

## BEYOND PHRENOLOGY: BRAIN AND LANGUAGE IN THE NEXT MILLENNIUM

Elizabeth Bates & Frederic Dick

“Postgenomic thinking” refers to the serious conceptual work that molecular biologists know they will soon have to do, once they have fully sequenced the human genome and still do not understand how it works. A similar fate faces those of us who study brain and language: In the next few years, we will have to engage in “postphrenological thinking,” formulating a new view of brain organization for language to replace the 19th-century perspective that has held sway for most of the 20th century. In both cases, the need for a new conceptual framework is the product of technological breakthroughs. In molecular biology, advances in gene sequencing have brought the goal of genomic description much closer than anyone would have predicted a few years ago. In cognitive neuroscience, new neural imaging techniques have given many investigators a golden opportunity to locate and characterize the discrete phrenological “faculties” or “mental organs” responsible for language, mathematics, social reasoning, etc. And herein lies a great historical irony: Neural imaging is destroying phrenology.

In genetics, as in cognitive neuroscience, our newfound ability to identify and visualize functional substrates has shown that it is fruitless to assume a one-to-one mapping between structure and function. Two examples come from “knockout” studies of genes associated with neural development. Early knockout studies of the ephrinB2 oncogene were conducted with the confident expectation that specific neural defects would follow. Instead, this knockout caused cardiovascular defects; neural development appears to be affected only when ephrinB2 is knocked out in tandem with other ephrinB oncogenes, suggesting substantial redundancy for neural development but (in this case) not for the cardiovascular system. In the same vein, Hoxa1 knockout mice lack part of the hindbrain, while Hoxb1 mice lack certain hindbrain nuclei; neither gene by itself causes large changes outside the nervous system, but their combined knockout causes defective hindbrain development plus almost complete agenesis of the lungs and thymus. It is now clear that genes provide context for each other, in redundant and plastic relationships. Furthermore, many genes respond to the outside environment throughout the animal’s lifetime (including genes involved in neurogenesis that are “turned on” when adult animals are placed in a rich

environment—Kempermann et al., 1998). The resulting picture is one of exquisitely complex bidirectional relationships, between individual genes and an environment that extends from the gene next door to the structure of rat society (Gerhart & Kirschner, 1998).

Likewise, in almost every laboratory that has conducted language activation studies, the first round of experiments was designed to uncover discrete and dedicated “language areas,” or at least “language-relevant areas,” which (by definition) activate selectively for specific language tasks. Language-relevant areas have been duly found. Dozens of them. Hundreds of them. Depending on the task, experimental design, population in question, and/or the protocols used in a given laboratory, virtually every region of the human brain has been implicated in at least one language activation study. The usual left perisylvian “regions of interest” show up in most studies, but the literature also abounds with positive results for right-hemisphere homologues of these zones, as well as prefrontal regions, parietal regions, temporal areas of various kinds (basal, medial, ventral), and (where they are possible to detect) robust cerebellar and subcortical findings.

Even when task, protocol and subject population are held constant, dramatic changes in language-related activation over the brain have been observed as a function of the individual subject’s increased familiarity with the task. Importantly, these task-based changes are not chaotic. Indeed, they are quite predictable. For example, the benchmark Petersen et al. “verb generation” task elicits strong patterns of activation in left prefrontal, anterior cingulate, and right cerebellar regions for subjects who are new at the task. But with less than 15 minutes of practice, activity in these areas lessens, and patterns of activation become indistinguishable from those observed for reading (primarily bilateral activity in the insula, after subtraction). This shift in activation is not language specific; in a parallel maze-learning task, similar changes with rapid skill learning are observed (Petersen et al., 1998). Differences between the two experiments do occur, reflecting changes over motor areas in the maze task vs. auditory areas in the verb-generate task, but the basic 15-minute “novice-to-expert” transition is remarkably similar.

Neural imaging has also shown us that "language areas" have not forgotten their sensorimotor roots. For example, activation in Broca's area is observed when subjects plan covert nonspeech mouth movements, make rhythmic judgments, or perform complex sequences with the hand and fingers. In fact, Broca's area is active when the subject merely observes such movements by another human being, or reacts to static objects (e.g., tools) that are associated with specific movements (Rizzolatti & Arbib, 1998). In other words, language areas are overlaid on regions that continue to mediate the basic sensorimotor skills for which the mammalian nervous system has evolved. These areas may work for language now, but they have kept their day jobs.

Do these data force the conclusion that the brain is essentially a *tabula rasa*, an equipotential blob? No. Rather, the key to postphrenological thinking (or at least one key on the chain) may be found in the labyrinth of neural development. Just as the ErbB and Hox studies illustrate the critical intertwining of brain and body, a better understanding of the *phylogenetically constrained*, but *highly plastic* sensorimotor foundations of cerebral development and organization may allow us to grasp how language colonizes the brain. Here is just one example: Children with early damage to left perisylvian cortex usually go on to attain language abilities within the normal range (Elman et al., 1996). However, a close look at the first stages of language learning in these children suggests that the brain is not equipotential at birth: Specific delays in language learning are associated with specific lesion sites, even though the patterns of lesion-symptom correlations observed in children are quite different from the patterns observed in adults, and disappear over the course of development (Bates et al., 1997). These data suggest that the brain is indeed differentiated at (and before) birth, but it is not set up along phrenological lines. Rather, the "primordial" architecture of the brain reflects phylogenetically consistent regional differences in (a) sensorimotor responsibilities (the sensory and/or motor parts of the body to which that region reports) and (b) style of computation (speed, relative density of interconnections, neurotransmitter properties, and so forth). Because of these "soft" constraints, certain regions are more or less optimal for the development of language processing, but if the best candidate is not available, others can "step in" and do the job—a linguistic example that parallels the

plasticity, redundancy and compensatory interactions that characterize our new understanding of how genes work.

A deeper understanding of these neural and computational constraints on language processing, and particularly the way they change and develop with learning, may finally allow us to come up with a neurobiologically principled account of brain-language relationships. The technologies we will need include high-resolution functional imaging, more neurally realistic neural network simulations of learning and development (Elman et al., 1996), and an improved data base in the developmental neuroanatomy of humans (including cytoarchitectonic studies that can explain what we mean by "regional differences in style of computation"). Such techniques are or soon will be at our disposal, so it is now up to us to make the conceptual leap: We must abandon the 19th-century search for isomorphic mappings between neural and cognitive structures, and use our increasing knowledge of dynamic neural events to build a new view of brain and language for the 21st century.

## REFERENCES

- Bates, E., Thal, D., Trauner, D., Fenson, J., Aram, D., Eisele, J., & Nass, R. (1997). From first words to grammar in children with focal brain injury. *Developmental Neuropsychology*, 13(3), 275-343.
- Elman, J., Bates, E., Karmiloff-Smith, A., Johnson, M., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.
- Gerhart, J., Kirschner, M., & Moderbacher, E.S. (1998). *Cells, embryos and evolution: Toward a cellular and developmental understanding of phenotypic variation and evolutionary adaptability*. Oxford: Blackwell.
- Kempermann, G., Brandon, E., & Gage, F. (1998). Environmental stimulation of 129/SvJ mice causes increased cell proliferation and neurogenesis in the adult dentate gyrus. *Current Biology*, 8, 939-942.
- Petersen, S.E., van Mier, H., Fiez, J.A., & Raichle, M.E. (1998). The effects of practice on the functional anatomy of task performance. *Proceedings of the National Academy of Sciences of the United States of America*, 95(3), 853-860.
- Rizzolatti, G., & Arbib, M.A. (1998). Language within our grasp. *Trends in Neurosciences*, 21(5), 188-194.