisphere. Higher, 'executive' cognitive functions like planning and behavioural control are located on the prefrontal cortex, the region on the front side of both left and right hemispheres of the cortex (Mareschal, Johnson and Grayson 2006). The functional units operate relatively independent from each other, as can be concluded from evidence about localized brain damage that disturb certain functions, but leave the remaining cognitive functions mostly intact. This modularity and specificity is vividly illustrated by the case study of a blind composer, who suffered a stroke, and consequently lost the ability to speak and to comprehend language as the stroke affected the left hemisphere of his brain (Mehler and Dupoux 1994). But his musical abilities, located on the right hemisphere, remained intact. While the composer could still read and understand musical notation in Braille, he was no longer able to understand Braille-encoded textual information, which shows the high degree of specialization in the functional brain structures involved. Other examples include extremely specific cognitive losses within the general unit, as when patients with damage to their language processing system lose only the ability to correctly process conjunctions, while retaining nouns and adjectives (Mehler and Dupoux, ibid.).

Fodor (1983) theorized the modularity of human cognitive functions. He stated that the mind consists of three types of cognitive modules: The transducers, concerned with processing raw sensory input, then the input modules which further process and integrate information from specific transducers, and finally the central processor, who receives from the input modules and is responsible for non-modular, higher cognitive functions involving abstract thought. Input modules are said to be domain-specific (functionally specialized), encapsulated (operate independently), mandatory (their processing cannot be consciously suppressed), and rapid (as a consequence of the other three properties). The above cited evidence supports the notion of domain-specificity of the input modules, as well as their relative encapsulation. But contradicting Fodor, there are indicators for modularity also of the higher mental functions, for example the autistic spectrum disorder which impairs the ability to understand other people's minds, but leaves other intellectual functions relatively intact, or William's Syndrome which goes along with impairments in mathematical abilities and spatial cognition, but few impairments in other cognitive aspects (Karmiloff-Smith 1992). Thus the evidence strongly suggests that human cognition is thoroughly modularized, from basic to higher cognitive functions. But according to which principles does this modular system develop?

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Proponents of the innateness view of cognitive development see the similarity of brain structures across humans as a strong indicator for cognitive development unfolding along a genetically predetermined plan, in an autonomous manner relatively unaffected by environmental influences (Mehler and Dupoux ibid.; Rakic 1988). Furthermore, Pinker (1994) makes a case for the innateness of human cognitive development applied to the area of language by proposing a ‘language instinct’, and bases this view also on the seemingly fixed location of language processing in the human brain. But if the typically observed locations of language processing structures in the brain were genetically determined, it would be difficult to explain how children are able to overcome damage to brain areas involved in language development. Studies have shown that lesions to certain brain regions impair language acquisition, but only causing a delay, no qualitative difference compared to typical development (Reilly et al. 1998; Stiles and Thal 1993). These findings are explained by the plasticity of the human cortex, its inherent ability to adapt to different circumstances.

Advances in brain imaging techniques have made it possible to visualize differences in cortical activity resulting from atypical development paths, providing further evidence for the brain’s plasticity. A study comparing brain activity patterns in hearing and congenitally deaf participants found the expected left hemisphere activation for both groups in response to their respective native languages, written English and American Sign Language (ASL). But interestingly, hearing participants showed no brain activation in response to ASL and generally no activation of the right hemisphere, whereas deaf participants responded with right hemisphere activation to both ASL and written English, in addition to left hemisphere activation (Neville et al. 1998). This shows how different sensory environments influence and shape the structural specialization of the cortex. There might be a genetic predisposition for the left hemisphere to take over language processing, but other development paths are possible, ruling out the thesis of genetic determination in favour of an epigenetic process, where genes and environment interact. On the other hand, the evidence does not support the notion of functional equipotentiality of the cerebral hemispheres. In their study about the consequences of focal lesions to language acquisition, Stiles and Thal (ibid.) found that language impairments in children with right hemisphere damage lasted longer than in cases of left hemisphere damage. This points out that the right hemisphere plays an important role in language acquisition, before the typical shift to the left temporal lobe takes place, and it shows that left and right hemispheres might not be equally well equipped for language processing tasks, while in the end being able to compensate for deficiencies in case of atypical development paths.

So if cognitive development is not genetically predetermined, what mechanisms guide the epigenetic process? The human cortex appears to start out relatively undifferentiated, with processing units not yet clearly separated. This is inferred from cross-modal transfers, for example when infant’s visual attention preferences can be influenced by prior exposure to auditory or tactile stimuli. Cross-modal transfers disappear during the first months after birth (Lewkowicz and Turkewitz 1981; Stetri 1987; Meltzoff and Borton 1979). From birth up to the age of 2 years, there must be an explosion in the number of neural connections which leads to synaptic density largely above the level found in adults (Huttenlocher 1990). According to the selectionist view, those neural connections that are used survive, while the others get lost, and so neural pathways become specialized and increasingly encapsulated. The process might be guided by self-organizational principles like the Hebb rule (Hebb 1949), which states that neural pathways which are actively used, for example through repeated exposition to certain stimuli, are strengthened, while those that are not used, are weakened and die. In this view, the brain appears as a self-organizing system that reaches a high level of internal structure by following simple, locally effective rules, while the environment continuously provides the needed stimulation for the developing neural pathways.

The prefrontal cortex (PFC) seems to be specifically important for cognitive development. During the first months, it undergoes a phase of physical maturation, in which it takes on its function for working memory. Studies analysing children's EEG responses confirm the importance of the PFC for working memory by showing that activation of the prefrontal cortex is related to the ability of retaining spatial information about objects in memory (Fox and Bell 1990; Bell 1992; Bell and Fox 1992). It is only from about 9 months of age that children reliably succeed in tasks assessing their understanding of object permanence and their ability to retrieve hidden objects by using their visual-spatial memory (Diamond 1985). Studies with infant monkeys on object permanence and retrieval tasks showed similar maturational patterns. Additionally, adult monkeys with lesions to the dorsolateral region of the prefrontal cortex were impaired on these tasks. This suggests that the PFC retains its importance for working memory up to adult age in monkeys, and that these findings might be applicable to the human PFC as well (Diamond and Goldman-Rakic 1989). Maturation of the PFC seems to correspond to children's beginning ability to retain mental representations of objects in memory, as theorized by Piaget (Oates, Sheehy and Wood 2006).

But the PFC is suggested to have a second role for cognitive development. It is proposed that the PFC is involved in skill acquisition, before with increasing proficiency, other specialized brain areas take over the associated processing. Possible support for this view comes from studies assessing infant's visual attention patterns, providing evidence for involvement of the PFC where for adults, the corresponding processing function is located in the parietal lobe. As infants must yet develop the ability to control their eye movements, the shift of activity to a different region might be related to mastering of this skill (Johnson et al. 1998; Csibra et al. 1998). The two positions for the role of the PFC are not contradictory. They suggest that physical maturation, possibly guided by genetic factors, initially enables the PFC to take on its function for working memory. Once this developmental stage is reached, the PFC assists in the acquisition of more complex skills, like language, which are later transferred to other, specialized cortical areas in an epigenetic process responsive to experience and learning.

The above findings can be summarized into an explanation of children's cognitive development largely consistent with Piaget's vision, but recognizing the domain-specificity of cognitive development. Piaget presumed an infant without genetically pre-wired information about the world, possessing only some behavioural reflexes (for example, sucking) and acquiring cognitive skills in stages, guided by the principles of 'assimilation, accommodation and equilibration' (Karmiloff-Smith, ibid.). On the physical level, this would correspond to the initially unstructured cerebral cortex and the brain acting as a self-organizing system, developing functional structures by following locally effective rules. But, as Karmiloff-Smith points out, Piaget theorized holistic developmental stages, where children must attain a domain-general cognitive level in order to perform whole sets of tasks in different domains, whereas the evidence rather supports the notion of domain-specific, modular cognitive development. The outlined role of the prefrontal cortex would be consistent with the modular explanation of cognitive development, with initially high involvement during the acquisition phase of a new skill, and increasing experience in the specific skill triggering the shift of processing activity to other, newly specialized cortical areas, thus freeing mental resources for new task learning. Domain-specific development would also explain why children's cognitive development does not follow Piaget's stages as clear-cut as predicted, but rather shows large overlaps (Oates, Sheehy and Wood, ibid.).

To summarize: For the development of language and higher cognitive functions, research evidence strongly supports the notion of an epigenetic development process, where genetic predispositions and environmental factors interact, resulting in a flexible system that adapts to diverse environmental circumstances. On the physical level, a self-organizing process leads to increasing specialization and encapsulation of functional structures, corresponding to the development of increasingly sophisticated cognitive modules. The brain responds to environmental stimuli and experience, and due to its plasticity, is able to overcome adverse conditions like lesions to regions that might have genetically predisposed functional advantages for processing of certain functions. Thus cognitive development in children can be explained as an epigenetic process of specialization of function in specific structures of the brain, with domain-specific developmental stages of increasing cognitive skills.

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