aspects of thought—perception, imagery, and memory—as contrasted with the "operative" aspects of mental activity. By far the largest part of this effort was centered on the study of perception: some sixty experimental papers, brought together in *The Mechanisms of Perception* (1969). But he also studied mental imagery, which resulted in yet another volume, *Mental Imagery in the Child: A Study of the Development of Imaginal Representation* (Piaget and Inhelder, 1971).

The work on imagery led on to work on memory, resulting in the book *Memory and Intelligence* (Piaget, Inhelder, and Sinclair-De Zwart, 1973). Perhaps the most striking finding of this work is that rather than remaining stable or decaying, a memory can actually improve with time because its evolving structure depends on the child's maturing operativity. For example, a young child shown a series of rods arranged from short to long may remember them 1 week later as a dichotomy, short rods and long rods. But 6 months later, reflecting the child's growing mastery of the scheme of seriation, the child may remember the series as it was originally presented. In contrast with his position in the 1920s, when he tried to separate memory from understanding, Piaget now concluded that "The structure of memory appears to be partly dependent on the structure of the operations" (Piaget, 1970, p. 719).

Collaborators

The work we call Piaget's was really teamwork. Its scope and volume are so vast that it cannot be imagined without the skillful leadership necessary to generate enthusiasm and maintain a sense of direction. Piaget had many collaborators, ranging from student assistants to distinguished scientists and scholars in various fields. Besides psychologists there were mathematicians, logicians, philosophers and historians of science, biologists, physicists, and linguists. Almost everyone he worked with called him *patron* (boss). His longest collaboration (50 years), and the most important, was with Bärbel Inhelder, who began as his student and became a distinguished scientist in her own right, almost always working together or in close proximity—both spatially and intellectually—with Piaget.

Conclusion

Since about 1970 there have been numerous critical studies of Piaget's empirical findings and of his theoretical approach. By about 1990, much of the anti-Piagetian criticism had ebbed and had given way to neo-Piagetian efforts to assimilate Piaget's findings, correct some of his errors, and synthesize his work with newer developments in cognitive and social psychology. Most of his empirical findings have been vetified by studies in many countries. Perhaps his most important contribution to developmental psychology was to reveal the child as a thinking being, and the child's intellect as growing through its own efforts in interaction with the physical and social world.

REFERENCES

Chapman, M. (1988). *Constructive evolution, origins and development of Piaget's thought.* New York: Cambridge University Press.

Gruber, H. E., and Vonèche, J. J. (1977). *The essential Piaget.* New York: Basic Books. A compendious anthology with explanatory comments.

Inhelder, B., Sinclair, H., and Bovet, M. (1974). *Learning and the development of cognition.* Cambridge, Mass.: Harvard University Press.

Kuhn, D., ed. (1989). *Human Development 32* (6), 325–387. A special issue devoted to reflections on the impact of Piaget's work.

Piaget, J. (1921). Essai sur quelques aspects du développement de la notion de partie chez l'enfant. *Journal de psychologie normale et pathologique 18,* 449–480.

——— [1961] (1969). *The mechanisms of perception.* Trans. G. N. Seagrim. New York: Basic Books.

——— (1970). Piaget's theory. In P. H. Mussen, ed., *Carmichael's manual of child psychology.* New York: Wiley.

——— [1967] (1971). *Biology and knowledge.* Trans. B. Walsh. Chicago: University of Chicago Press.

Piaget, J., and Inhelder, B. [1966] (1969). *The psychology of the child.* Trans. H. Weaver. New York: Basic Books. An excellent, readable introduction to the psychological work.

——— [1966] (1971). *Mental Imagery in the child: A study of the development of imaginal representation.* Trans. P. A. Chilton. New York: Basic Books.

Piaget, J., Inhelder, B., and Sinclair-De Zwart, H. [1968] (1973). *Memory and intelligence.* Trans. A. J. Pomerans. New York: Basic Books.

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From R.L. Squire, ed. Encyclopedia of Learning and Memory. New York: Maxwell Macmillan International, 1992: 527–532

POSITRON EMISSION TOMOGRAPHY

Positron emission tomography (PET) is a technology that creates images of the distribution of radioactivity within any tissue that is placed within the central opening of a doughnut-shaped PET camera. In the case of brain imaging, a small amount of radioactive substance, called a tracer, is given to a subject, usually by injection into the bloodstream or by inhalation of gas. Most tracers have short half-lives and must therefore be manufactured on site with a cyclotron. The tracers emit positrons, which travel a short distance within the tissue before encountering an electron. The annihilation event resulting from this encounter results in two photons, which travel from their source in precisely opposite directions. The ring of detectors surrounding the head is constructed to record an event only when two photons reach the detectors simultaneously. Computer algorithms are then applied to reconstruct a three-dimensional image of radioactivity.

The most commonly used tracer for cognitive studies is radioactively tagged water to measure brain blood flow. Because the tracer in this case is carried through the circulatory system, radioactivity will be high in those parts of the brain that have high local blood flow and low in those parts that have low local blood flow. The rationale behind imaging local regional blood flow is based on observations of higher blood flow in those parts of the brain that are "working harder" (i.e., those parts with high rates of neuronal activity).

An important feature of PET methodology, as it applies to the study of cognition in general and of memory in particular, is the use of subtraction techniques. If one simply recorded a PET image while a subject engaged in a task, many different areas of the brain would prove to be involved. However, one can potentially isolate specific components of cognition by imaging the brain on two occasions several minutes apart, while subjects engage successively in two closely related tasks. The subtraction of the first image from the second then identifies those areas of the brain that are active in the second task but not in the first.

In the case of studies of memory involving PET, the strategy is to ask subjects to engage in a memory task in which they attempt to recollect recent information, and a related task in which they read, process, and otherwise interact with the same stimuli but do not retrieve from recent memory. Studies of this kind have revealed activation of the hippocampal region and prefrontal cortex, areas known through studies of brain-damaged patients and of experimental animals to be associated with memory functions. Other information from these same studies illuminated the anatomical basis of word priming, a simple form of nonconscious memory in which the ability to detect or identify words is facilitated by their recent exposure. An area of decreased activation was observed in posterior visual cortex during priming, as compared with a similar condition when priming could not occur. These results suggest that when a word is presented visually, modifications occur along the visual pathways that process the word, so that on subsequent exposure less neural work is required to process the same word.

In another series of studies, PET has been used to gain insight into how subjects process single words that are presented visually. One important finding is the activation of an area in left posterior cortex by words and orthographically regular nonwords (e.g., *glone, stog*) but not by illegal nonwords (e.g., *glxqr, patjk*). These findings thus identify an area of the brain that must be organized during normal development and that can achieve its final organization only after a person learns to read. These findings provide direct evidence for the long-term storage of memories in neocortex (in this case, memory for word forms that are legal in written English).

Studies of cognition with PET are just beginning. Much more can be expected to be learned about cognition and memory through use of this new technique.

Steven Petersen
Larry R. Squire

POSTTETANIC POTENTIATION

The synapse is the point of transmission of information between one neuron and another. Electrical activity in the presynaptic neuron influences electrical activity in the postsynaptic cell. This influence can be excitatory, in which case presynaptic action potentials trigger postsynaptic action potentials, or at least increase the probability of their

ccurrence in response to other inputs. Synaptic
nteractions can also be inhibitory, in which case
resynaptic action potentials reduce the post-
ynaptic firing frequency or reduce the probability
f firing action potentials in response to other ex-
itatory inputs. *Posttetanic potentiation* is an in-
reased effectiveness of synaptic transmission that
sts for minutes following high rates of neuronal
ctivity.

Most synapses operate by means of an electrical-
)-chemical transduction at the presynaptic neu-
)n, followed by a chemical-to-electrical transduc-
on at the postsynaptic cell. An action potential
) the presynaptic neuron opens calcium channels
) the membrane, and calcium rushes into the pre-
/naptic terminal, the region of the presynaptic
curon that comes into contact, or synapses, with
ie postsynaptic cell. The rise in presynaptic cal-
ium triggers the release of a chemical substance,
tlled a transmitter, that diffuses across the synap-
c cleft separating presynaptic from postsynaptic
ells and binds to receptor proteins in the mem-
rane of the postsynaptic cell. In fast-acting syn-
)ses, the activation of these receptors opens post-
ynaptic ion channels, and the flow of current
hrough these channels makes the postsynaptic
ell more electrically positive (depolarizes it) or
)ore negative (hyperpolarizes it). Depolarization
nds to trigger postsynaptic action potentials, ex-
ting the postsynaptic cell, so the signal generated
the postsynaptic cell is called an excitatory post-
ynaptic potential (EPSP). Hyperpolarization
locks postsynaptic action potentials, inhibiting
e postsynaptic cell; such a response is called
inhibitory postsynaptic potential (IPSP). (See
SO MEMBRANE CHANNELS AND THEIR MODULATION IN
ARNING AND MEMORY.)

ynaptic Plasticity

napses are not static in their transmission proper-
es. Rather, the effectiveness of a presynaptic ac-
on potential depends on its proximity to prior
tivity. At some synapses, following a presynaptic
tion potential, a second action potential is likely
be more effective for about 1 second. This short-
sting increase in the size of the postsynaptic po-
ntial (PSP) is called synaptic facilitation. At many
napses, a slightly longer-lasting (several seconds)
ase of increased transmission has been detected,
hich is called augmentation. At other synapses, a second action potential will have less effect than the first for several seconds. The decrease in PSP amplitude is called synaptic depression. Although these effects can be observed following a single action potential, they accumulate or increase during repeated presynaptic activity. They are especially prominent during *tetanus*, high-frequency repetitive stimulation of the presynaptic neuron. Some synapses show a mixture of facilitation, augmentation, and depression, such that the first few PSPs in a tetanus grow for one or a few seconds due to facilitation and augmentation, while subsequent responses decline for several more seconds due to depression. These short-lived changes in the strength of synaptic transmission are collectively called short-term synaptic plasticity (Figure 1).

Another form of short-term synaptic plasticity is called synaptic potentiation. It is similar to synaptic facilitation or augmentation in that it consists of an increase in the strength or effectiveness of synaptic transmission, and is expressed as an increase in the size of the EPSP or IPSP. It differs in its kinetics. Potentiation is a slowly accumulating increase in PSP amplitude seen during a tetanus. It consists of a gradual growth in the PSPs over a period of minutes during continued presynaptic electrical activity. Tetanic potentiation therefore continues to grow long after facilitation has reached a steady state (usually about 1 second). However, it may be obscured by depression occurring simultaneously during a tetanus. Often depression is stronger than potentiation, so that the net effect of continued stimulation is reduction of the PSP. In that case, tetanic potentiation can be observed only when techniques are used to block the development of depression. One such technique is use of a low-calcium medium to reduce the amount of transmitter released by action potentials. This prevents the depletion of presynaptic transmitter stores during the tetanus, and avoids depression. Such a reduction in calcium has little effect on the opposing processes of synaptic facilitation and potentiation.

In normal medium, depression usually lasts for a few seconds or perhaps a minute after repetitive stimulation ceases, while the effect of potentiation lasts for tens of minutes. Thus, after a tetanus sufficiently long (usually several minutes) to initiate a significant degree of potentiation, and after the synapse has recovered from depression, single presynaptic test stimuli evoke PSPs that remain potentiated for minutes; that is, they are larger than

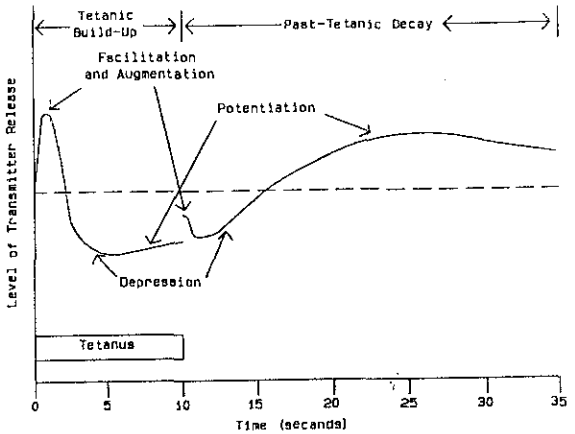

Figure 1. Changes in strength of synaptic transmission due to facilitation, augmentation, depression, and potentiation operating simultaneously, measured during a tetanus and as a function of time after a tetanus.

the original isolated PSP that follows a long period of silence. This phenomenon is called posttetanic potentiation, frequently abbreviated PTP. It is really the persistent effect of tetanic potentiation, observed most clearly after recovery from depression.

Presynaptic Locus

In principle, short-term synaptic plasticity could arise at either presynaptic or postsynaptic sites. Presynaptically, action potentials could evoke the release of more or less transmitter. Postsynaptically, the transmitter receptors could become more or less sensitive, or the electrical response of a neuron to the postsynaptic current could change. In fact, at almost all synapses that have been studied, short-term synaptic plasticity is due to changes in the amount of transmitter released by an action potential. Transmitter is released in small packages of about 5,000 molecules, probably by the fusion of membrane-bound transmitter-containing vesicles with the presynaptic membrane, followed by exocytosis of their contents. Facilitation, depression, and potentiation or PTP are all caused by changes in the number of these packages, called quanta, that each action potential causes to be released at the presynaptic nerve terminals. The size of the quanta and their postsynaptic effectiveness change little during these processes.

Prevalence and Significance

Practically all chemically transmitting synapses that have been studied show a mixture of facilitation, depression, augmentation, and potentiation. This includes central synapses between neurons in the mammalian brain and spinal cord, sensory nerve synapses, peripheral synapses in the ganglia of the autonomic nervous system, release of transmitter from neurosecretory terminals in the pituitary, synapses between neurons in invertebrate ganglia (especially mollusks and annelids), and synapses from motor neurons onto muscles (neuromuscular junctions) in vertebrates, crustaceans, and insects.

The effect of these forms of short-term plasticity is to make synapses selective for certain patterns of presynaptic activity. Potentiation in particular causes only sustained and prolonged activity to be maximally effective in exciting or inhibiting the postsynaptic neuron. This can be important

n extracting significant signals from noise. Differnces in the mixture of plasticities can cause the arious terminals of a neuron to select different atterns of activity for transmission to different ostsynaptic targets. This adds greatly to the inforation-processing capabilities of synapses, and ay allow certain pathways to respond only to pecific patterns corresponding to particular signifcant stimuli. The ability to distinguish such patrns is an important aspect of many neural netvorks proposed as models of neural circuits apable of learning. These forms of plasticity are orms of synaptic modifiability, which plays an imortant role in most theoretical models of learning etworks.

tole of Calcium

Calcium can be manipulated rapidly in the neighorhood of nerve terminals by ejecting it iontophoetically from a micropipette in a calcium-free nedium. Such experiments show that facilitation, ugmentation, and potentiation all require calcium o be present during the conditioning stimulation or the effects to be expressed by test stimuli. This as led to the hypothesis that all three effects require the entry and accumulation of presynaptic alcium during conditioning stimulation. Transmitter release by single action potentials depends in highly nonlinear way on external calcium concentration and the influx of calcium during action otentials. When calcium-sensitive dyes are injected into nerves near their terminals, changes n external calcium relate nearly linearly to hanges in influx and calcium accumulation. Thus here appears to be a highly cooperative action f calcium ions at their presynaptic receptor site n releasing transmitter. Roughly speaking, release s proportional to the fourth power of external alcium concentration, calcium influx, or calcium ctivity at presynaptic release sites.

One might imagine that a small residual amount $R(t)$) of the calcium that enters during action otentials (E) remains at time t after one or more pikes. Then a single action potential will release T_1 quanta according to $T_1 = K(E)^n$, where K is a roportionality constant. A second action potenial, or one following a tetanus, will release T_2 uanta according to $T_2 = K(E + R)^n$. Suppose hat at time t, $R(t)$ is 10 percent of E. Then the egree of facilitation, augmentation, or potentiation, T_2/T_1, will be $(1 + R(t)/E)^n$, which for $n = 4$ and $R(t)/E = 0.1$ comes to 1.46 (i.e., the second response will be 46 percent larger than the first). Meanwhile, transmitter release to the residual calcium itself will be negligible: $(R(t)/E)^n$, or 0.01. Finally, the ratio of T_2/T_1 will be independent of calcium concentration in the bath, because E and $R(t)$ are scaled by the same amount as calcium influx changes. These are all properties of facilitation, augmentation, and potentiation, and thus this is a very attractive explanation for these phenomena. Their different time courses would simply reflect the different phases for the accumulation of residual calcium during a tetanus, and of its removal afterward.

Qualitative evidence for such a critical role of residual calcium in potentiation has been obtained. The time course of PTP closely matches the time course of residual calcium actually measured in nerve terminals. In fact, the correspondence is better than expected. The above formulation predicts a nonlinear relationship between $R(t)$ and potentiation. PTP should decay faster than $R(t)$. The linear relation observed means that PTP was greater than expected from the simple hypothesis (Figure 2). Perhaps calcium acts at another site to potentiate the release of more transmitter than predicted by the above model. There is some evidence that calcium can bind to a calmodulin receptor on a kinase that phosphorylates a protein called synapsin I. Phosphorylated synapsin I may release synaptic vesicles from cytoskeletal attachment sites and allow them to move up to release sites, contributing to PTP. This mechanism, if present, acts in addition to the nonlinear summation of residual calcium with entering calcium postulated above, which may be more uniquely responsible for facilitation and augmentation. This would explain why potentiation does not simply summate with facilitation and augmentation but, rather, seems to interact with it multiplicatively. The exploration of these possibilities remains an active area of research.

Role of Sodium In PTP

In addition to calcium, sodium influx during a tetanus contributes to PTP. Action potentials are generated by a brief increase in nerve permeability to sodium ions. Sodium flows into nerves down its electrochemical gradient, briefly depolarizing the membrane before the sodium channels shut. During a tetanus, the presynaptic sodium concentration gradually rises. This accumulation of sodium can be augmented by blocking the sodium pump, which normally slowly restores intracellular sodium to its resting level, with ouabain. This treatment augments PTP and prolongs its decay. Moreover, injection of sodium directly into nerves near their terminals potentiates transmitter release. Conversely, sodium entry can be prevented with the sodium channel blocker tetrodotoxin, and transmitter release can be triggered by direct pulsed depolarization of the nerve terminals with electrodes placed next to them. Transmitter release to a tetanus of such pulses shows reduced PTP. How does sodium exert this influence on PTP? Normally, the calcium that accumulates presynaptically in a tetanus is extruded by a membrane transport pump that exchanges external sodium for internal calcium. Elevation of internal sodium in a tetanus retards this pump, so that more calcium accumulates during the tetanus and its subsequent removal is retarded. Thus the time course of PTP is determined by the rate at which calcium is removed from the terminals, and this in turn depends on the accumulation of presynaptic sodium. Theoretical calculations of the extrusion of calcium from nerve terminals by such membrane pumps predict a late phase of decay of potentiated release similar to PTP (Figure 3).

PTP, then, is a fascinating property of chemical synaptic transmission. It contributes to the information-processing capabilities, temporal selectivity, and modifiability of synaptic transmission. It appears to be triggered by residual calcium remaining after action potentials. It may arise in part from the nonlinear dependence of transmitter release upon calcium, and in part from calcium acting independently to mobilize vesicles to release sites. Sodium accumulation contributes to PTP by impeding the removal of presynaptic calcium by sodium/calcium exchange. PTP is an entirely presynaptic process, and as such is distinct from the

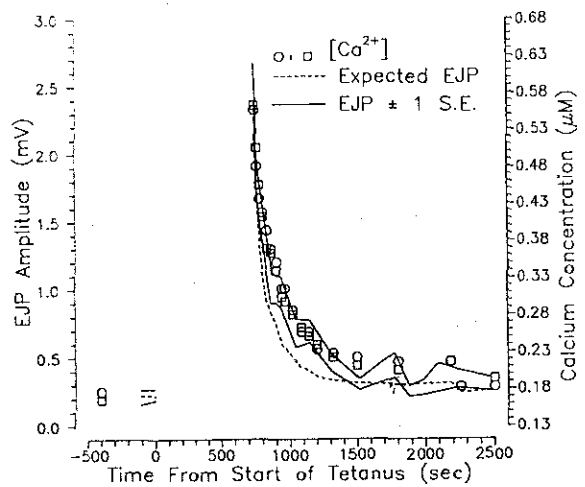

Figure 2. EPSPs from a crayfish muscle fiber (solid lines show average values ± one standard error) before and after a 20-hertz tetanus lasting 12 minutes closely follow the presynaptic calcium concentration measured in two presynaptic terminals using the indicator dye fura-2 (squares and circles). The dashed line is a prediction of the decay of the posttetanic potentiation of the EPSPs, calculated from the simple nonlinear residual calcium model described in the text, from the decay of posttetanic calcium concentration.

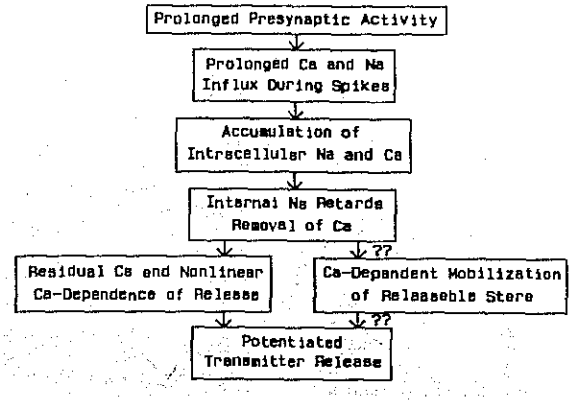

Figure 3. A block diagram of the roles of calcium and sodium in PTP.

ich longer-lasting and more complex class of enomena called LONG-TERM POTENTIATION.

REFERENCES

wood, H. L., and Wojtowicz, J. M. (1986). Short-term and long-term plasticity and physiological differentiation of crustacean motor synapses. *International Review of Neurobiology 28,* 275–362. Summarizes the evidence for roles for calcium and sodium in PTP.

lancy, K. L., Zucker, R. S., and Tank, D. W. (1989). Calcium in motor nerve terminals associated with posttetanic potentiation. *Journal of Neuroscience 9,* 3558–356". Describes experiments on the relationship between residual calcium and PTP.

gelson, A. L., and Zucker, R. S. (1985). Presynaptic calcium diffusion from various arrays of single channels: Implications for transmitter release and synaptic facilitatinn. *Biophysical Journal 48,* 1003–1017. Describes simulations of residual calcium underlying synaptic plasticity.

tz, B. (1969). *The release of neural transmitter substances.* Springfield, Ill.: Charles C. Thomas. The classic treatise on transmitter release.

igleby, K. L., and Zengel, J. E. (1982). A quantitative description of stimulation-induced changes in transmitter release at the frog neuromuscular junction. *Journal of General Physiology 80,* 613–638. Summarizes extensive work by these authors on the kinetics and interactions between the various phases of short-term synaptic plasticity.

:Guinness, T. L., Brady, S. T., Gruner, J. A., Sugimori, M., Llinas, R., and Greengard, P. (1989). Phosphorylation-dependent inhibition by synapsin I of organelle movement in squid axoplasm. *Journal of Neuroscience 9,* 4138–4149. Suggests that calcium-sensitive protein phosphorylation may contribute to PTP.

Smith, S. J., and Augustine, G. J. (1988). Calcium ions, active zones and synaptic transmitter release. *Trends in Neuroscience 11,* 458–464. A good discussion of calcium action in transmitter release.

Zucker, R. S. (1989). Short-term synaptic plasticity. *Annual Review of Neuroscience 12,* 13–31. A general review with many references.

Zucker, R. S., Delaney, K. R., Mulkey, R., and Tank, D. W. (1991). Presynaptic calcium in transmitter release and post-tetanic potentiation. *Annals of the New York Academy of Sciences 635,* 191–207. Includes recent results on sodium-calcium interactions in PTP.

Robert S. Zucker

PREFRONTAL CORTEX AND MEMORY IN PRIMATES

A primate needs its prefrontal cortex whenever and wherever it has to perform an action based on information that is not available at the time to act but has been available in the recent past. The prefrontal cortex is especially important if the information is new to the organism or is in conflict with prior cues or memories that call for different actions. Whether the information is new or old, it must be retained in memory until the time to act in accord with it. That is the kind of memory the prefrontal cortex supports. It is short-term memory (also called WORKING MEMORY) at the service of behavior. Prefrontal memory is defined not by content or by duration but by context, the context of action. Short-term memory is not the only function of the prefrontal cortex, nor is it exclusively the role of the prefrontal cortex. But, inasmuch as short-term memory is needed in and for action, the prefrontal cortex is needed. It follows that this part of the cortex is essential for the construction of sequential behaviors, especially if they are novel or require choices between competing alternatives. It is needed for the *syntax of the action,* including of course the syntax of the spoken language, particularly creative speech.

The prefrontal cortex is the cortex of the pole of the frontal lobe. It is conventionally defined as that part of the cerebral cortex to which the nucleus mediodorsalis of the thalamus projects. Phylogenetically, it is the neocortical region to undergo the greatest and latest expansion (Figure 1). It reaches maximum development in the brain of the human, where it occupies almost one-third of the totality of the neocortex. In the course of evolution, its dorsolateral aspect, that is, the cortex of the external convexity of the frontal lobe, develops relatively more than its medial and inferior aspects. This is an important consideration because the dorsolateral prefrontal cortex supports mainly cognitive functions, whereas the orbitomedial prefrontal cortex is involved predominantly in emotional and visceral functions.

Cytoarchitectonically, the prefrontal cortex of the primate (area FD of Von Bonin and Bailey, 1947) includes areas 9, 10, 11, 12, and 13 of Brodmann (1909). It is one of the best-connected of all neocortical regions; it is directly and reciprocally connected to the anterior and dorsal thalamus, the hypothalamus, and limbic structures, especially the amygdala and the hippocampus. It sends profuse efferent fibers to the basal ganglia. Dorsolateral prefrontal areas have rich reciprocal connections with many other neocortical areas of the frontal lobe and of the temporal and parietal lobes. (See GUIDE TO THE ANATOMY OF THE BRAIN.)

The first clear indication of the involvement of the prefrontal cortex in short-term memory was provided by Jacobsen in the early 1930s (Jacobsen, 1935). He showed that monkeys with lesions of the dorsolateral prefrontal cortex are impaired in the learning and performance of delayed response (DR) and delayed alternation (DA) tasks. These tasks fall within a general category of behavioral tasks—*delay tasks*—that demand from the animal the performance of motor acts in accord with sensory information presented a few seconds or minutes earlier. In other words, delay tasks demand short-term memory for the logical and consequent bridging of temporal gaps between perception and action, the mediation of cross-temporal contingencies of behavior. Primates deprived of substantial portions of dorsolateral prefrontal cortex cannot properly perform delay tasks, regardless of the nature of the sensory information that guides them, especially if a long lapse of time (delay) is interposed between sensory cue and motor response.

There appears, however, to be some specificity of prefrontal areas with regard to the type of sensory information they help retain. Lesions of the cortex of the sulcus principalis are most detrimental to performance of delay tasks with spatially defined sensory cues, such as DR and DA. However, time seems to override space on this matter. Those "spatial tasks" are impaired only *if* a temporal gap, a delay, is interposed between cue and response. The critical factor is time, the time during which the cue must be retained. Furthermore, dorsolateral prefrontal lesions also impair performance of delay tasks in which the sensory cue is not spatially defined. This has been demonstrated by local cortical cooling. The cryogenic depression of a large portion of dorsolateral cortex (area 9), including the sulcus principalis, induces a reversible deficit in performance of delay tasks, whether the cue is visual and spatially defined (as in DR) or not (as in delayed matching to sample). Furthermore, the cryogenic deficit also affects delayed matching tasks in which the cue (sample) is perceived by active touch (haptically).

Humans with dorsolateral prefrontal lesions also show impairments in delay tasks. Tasks in which the material to be retained can be verbally encoded are more affected by lesions of the left than of the right prefrontal cortex. They are impaired most of all by bilateral lesions. The human prefrontal syndrome is usually characterized by disorders of attention, planning, and language. Prefrontal patients have difficulty maintaining attention on internal cues or mental material to be retained for the short term. Their planning is poor for both the short and the long term; it is as if they lacked "memory of the future" in addition to memory of the recent past. Both retrospective and prospec-