

---

# The MIT Encyclopedia of the Cognitive Sciences

EDITED BY  
Robert A. Wilson and  
Frank C. Keil

A Bradford Book

The MIT Press  
Cambridge, Massachusetts  
London, England

ipsilateral and contralateral cerebral hemispheres (Rosen and Galaburda 1996). This provides a possible conduit for the propagation of changes from the ectopias to the thalamus and/or vice versa. Additional research has shown that induction of cortical malformations related to ectopias lead to secondary changes in the thalamus, namely the appearance of excessive numbers of small neurons and a paucity of large neurons (Herman et al. 1997). The animals with the induced malformations also exhibit slow temporal processing involving rapidly changing sounds. There are sex differences in these findings, such that induction of cortical malformations produce both behavioral changes and changes in thalamic neuronal sizes only in treated males. Females demonstrate the anatomic changes in the cortex, but no changes in the thalamus and no abnormal slowing in auditory processing. Moreover, administration of testosterone to pregnant rat mothers in the perinatal period produces masculinization of the female offspring complete with thalamic neuronal changes (Rosen, Herman, and Galaburda 1997).

In summary, animal models for the brain changes seen in association with developmental dyslexia indicate that abnormal cortical development can lead to abnormal development of the thalamus, and that it is likely that brain areas that deal with cognitive tasks and brain areas that deal with sensory-perceptual tasks are both affected in dyslexia. Moreover, the research indicates that multiple modalities, as well as multiple stages of processing, are involved, which may limit the ability of the developing brain to compensate. On the other hand, because of the relative discreteness of the neural connections even during development, not all cortical and thalamic areas are affected, setting up the possibility for a relatively delimited form of learning disorder.

See also APHASIA; GESCHWIND; LANGUAGE IMPAIRMENT, DEVELOPMENTAL; MODELING NEUROPSYCHOLOGICAL DEFICITS; VISUAL WORD RECOGNITION; WRITING SYSTEMS

—Albert M. Galaburda

## References

- Annett, M., E. Eglinton, and P. Smythe. (1996). Types of dyslexia and the shift to dextrality. *J. Child Psychol. Psychiat.* 37: 167–180.
- Association, A. P. (1994). *Diagnostic and Statistical Manual of Mental Disorders—DSM-IV*. Washington, DC: 4th ed. American Psychiatric Association.
- Cornelissen, P., L. Bradley, S. Fowler, and J. Stein. (1991). What children see affects how they read. *Dev. Med. Child Neurol.* 33: 755–762.
- Eden, G. F., J. W. Vanmeter, J. M. Rumsey, J. M. Maisog, R. P. Woods, and T. A. Zeffiro. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature* 382: 66–69.
- Galaburda, A. (1993). Neuroanatomic basis of developmental dyslexia. *Behavioral Neurology* 11: 161–173.
- Galaburda, A. (1994). Developmental dyslexia and animal studies: At the interface between cognition and neurology. *Cognition* 50: 133–149.
- Galaburda, A. M., M. T. Menard, and G. D. Rosen. (1994). Evidence for aberrant auditory anatomy in developmental dyslexia. *Proc. Natl. Acad. Sci. USA* 91: 8010–8013.
- Greatrex, J. C., and N. Drasdo. (1995). The magnocellular deficit hypothesis in dyslexia: A review of the reported evidence. *Ophthalmic Physiol. Opt.* 15: 501–506.

- Herman, A. E., A. M. Galaburda, H. R. Fitch, A. R. Carter, and G. D. Rosen. (1997). Cerebral thalamic cell size and microgyria auditory temporal processing in male and female rats. *Cerebral Cortex* 7: 453–464.
- Livingstone, M., G. Rosen, F. Drislane, and A. Galaburda. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proc. Natl. Acad. Sci.* 88: 7943–7947.
- Lovegrove, W. J. (1991). Is the question of the role of visual deficits as a cause of reading disabilities a closed one? Comments on Hulme. *Cognitive Neuropsychology* 8: 435–441.
- Merzenich, M. M., W. M. Jenkins, P. Johnston, C. Schreiner, S. L. Miller, and P. Tallal. (1996a). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science* 271: 77–80.
- Merzenich, M. M., W. M. Jenkins, P. Johnston, C. Schreiner, S. L. Miller, and P. Tallal. (1996b). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science* 271: 77–81.
- Morais, J., M. Luytens, and J. Alegria. (1984). Segmentation abilities of dyslexics and normal readers. *Percept. Motor Skills* 58: 221–222.
- Neurology, T. A. A. o. (1994). *ICD-9-CM for Neurologists*. 3rd ed. Minneapolis: The American Academy of Neurology.
- Paulesu, E., U. Frith, M. Snowling, A. Gallagher, J. Morton, R. S. J. Frackowiak, and C. D. Frith. (1996). Is developmental dyslexia a disconnection syndrome? Evidence from PET scanning. *Brain* 119: 143–157.
- Pennington, B. F. (1995). Genetics of learning disabilities. *J. Child Neurol.* 10: S69–S77.
- Rosen, G. D., and A. M. Galaburda. (1996). Efferent and afferent connectivity of induced neocortical microgyria. *Soc. Neurosci. Abstr.* 22: 485.
- Rosen, G. D., A. E. Herman, and A. M. Galaburda. (1997). MGN neuronal size distribution following induced neocortical malformations: The effect of perinatal gonadal steroids. *Soc. Neurosci. Abstr.* 23: 626.
- Shankweiler, D., S. Crain, L. Katz, A. E. Fowler, A. M. Liberman, S. A. Brady, R. Thornton, E. Lundquist, L. Dreyer, J. M. Fletcher, K. K. Stuebing, S. E. Shaywitz, and B. A. Shaywitz. (1995). Cognitive profiles of reading-disabled children: Comparison of language skills in morphology, phonology, and syntax. *Psychological Science* 6: 149–156.
- Shaywitz, B., J. Fletcher, J. Holahan, and S. Shaywitz. (1992). Discrepancy compared to low achievement definitions of reading disability: Results from the Connecticut longitudinal study. *Journal of Learning Disabilities* 25: 639–648.
- Stein, J. F. (1994). Developmental neural timing and dyslexia hemispheric lateralisation. *Int. J. Psychophysiol.* 18: 241–249.
- Tallal, P., S. Miller, R. H. Fitch, J. F. Stein, K. McAnally, A. J. Richardson, A. J. Fawcett, C. Jacobson, and R. I. Nicholson. (1995). Dyslexia update. *The Irish Journal of Psychology* 16: 194–268.
- Tallal, P., and M. Piercy. (1975). Developmental aphasia: The perception of brief vowels and extended stop consonants. *Neuropsychologia* 13: 69–74.
- Vellutino, F. R. (1987). Dyslexia. *Sci. Amer.* 256: 34–41.

## Ebbinghaus, Hermann

Hermann Ebbinghaus (1850–1909) was the first psychologist to apply experimental methods to the study of human MEMORY. His groundbreaking book summarizing his experimental work, *Über das Gedächtnis*, was published in 1885.

The English translation appeared in 1913 as *Memory: A Contribution to Experimental Psychology* and is still in print and well worth reading today.

Ebbinghaus was born in Barmen, Germany, studied at the University of Bonn, and began his pioneering research on memory in Berlin in 1878. His work is notable for its many original features. In addition to performing the first experiments on memory, he provided an authoritative review of probability and statistics, an elegant command of experimental design, a mathematical model of the forgetting function, an enlightened discussion of problems of experimenter bias and demand characteristics in research, and a set of experimental results that has stood the test of time. All the experiments reported by Ebbinghaus have been replicated.

No one knows how he created his ingenious methods, although historians have speculated that his purchase of a copy of Fechner's book (in English) (1860/1966) and his reading about psychophysical methods may have been the source of his own clever methodology (see PSYCHOPHYSICS). Ebbinghaus solved the three problems faced by all cognitive/experimental psychologists in their work: to convert unobservable mental processes into observable behavior; to measure the behavior reliably; and to show how the behavior is systematically affected by relevant factors and conditions.

Ebbinghaus solved these problems by creating long lists of nonsense syllables (ZOK, VAM, etc.) to be memorized. He hoped that using these materials would permit him to study formation of new associations with relatively homogeneous materials. He learned the lists by reciting them in time to a metronome and measuring the amount of time or the number of repetitions taken until he could recite a list perfectly. He discovered quickly that the longer the list, the more repetitions were required to effect a perfect recitation. Although this was hardly a surprising finding, Ebbinghaus plotted the exact relation between the length of the series and the amount of time (or number of repetitions) to recall it once perfectly, a measure known as *trials to criterion*. He then had to determine how to measure retention of the series at some later point in time. Ebbinghaus's clever idea was to have himself relearn the list to the same criterion (of one perfect recitation); he could then obtain the savings (in time or repetitions) in relearning the series and use it as his measure of list retention. The greater the savings (the fewer trials to relearn the series), the greater is retention; conversely, if the same number of trials is needed to relearn the series as was originally required to learn it, then its forgetting was complete.

The beauty of Ebbinghaus's relearning and savings method is that measures of retention could be obtained even when recall of the list items was absent. This is one reason Ebbinghaus preferred his objective savings technique over what he called introspective techniques, such as recall or recognition. In a sense, ten years before FREUD proposed his ideas of unconscious mentation, Ebbinghaus had already devised a method whereby they could be studied. Even if someone failed to bring information to mind consciously, the unconscious residue could be examined through his relearning and savings technique.

Ebbinghaus made many discoveries with his new methods. He obtained a relatively precise relation between number of repetitions and forgetting: For every three repetitions

of a list, he saved one repetition in relearning it a week later. He also discovered the logarithmic nature of the forgetting function; great forgetting occurred soon after learning, with the rate of forgetting slowing over time. In addition, he fitted an equation to the forgetting function. He also discovered the advantage of spaced repetitions of lists to massed repetition, when he found that "38 repetitions, distributed in a certain way over the three preceding days, has just as favorable an effect as 68 repetitions made on the day just previous" (page 89).

Ebbinghaus asked the question of whether associations were only formed directly, between adjacent nonsense syllables, or whether in addition remote associations were formed between syllables that were not adjacent. Using the symbols A, B, C, D, E, F, G, and H to represent syllables in a list to be learned, he asked whether there are only associations between A and B, B and C, and so on, or whether there are also associations (albeit presumably weaker ones) between A and C, A and D, and so on. Ebbinghaus developed a clever transfer of training design to answer the question. He derived lists for relearning that had associations of varying remoteness, which can be symbolized as ACEG . . . BDFH (for one degree of remoteness) or ADG . . . BEH . . . CF for two degrees of remoteness, and so on. He discovered that he did show savings in relearning these derived lists relative to control lists (that had no associations), and he concluded that the savings were the result of remote associations. In reviewing Ebbinghaus's work, William JAMES (1890) noted that "Dr. Ebbinghaus's attempt is as successful as it is original, in bringing two views, which seem at first sight inaccessible to proof, to a direct and practical test, and giving the victory to one of them" (page 677). The derived list experiments might be the first case of competitive hypothesis testing between two theories in experimental psychology.

Ebbinghaus was the only subject in all of his experiments, and this fact might give rise to doubt about the results. But he was a meticulous scientist, employing LOGIC, controls, and precise techniques far ahead of this time. All his results have stood the test of time. His particular methods of studying memory were rather quickly supplanted by other techniques—the introspective techniques of recall and recognition that he had wished to avoid—but his great achievements live on. He was the pioneer in showing how complex and unconscious mental processes could be studied through objective means by careful, systematic observation. As such, he helped pave the way for modern cognitive/experimental psychology.

See also BARTLETT; EPISODIC VS. SEMANTIC MEMORY; IMPLICIT VS. EXPLICIT MEMORY; INTROSPECTION

—Henry L. Roediger

## References

- Ebbinghaus, H. (1964). *Memory: A Contribution to Experimental Psychology*. Trans. H. A. Ruber and C. E. Bussenius. New York: Dover. Original work published 1885.
- Fechner, G. (1860/1966). *Elements of Psychophysics*. Vol. 1. H. E. Adler, D. H. Howes, and E. G. Boring, Eds. and Trans. New York: Holt, Rinehart, and Winston.

- James, W. (1890). *Principles of Psychology*. New York: Holt.
- Postman, L. (1968). Hermann Ebbinghaus. *American Psychologist* 23: 149–157.
- Roediger, H. L. (1985). Remembering Ebbinghaus. *Contemporary Psychology* 30: 519–523.
- Tulving, E. (1992). Ebbinghaus, Hermann. In L. R. Squire, Ed., *Encyclopedia of Learning and Memory*. New York: Macmillan.

## Echolocation

*Echolocation*, a term first coined by Donald Griffin in 1944, refers to the use of sound reflections to localize objects and orient in the environment (Griffin 1958). Echolocating animals transmit acoustic signals and process information contained in the reflected signals, permitting the detection, localization and identification of objects. The use of echolocation has been documented in bats (e.g., Griffin 1958), marine mammals (e.g., Norris et al. 1961; Au 1993), some species of nocturnal birds (e.g., Griffin 1953) and to a limited extent in blind or blindfolded humans (e.g., Rice 1967). Only in bats and dolphins have specialized perceptual and neural processes for echolocation been detailed.

Acoustic signals for echolocation in bats and marine mammals are primarily in the ultrasonic range, above 20 kHz and the upper limit of human hearing. The short wavelengths of these ultrasound signals permit reflections from small objects in the environment. All bat species of the sub-order Microchiroptera produce echolocation calls, either through the open mouth or through a nose-leaf, depending on the species. The signal types used by different bat species vary widely, but all contain some frequency modulated (FM) components, which are well suited to carry information about the arrival time of target echoes. Constant frequency (CF) signal components are sometimes combined with FM components, and these signals are well suited to carry information about target movement through Doppler shifts in the returning echoes. There is evidence that species using both FM and CF signals show individual variations in signal structure that could facilitate identification of self-produced echoes (see Suga et al. 1987; Masters, Jacobs, and Simmons 1991). One species of echolocating bat of the sub-order Megachiroptera, *Rosettus aegyptiacus*, produces clicklike sounds with the tongue for echolocation (Novick 1958). The most widely studied echolocating marine mammal, the bottlenose dolphin (*Tursiops truncatus*), emits brief clicks, typically less than 50  $\mu$ s in duration, with spectral energy from 20 kHz to over 100 kHz, depending on the acoustic environment in which the sounds are produced (Au 1993).

In echolocating animals, detection of a sonar target depends on the strength of the returning echo (Griffin 1958). Large sonar targets reflecting strong echoes are detected at greater distances than small sonar targets (Kick 1982; Au 1993). Psychophysical studies of echo detection in bats and dolphins indicate a strong dependence of performance on the acoustic environment. Forward and backward masking, background noise level, and reverberation can all influence sonar target detection (Au 1993; Moss and Schnitzler 1995).

Once an animal detects a sonar target, it must localize the object in three-dimensional space. In bats, the horizontal location of the target influences the features of the echo at the two ears, and these interaural cues permit calculation of a target's azimuthal position in space (Shimozowa et al. 1974). Laboratory studies of target tracking along the horizontal axis in bats suggest an accuracy of approximately 1 deg (Masters et al. 1985). The vertical location of a target results in a distinctive travel path of the echo into the bat's external ear, producing spectral changes in the returning sound that can be used to code target elevation (Grinnell and Grinnell 1965). Accuracy of vertical localization in bats is approximately 3 deg (Lawrence and Simmons 1982). The third dimension, target distance, depends on the time delay between the outgoing sound and returning echo (Hartridge 1945; Simmons 1973). Psychophysical studies of distance discrimination in FM bats report thresholds of about 1 cm, corresponding to a difference in echo arrival time of approximately 60 microseconds. Experiments that require the bat to detect a change in the distance (echo delay) of a jittering target report thresholds of less than 0.1 mm, corresponding to a temporal jitter in echo arrival time of less than 1 microsecond. Successful interception of insect prey by bats requires accuracy of only 1–2 cm (summarized in Moss and Schnitzler 1995). In marine mammals, psychophysical data show that the dolphin can discriminate a target range difference of approximately 1 cm, performance similar to that of the echolocating bat (Murchison 1980).

Many bats that use CF-FM signals are specialized to detect and process frequency and amplitude modulations in the returning echoes that are produced by fluttering insect prey. The CF components of these signals are relatively long in duration (up to 100 ms), sufficient to encode target movement from a fluttering insect over one or more wingbeat cycles. The CF-FM greater horseshoe bat, *Rhinolophus ferrumequinum*, can discriminate frequency modulations in the returning echo of approximately 30 Hz (less than 0.5% of the bat's 83 kHz CF signal component), and can discriminate fluttering insect species with different echo signatures (von der Emde and Schnitzler 1990). Several bat species that use CF-FM signals for echolocation exhibit Doppler shift compensation behavior: the bat adjusts the frequency of its sonar transmission to offset a Doppler shift in the returning echo, the magnitude of which depends on the bat's flight velocity (Schnitzler and Henson 1980). Doppler shift compensation allows the bat to isolate small amplitude and frequency modulations in sonar echoes that are produced by fluttering insects.

High-level perception by sonar has been examined in some bat species. Early work by Griffin et al. (1965) demonstrated that FM-bats can discriminate between mealworms and disks tossed into the air. Both mealworms and disks presented changing surface areas as they tumbled through the air, and this study suggested that FM-bats use complex echo features to discriminate target shape. The acoustic basis for target shape discrimination by FM-bats has been considered in detail by Simmons and Chen (1989); however, researchers have not yet determined whether FM bat species develop three-dimensional representations of objects using sonar (see Moss and Schnitzler 1995). Three-dimensional recognition