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"Memory of the future": an essay on the temporal organization of conscious awareness

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Summary. The classical tripartite concept of time divided into past/present/future components, has been applied to the analysis of the functional cerebral substrate of conscious awareness. Attempts have been made to localize and to separate the neuronal machineries which are responsible for the experience of a past, a present, and a future. One's experience of a past is obviously related to one's memories. Memory mechanisms (in the conventional sense) have a well known functional relation to superficial and deep parts of the temporal lobe. Some such mechanisms presumably have a more widespread distribution. The experience of a present or a "Now-situation" is mediated by the sensory input. This input also exerts a role for conscious awareness of an inner Now-situation, independent of current afferent impulses, as shown by numerous observations on sensory deprivation. The main discussion is devoted to the experience of a future. Evidence is summarized that the frontal/prefrontal cortex handles the temporal organization of behaviour and cognition, and that the same structures house the action programs or plans for future behaviour and cognition. As these programs can be retained and recalled, they might be termed "memories of the future". It is suggested that they form the basis for anticipation and expectation as well as for the short and long-term planning of a goal-directed behavioural and cognitive repertoire. This repertoire for future use is based upon experiences of past events and the awareness of a Now-situation, and it is continuously rehearsed and optimized. Lesions or dysfunctions of the frontal/prefrontal cortex give rise to states characterized by a "loss of future", with consequent indifference, inactivity, lack of ambition, and inability to foresee the consequences of one's future behaviour. It is concluded that the prefrontal cortex is responsible for the temporal organization of behaviour and cognition due to its seemingly specific capacity to handle *serial* information and to extract causal relations from such information. Possibly the serial action programs which are stored in the prefrontal cortex are also used by the brain as templates for extracting meaningful (serial) information from the enormous, mainly *non-serial*, random, sensory noise to which the brain is constantly exposed. Without a "memory of the future" such an extraction cannot take place.

Key words: Cerebral circulation – Cerebral metabolism – Concepts of the future – Consciousness – Front

> It is perfectly true, as philosophers say, that life must be understood backwards. But they forget the other proposition, that it must be lived forwards. Kierkegaard (1843)

> The problems are solved, not by giving new information, but by arranging what we have known since long. Wittgenstein (1953)

This essay originates from two sets of data which have been available for a number of years. The first set concerns the "functional landscapes" (Ingvar 1974; Lassen et al. 1978) recorded in the resting and activated brain, in normal subjects and in patients, by measurements of its regional blood flow (Lassen and Ingvar 1961; Lassen et al. 1963; Ingvar and Lassen 1975; Roland 1985, this issue) and metabolism (Reivich et al. 1978; Alavi et al. 1982; Phelps et al. 1982; Mazziotta et al. 1982; Duara et al. 1985). The second set stems from older and recent analyses of conscious awareness (Bianchi 1921; Hebb 1949; Corning and Balabau 1968; Popper and Eccles 1977; Granit 1977; Buser and Rougeul-Buser 1978; Bindra 1980; Bunge 1980; Gregory 1981; Lundh 1983; Prinz and Sanders 1984). By relating these two sets, a hypothesis is formulated here on how the brain handles information on the past, the present, and especially the future. Several aspects of this hypothesis, it is suggested, might be made the object of direct neuropsychological and clinical investigations.

Our concepts of the future and capacity to remember such concepts will receive special attention. Observations in human subjects show that cognitive activity which to a great extent is based upon concepts about the future, often clearly coupled with feelings of anticipation and/or expectation, is in general accompanied by activation of the frontal, mainly prefrontal, cortex. For precise cytoarchitectonic definitions of activated cortical regions in the studies to be quoted, reference is made to Roland (1985, this issue). It should be stressed that the observations upon which this essay is mainly based concern the lateral hemispheric surface and that the spatial and temporal resolution of the methods used is somewhat limited (cf. Roland 1985). Activations of deeper parts of the frontal lobes and of its mesial areas will only be considered to a limited extent, since only few measurements in these regions, related to the present topic, have been made. It is hoped, however, that the views presented will inspire further neuropsychological studies, especially with three-dimensional techniques (see below), of mesial and deeper brain structures and of the manner by which their activity relates to the temporal organization of cognitive and behaviour.

The neurophysiological evidence will then be related to some prevalent concepts derived from analysis of the phenomenon of consciousness which support the view that the frontal cortex in man (as well as in mammals in general, see below) plays a leading role in the temporal organization of behaviour and cognition (Bechterew 1908–1911; Bianchi 1921; Luria 1966, Fuster 1980, 1985 this issue). In the present context, conscious experience is thought to be based on (1) memories of the past, (2) the experience of actual events in the Now-situation, and (3) concepts of future behaviour and cognition, i.e. concepts of events which have not taken place. It appears that the frontal cortex preserves and continuously rehearses and optimizes the programs, or "sets" (Shakow 1967) that it contains; that explains why frontal activity is high in the resting conscious state (Ingvar 1979). The capacity to retain and to be conscious of concepts of future events is here termed "memory of the future". This unconventional and simple term was chosen since concepts about the future, like memories of past events, can be remembered, often in great detail. They can also, like memories of the past, be recalled spontaneously, or at will.

The important question to be raised here is to what extent do events in the brain, related to the past, the present, and the future, take place at a conscious (attentive) level or at a subconscious (pre- or subattentive) level, or at both levels simultaneously. Although this question cannot be answered at present, reference will be made to classical (Freud 1915) and current discussions on this topic. All agree that information is probaly processed continuously at both levels. However, the neuronal mechanisms for this processing are unknown (Ornstein 1972; Edelman and Mountcastle 1978; Davidson and Davidson 1980; Bindra 1980; Gregory 1981).

Consciousness and the concept of time

The main topic, the temporal organization of conscious awareness and its neuronal substrate, necessitates a general consideration of the concept of time.

As shown by Toulmin and Goodfield (1963), and others (cf. Frankenhaeuser 1959; Melges 1982), man's ideas about time have developed slowly. In biology, a linear concept dominates. Biological systems, like the brain, function only for a limited time and, at any point on the time axis of their existence, a past and a future can be conceived (Miller 1976). The point in time on the same axis dividing the two, constitutes the present, the evanescent hypothetical moment of *Now* (cf. Granit 1985, this issue). Such a tripartite past/present/future concept of time is, as many readers are well aware, a very old one. St. Augustine (354– 430) was one of the first to formulate it; he did it exquisitely in his *Confessions*. Immanuel Kant (1781/1919) also stressed a similar notion in the definition of his two fundamental categories of cognitive experience: time and space.

In the present context, it is stressed that the past/present/future time paradigm appears to be very helpful in considerations of conscious awareness and its neuronal prerequisites. Several authors who discuss consciousness have, in fact, stressed that when humans are aware of being conscious – Now – this experience contains both memories of past events as well as concepts, ideas, and hypotheses of anticipated future events. It is also generally taken for granted that the very experience of being conscious can only taken place in the *Now*, in the present (for references, see above).

In two recent papers by the author, the above mentioned tripartite time paradigm was used tentatively to analyze conscious awareness (Ingvar 1979, 1983b). An attempt was made to identify the functional substrates in the brain, i.e. the neuronal structures which are indispensable for the experience of a past, a present, and especially a future. Together, those experiences constitute the total, unitary, experience, which in the view of so many authors, forms the essence of conscious awareness (Melges 1982; Lundh 1983; Wollheim 1984). The discussions in the two papers mentioned (Ingvar 1979, 1983b), are extended in this article, and the functions of the frontal cortex in normals and in patients with brain disorder are especially emphasized.

Basic questions

If one attempts to apply more rigorously the tripartite past/present/future time paradigm to an analysis of consciousness, and to identify its cerebral substrates, three basic questions might be asked:

The past

Which is the neuronal substrate, that is the parts of the brain that are indispensable for storing information of events (memories of motor/behavioural reactions, sensory percepts, sounds, cognitive structures, etc.) which have taken place in the past, events which are remembered and which might be recalled, spontaneously, or at will?

This is, as is well known, the most fundamental question that memory researchers have been asking for centuries. As is also well known, it is not possible to give a complete answer to it, one major reason being that the ultimate neuronal (molecular/electrochemical) nature of memories is not known. However, recent memory research has made substantial advances, both in defining basic cognitive components of human memory and in outlining brain structures which participate in the formation and storage of engrams and in the recall of memories (Tulving 1972, 1985; Nilsson 1979; Deutsch 1983). A widely held notion is that memories, in general, have a diffuse localization in the cerebral cortex (Lashley 1950). Although this notion is supported by much experimental evidence and in the present discussion it cannot by any means be treated as obsolete, an attempt will be made to define somewhat more explicitly the neuronal substrates for memories of the past in contrast to "memories" of the future. It is important to emphasize that, to date, research on memory and research on the memory/consciousness relationship have been concerned almost exclusively with memories of past events and their neuronal correlates.

The present (the Now-situation)

Which parts of the brain are indispensable for the experience of a present, of a (hypothetical) Now?, for the experience that in this very Now-moment you are aware, conscious, that you exist in a given sensory situation, in a given (spatial) context, as a separate human being with your own self identity?

This second basic question can also be found in the vast literature on the phenomenon of consciousness (for references, see above). However, the notion discussed here, of a more or less separate neuronal substrate for the Now-experience, does not seem to have been previously raised in explicit form.

The future

Finally, what is the neuronal substrate for the experience of a future? Which are the parts of the brain that make it possible for us to be aware of, to be conscious of, to anticipate, to expect, to plan for, and to remember events in the future which have not yet taken place?

Concerning the conscious experience of a future, a separate neuronal substrate will be postulated here for two main reasons. First, a number of reports, notably the monographs of Fuster (1980), Melges (1982), and Wollheim (1984), have stressed the fundamental capacity of the central nervous system to deal with the future, to make up action plans and to program anticipatory goal-directed behaviour and cognition. This capacity of the brain is specially pronounced in man; it is closely coupled to man's language ability (cf. Ingvar 1983a). In this context, it is noteworthy that recent research on memory (Tulving 1972, 1985; Lundh 1983) has identified a *semantic* type of memory, on the one hand, which is mainly involved in the cognitive or future consequences and meaning of events and, on the other hand, an *episodic* memory, which pertains to actual sensory and cognitive percepts in the past and in the present.

The second reason to postulate a separate neuronal "future system" in the brain, comes from both experimental and clinical observations which strongly support the main message of the present essay, namely, that the frontal/prefrontal cortex is selectively responsible for the temporal structuring of future behaviour and cognition, during the next moments and minutes, during coming hours, days, weeks, years, and so on. Lesions of the prefrontal cortex or dysfunction thereof reduces or eliminates one's concepts (memories) of the future, such as plans, ambitions and "sets" (Shakow 1963) for the future, which concern short- and long-term goals in one's life. Such plans can, as mentioned, normally be remembered and recalled in great detail, just as we can reconstruct memories of the past. It is a well established clinical fact (see below) that this "inner future" (Melges 1982) of ours is interfered with by frontal lesions or dysfunctions which highly reduce the capacity to conceptualize future events and to foresee future consequences of behavioural acts performed in the past and the present.

The neuronal substrate of the past

Only a few observations from the vast field of research concerning memory (of the past), as it relates to consciousness, will be recalled here. They are especially significant in the present attempt to set aside the awareness of the past, and its neuronal substrate, from awareness of the present and the future and their respecitve substrates.

Experimental and clinical observations have shown that the formation and consolidation, as well as the recall, of engrams which enter short-term and later, in some instances, long-term memory, depend upon structures located in the cortex and deep regions of the temporal lobes, including the amygdalae, the unci, the hippocampi, and related structures (Milner 1972; Mishkin 1982; Deutsch 1983). Bilateral lesions in these regions have severe and tragic consequences for the individual's cognition and behaviour, with a marked (but not total) inability to memorize and recall recent and more remote events and also to use memories of past events as correctives and components of action programs for future behaviour and cognition.

At this point, the by now classical, but relatively few, observations by Penfield and his associates (Penfield and Jasper 1952) on electrical stimulation of the lateral cortical surface of the temporal lobe should be recalled. Such stimulation, as well as stimulations deep in the temporal lobes, provoke instant awareness of memories which are all episodic in character and which concern fractions of past events. To the present author's knowledge, there is no evidence that electrical activation of superficial or deep parts of the temporal lobes gives rise to concepts, ideas or "memories" of future events. This holds true also for electrical activation of other (higher order) postcentral (parietal and occipital) cortical fields; stimulation of these regions has not been reported to give rise to experiences of the future, nor to interfere with concepts of the future. As to stimulation of primary sensory projection areas, see below. A great number of reports of conscious mental experiences following stimulation of subcortical structures have been made. However, as far as these highly scattered reports can be understood, such stimulations do not alter concepts or memories of the future.

To summarize, components of conscious awareness which concern memories of past events and experiences, as well as their recall, appear to have their main neuronal substrate in postcentral cortical areas, espeially in superficial and deep structures of the temporal lobes. Electrical activation of these structures has so far not been reported to provoke – or alter – concepts about the future. Again, the notion of a diffuse localization of memories (Lashley 1950) should be mentioned here, and emphasis given to the fact that the present essay is only a tentative attempt to disentangle some matters concerning the neuronal substrates of memories related to the past and to concepts of anticipated future events.

The present

It goes without saying that the primary sensory systems are indispensable for much of the actual experience of a Now-situation. We are conscious of the fact that we see, hear, and feel things in the present with the aid of our sensory inputs. One or several of the sensory modalities may be lacking, in part or completely, but adequate conscious awareness of the present can still be produced with the aid of modalities which are intact.

Electrical stimulation of primary sensory areas, or pathways to and from them, give the stimulated subject an immediate conscious awareness of seeing, hearing, or feeling things (phosphenes, sounds, paresthesias, etc.) depending on the modality activated (Penfield and Jasper 1954; Ojemann

1983). Such experiences have a clearcut Now-character, and they cease when the stimulation ends, unless an epileptic after-discharge is produced. As far as one may interpret the few reports published, such experiences all lack "meaning", i.e., they are not related to past or future events. Thus, they are of no concern for the mental time sequence from the past into the future which pertains to the normal "stream" of conscious awareness (Davidson and Davidson 1980).

A second form of Now-awareness, unrelated to actual sensory signals, is indeed possible by mere introspective activity. One may lie undisturbed in a dark silent room and still be conscious (see below). The neuronal substrate of such purely cognitive Now-awareness is at present not possible to define. It may, in fact, include an active inhibition of both extero- and interoceptive sensory input (cf. Ingvar 1979). There is introspective evidence that such Now-awareness is made up of *both* memories of the past *and* of the future; it is, we know, contextual in nature, as it is inherently related to cognitive concepts about both the past and the future (cf. Lundh 1983).

The greatly abundant extero- and interoceptive sensory input which during our entire life incessantly impinges upon the nervous system every Now-moment exerts, via primary sensory systems and the brain stem, a fundamental and well established role in conscious awareness. Part of the random and seemingly insignificant sensory input of which one is not aware, is apparently fed into neuronal systems of the brain stem from which a basic activation of the cerebral cortex is exerted. This activation is a prerequisite for adequate wakefulness and consciousness (Magoun 1963; Jasper et al. 1958), as is evident from numerous experiments on sensory deprivation (Solomon 1961; Zubeck 1969; Rasmussen 1973). A deliberate reduction to a minimum of visual, auditory, vestibular, proprioceptive, cutaneous, thermal, and other afferent impulses, drastically changes an individual's consciousness. It may give rise to confusional, almost psychotic states in which not only spatial but also temporal concepts are highly distorted, or lost. In such states, the subject's concept of the future may also be abnormal, although this matter does not appear to have been specifically studied.

To summarize, a basic type of awareness of the present, of a Now, is obviously to a great extent directly mediated by the actual exteroceptive sensory input pertaining to the present moment. Electrical stimulation of primary sensory projection fields in the cortex induces fractions of Now-experiences representing the modality activated. Such stimulation has so far not been reported to produce, or alter, concepts about the future. Albeit indirectly, as shown by sensory deprivation experiments, the continuous sensory input of every Now-moment is of fundamental importance for the "production" of a spatially and temporally adequate conscious awareness with components of a past, a present, and a future. The sensory deprivation experiments indicate that the continuous subattentive inflow of afferent signals is a prerequisite for another type of (inner) Now-awareness, the one prevailing in the resting "unstimulated" conscious state.

The future

The neuronal substrate of ideas and concepts about the future could not be studied until it became possible to measure the distribution of function in the cortex and in subcortical structures in conscious unanaesthetized human subjects at rest or performing various types of mental activity. Such studies were first carried out by *two-dimensional* multiregional cerebral blood flow measurements (2D-rCBF) (see Ingvar 1983c and Roland 1985 this issue for references), and later by *three-dimensional* metabolic (3D-rCMR) (see above) and blood flow (3D-rCBF; Stokeley et al. 1980) studies. So far, however, very few systematic studies of mental functions and consciousness have been made with the 3D techniques. Nevertheless, there are many simularities between the 2D-rCBF landscapes and the 3D-RCMR and 3D-rCBF maps. However, for technical reasons, the 2D-rCBF landscapes recorded by detectors placed lateral to the head have, in the experience of the author and others (Phelps et al. 1981; Duara et al. 1985), proved easier to interpret and to correlate to the general activity distribution in the cortex. The 2D-rCBF studies, therefore, occupy the main part of the following discussion.

Three separate rCBF-observations of specific cortical "landscapes of the future" will now be summarized. They will then be related to the resting "hyperfrontal" cortical landscape (Ingvar 1979) and to findings during various forms of mental activity in which a concept of the future is essential.

The first observation concerns *motor ideation*, the willed conceptualization of a rhythmic movement of one hand (Ingvar and Philipson 1977). This constitutes, as everybody would agree, the construction in the mind of a serially organized sequence of imagined movements, a series which proceeds from Now into the future. Such a mental construct may be taken to represent a simple "pure" concept about a certain type of behaviour in the future. At the moment in which this concept occupies conscious awareness, it is unrelated to any sensory input and also unrelated to any motor output (no movements being carried out). Motor ideation of this type gives a marked frontal/prefrontal activation which, with the technique used at the time, appeared rather diffuse, involving most of the frontal lobe. This 2D-rCBF pattern differed distinctly from the mainly rolandic activity augmentation during the actual performance of the same hand movements as those which had been imagined (Olesen 1971; Ingvar 1975). In later similar experiments in trained subjects, a more limited upper prefrontal activation was recorded during hand and finger movement ideation (Roland et al. 1980, 1985 this issue).

The second observation concerns *silent speech*. Counting silently from 1 to 100 also gave a clearcut and selective activation of upper prefrontal regions (Lassen et al. 1978; Lassen and Larsen 1980). Again, such a mental performance requires setting up in the brain a cognitive verbal action plan which is to be followed (silently) into the future, unaccompanied by any sensory input or motor output.

The third series of observations were made by Roland (1982), who studied cortical landscapes pertaining to *anticipation of cutaneous stimulation* of a finger tip, or of the lips. Clearcut prefrontal activations were then also recorded, as well as activations of the finger or face area, respectively – in spite of the fact that no cutaneous stimulation had occurred. Here again, the concept of an anticipated future event which the subject was familiar with and could remember, or at least "have an idea about", augmented the activity in widespread prefrontal areas.

These three observations should be related to the important finding, first reported some 20 years ago, that memorization and/or problem solving also activates frontal/prefrontal regions significantly (Ingvar and Risberg 1965, 1967; Risberg and Ingvar 1973). This has been confirmed by a number of subsequent studies in normal subjects performing different mental tasks. As far as one can judge, it is evident that all forms of cognitive activity which have been tested so far activate prefrontal regions, in addition to activating specific motor and postcentral regions related to the modality involved in the cognitive tests (Risberg 1980; Risberg and Prohovnik 1983). These findings are highly pertinent in the present context, since they demonstrate that cognitive action plans underlying memorization, recall, reasoning, and various types of problem solving, indeed, cognition in general, apparently have an important neuronal substrate with a wide distribution in the prefrontal cortex. All the cognitive activities mentioned have a component of "future". They contain an action plan, or rather, as for example in problem solving, alternative action plans which determine different directions of cognition to be tried in order to reach the future goal: the solution of the problem. As generally recognized, such cognitive action plans are not always accessible to conscious awareness, nor to verbal description (Davidson and Davidson 1980; Ingvar 1983a; Lundh 1983). In any event, the action plans concern the future and are mobilized (recalled) in the Now-situation, when the problem has to be solved, indeed with the aid of past experiences.

It should also be recalled here that many different types of *serial* (sequential) motor performance activate certain, mainly upper, prefrontal regions. This has been shown in man with 2D-rCBF techniques for hand movements of various types (Olesen 1971; Ingvar 1975; Roland et al. 1980; Roland 1985 this issue), as well as for automatic speech (Ingvar and Schwartz 1974; Ingvar 1983a; Brådvik et al. 1984) (see below). Again, even seemingly simple series of hand or finger movements (Roland et al. 1980), or simple repetition of well-known word series, follow an action plan which stretches from Now into the future (Prinz and Sanders 1984). The coupling of such inner action plans with prefrontal cortical activation was especially evident in Roland's crucial experiments (1982). A steady isometric clenching of one hand gave a contralateral activation of the rolandic hand area. Rhythmic, serial, movements of the same hand, however, activated in addition to supplementary motor area bilaterally, and adjacent upper prefrontal regions, as well as the basal ganglia, also bilaterally (Roland 1985).

To summarize, many different forms of behavioural or cognitive performance in *sequential* form, also including "pure" cognition, imagination, ideation, expectancy, etc., unrelated to actual sensory input or motor output, give rise to an activation of frontal/prefrontal cortical areas. The common denominator of these observations appears to be the fact that all the behavioural (motor) and cognitive acts studied concern events which are performed Now but require a plan, a concept, of the future. Action plans for movements, as well as for cognition, for example in problem solving, contain programs in the form of temporally structured neural events which can be stored (and remembered) and thus can critically determine the future beyond Now. To judge from the 2D-rCBF studies quoted, such action plans for future behaviour and cognition are evidently handled, to a major extent, by the prefrontal cortex. At present, the detailed neuronal nature of such plans is, however, unknown, and also unknown, especially concerning cognition, is the collaboration between cortical and subcortical structures (e.g. the basal ganglia and the cerebellum) for the establishment of action plans and their execution.

Speech

In a recent review (Ingvar 1983a), the cortical neuronal substrate of speech, as reflected in 2D-rCBF studies, was discussed. "Automatic" speech (enumaration of days of the week, months, etc.) activates the upper speech cortex of Penfield (Penfield and Jasper 1954), which encompasses the supplementary motor area and adjacent prefrontal regions, in addition to rolandic regions controlling the mouth, tongue, and larynx (Ingvar and Schwartz 1974). The similarity with the results of experiments with hand-motor patterns, mentioned above, is obvious. Any sequential motor performance requires an action plan which involves the upper prefrontal cortex and adjacent regions, and which then, during the actual movement, it "uses" primary rolandic centers for execution (Roland 1985, this issue). This conclusion is strongly supported by the findings, already mentioned, that motor ideation (Ingvar and Philipson 1977; Roland et al. 1980) and silent speech (Lassen et al. 1978) activate *only* prefrontal regions (see above). Recent studies of non-verbal vocalisation should also be mentioned here. The humming of a melody also induces bilateral prefrontal activation, especially marked on the right side (Brådvik et al. 1984). Hence, the execution of the sequences of musical melodies, which indeed by their temporally structured nature have a clear component of "future", also gives rise to prefrontal activations.

It is of interest that, as shown by Nishizawa et al. (1982) (cf. Risberg and Prohovnik 1983), the (silent) perception of spoken words (induces in addition to asymmetric activations of the auditory and adjacent temporal cortices), a clearcut activation of prefrontal regions, most often pronounced in the lower inferior left frontal region. The finding that perception of words activates the prefrontal cortex is compatible with the "motor theory of speech perception" (Liberman et al. 1967). This theory postulates the necessary access to the templates, the complex motor programs for the articulation (and semantically adequate usage?) of given words, in order to understand their meaning and their future implications when they are simply heard spoken. Only in this way, by what might be termed symbol anticipation, can the brain perceive speech as rapidly as it does.

The "hyperfrontal" cortical activity landscape of resting consciousness

Normally, in undisturbed, resting, non-moving, conscious subjects, the blood flow and metabolism (activity) in frontal/prefrontal parts of the cortex are considerably higher than in postcentral, especially temporal regions; in some parts they are about twice as high (Ingvar 1979; Risberg 1980; cf. Mazziotta et al. 1981; Duara et al. 1985). This "hyperfrontal" pattern, which represents the distribution of the "idling" activity of the resting brain, may signal a simulation of behaviour, including the "inner" behaviour related to cognition (Ingvar 1979). By this it is meant that, when conscious, the brain rehearses stored information from the past, relates it to the present Now-situation, and makes up a behavioural repertoire for the future (cf. Edelman and Mountcastle 1978). Such an interpretation is based both upon introspective evidence and upon clinical rCBF observations. Since the interpretation was presented (Ingvar 1979), several new observations have been made (some of them reviewed above) which strengthen it; the relevant observations were made while the subject was at rest, just conscious, and thinking "of nothing specific", letting his thoughts drift, his mind considering and anticipating the future, or rather futures, in the light of the past and the present. Our hypothesis is supported by the fact that, in sleep (Ingvar 1977) and in coma (Ingvar and Gadea Ciria 1975), the hyperfrontal activity distribution is much less marked or may even disappear altogether.

Two recent independent studies in normal subjects have demonstrated that the resting hyperfrontal pattern is asymmetrical (Brådvik et al. 1982; Hagstadius and Risberg 1984). The level of activity (blood flow) in the right prefrontal region is somewhat higher than in the left, and also more diffusely distributed. On the left side, two main regions of higher flow are usually seen: the lower and the upper prefrontal regions. The significance of that asymmetry is not yet known. But it is a suggestive fact that the resting pattern on the left side shows similarities to the one recorded in subjects actually listening to spoken words (Nishizawa et al. 1982). Possibly, one may speculate, the resting brain "listens" to the silent flow of thoughts, be they formulated in words or not. Activity in the frontal eye fields (Melamed and Larsen 1979), due to involuntary scanning eye movements during resting awareness, may also activate some premotor areas. The resting hyperfrontal 2D-rCBF pattern is, however, fairly pale. It shows a lower general flow level and less contrast, i.e. less pronounced activity peaks, than the pattern during active listening. Further studies of resting situations, with idling brain activity, should give further insight into the nature of consciousness and how the two hemispheres contribute to its cognitive content.

Experimental evidence

As Fuster emphasizes (1980, 1985 this issue), there is abundant experimental evidence that the prefrontal cortex handles the temporal organization of behaviour in mammals. His own delayed-response experiments clearly show that prefrontal neurons are involved in mechanisms pertaining to what is here termed "memory of the future", i.e. anticipatory programming as well as storing of information to be used later (in the future beyond Now) to control behaviour. Much experimental evidence, recently reviewed by Goldman-Rakic (1984) and others (cf. Fuster 1980, 1985 this issue) also clearly shows that dorsolateral prefrontal lesions in monkeys lead to severe deficits in the programming of complex sequential behaviour, that is in functions which necessitate a memory of the future. Kolb's recent review (1984) on the frontal cortex of the rat is very pertinent here. He stresses the fact that in all mammals, from rodents to man, there is solid evidence that the prefrontal cortex subserves the temporal organization of behaviour. However, the animal data on the prefrontal cortex concern, for the most part, relatively short-term mechanisms. Deep lesions which sever pathways between prefrontal cortex and thalamus in man have been shown to have long-term effects on both cognition and behaviour, including effects upon their emotional components (Rylander 1939; Fulton et al. 1948; Fulton 1951; Davidson and Davidson 1980; Fuster 1980).

Clinical evidence

A vast number of clinical observations on the frontal lobes could be invoked in the present context to support the concepts discussed above. Only a few will be cited.

Patients with frontal/prefrontal lesions often suffer from inadequate concepts about the future. This inadequacy manifests itself in lack of ambition, foresight, initiative, and spontaneity, as well as in apathy, and unawareness of the future consequences of behaviour; the patients sometimes show, verbally and behaviourally, indifference to ethical and moral values. All such symptoms all represent interference with the long range purposive concepts about the future which normally form an integral part of the intellect. Using the terminology of this essay, frontal patients have a defective "memory of the future". On a shorter range scale, prefrontal lesions may also interfere with motor performance, e.g. the ability to perform and to maintain repetitive movements and to uphold normal fluency of speech (Bechterew 1908–1911; Bianchi 1921; Rylander 1939; Fulton et al. 1948; Denny-Brown 1951; Lhermitte et al. 1972; Ingvar 1983a; Prinz and Sanders 1984).

Animal experiments, as well as clinical studies of the effects of circumscribed prefrontal lesions, indicate strongly the existence of prefrontal subsystems for control of cognitive activity and behaviour and their emotional components (Fuster 1980; Goldman-Rakic 1984). The mesial and basal prefrontal cortex has, for example, a well-known importance for emotional reactions and for the suppression of insignificant information. That function of suppression of interference is generally assumed to be a prerequisite for undisturbed short- and long-range programming of future cognition and behaviour (Rylander 1939; Fulton et al. 1948; Fuster 1980). However, studies of functional subsystems in the prefrontal cortex will not be included in this comprehensive summary, since that field has not yet been sufficiently investigated. Nor is it possible to outline the contribution by subcortical and cerebellar structures to the prefrontal functions. The specific prefrontal innervation by catecholaminergic and other transmitter pathways is of obvious interest in this context (Descarries and Jasper 1984). All these aspects, however, would by themselves justify another review.

Psychometric measurement of prefrontal functions in normals and in patients is beset by well known difficulties. Conventional psychological tests are often not sensitive enough to pick up defects caused by prefrontal lesions. A major reason for this might be that they do not adequately consider a time concept of the type presented in this essay. The tests do not seem to include a specific analysis of the anticipated future of the subjects tested. However, new types of psychometric instruments attempt to do so, as shown by

Milner and collaborators (Milner et al. 1985, this issue), by exploring the patient's capacity to retain behavioural and cognitive sequences, for future usage. Tulving (1985) has recently described a new approach for study of the anticipatory capacity, the "memory of the future" in our terminology, in a patient who suffered from severe deficits in his concepts of the future. Memory research should most likely profit by further such studies.

Findings in *organic dementia* are of special interest. When the neuronal loss involves the frontal/prefrontal cortex, symptoms of progressive apathy develop, with a striking lack of plans for the future, as well as a marked emotional indifference. In such states, a corresponding reduction of the frontal blood flow and metabolism is also seen (as well as other regional abnormalities) (Ingvar and Gustafson 1970; Hagberg and Ingvar 1976; Risberg 1980; Ingvar 1982, 1983c; Reisberg 1983; Chase et al. 1984). Psychological testing shows highly defective performance, and the normal prefrontal activation during attempts to solve problems is reduced or absent (Ingvar et al. 1975).

Low prefrontal activity is also recorded in patients with *Parkinson's disease,* who demonstrate typical defects, or even inability, to initiate "future" movements and to maintain sequential motor performance (Bès et al. 1983). Finally, the hypofrontal pattern, i.e. low prefrontal activity (blood flow and metabolism), in certain patients with chronic *schizophrenia* should be recalled (Ingvar and Franzén 1974). As emphasized elsewhere (Ingvar 1980, 1982), the well known symptoms in this mental disorder are accompanied by a defective anticipatory programming of goal-directed cognition and behaviour, including speech in some cases. The reductions of the frontal flow correlate significantly with symptoms of autistic behaviour, including mutism, motor inhibition, and emotional indifference. Other psychiatric states involving the brain's anticipatory "future" mechanisms have been analyzed by Melges (1982) and Tysk (1985).

To summarize this brief review of clinical observations, it has been well established that a number of neurologic and psychiatric disorders with frontal lesions or disturbances of prefrontal activity demonstrate a defective production and maintenance of sequential cognitive and behavioural programs for future usage. In several such states, a clearcut deficit in the patient's "memory of the future" might be recognized which leads to lack of foresight and ambitions as well as a general inability to anticipate the future consequences of the patient's behaviour.

Concluding remarks

In this essay it is advocated that the classical tripartite concept of time divided into a *past*, a *present*, and a *future*, is very helpful to the analysis of conscious awareness and of higher nervous functions which determine cognition and behaviour. The application of this concept to the future component is especially emphasized, i.e. the capacity of the human brain to make up, and to retain ("remember") – and to be able to recall – short- and long-range plans for future behaviour and cognition.

An attempt is made to determine whether the past, the present, and the future are dependent upon different neuronal substrates in the brain. The past, namely awareness and recall of past experiences and events, is obviously handled by structures subserving memory (in conventional sense). Apart from the postulated, but still enigmatic, diffuse representation of memories (Lashley 1950), it is well known that memory and recall of past events are highly related to deep and superficial structures of the temporal lobe. Awareness of the present is, no less obviously, directly dependent upon the sensory input which feeds information into consciousness about the actual Now-situation of the organism and its surroundings. Another form of Now-awareness pertains to the resting (unstimulated) conscious state, which appears not directly related to, but still, as shown in sensory deprivation experiments, unconditionally dependent upon, the continuous background of sensory inflow taking place in the Now-situation. As suggested elsewhere (Ingvar 1979), this second type of Now-awareness appears definitely to include concepts of the future, i.e., of the future behavioural and cognitive repertoires and of future consequences of past experiences which are related to the moment of Now.

An attempt is also made to systematize evidence from experimental and clinical studies and from cognitive psychology suggesting that the future, i.e. our anticipation of sequences of events which follow the Now-situation, are handled by the frontal, mainly prefrontal, cortex.

A broad simplistic theory of this type raises several questions. It does not describe the collaboration of the neuronal substrates for the awareness of a past, a present, and a future. Obviously, such an interaction must take place. Several of the neuroanatomical and neurophysiological prerequisites for this interaction are indeed known. However, its general nature still remains highly enigmatic. To take up only one central and critically important question. How does our brain use primary sensory information to construct images of the future? By what mechanisms is, for example, the highly differentiated visual information, reaching primary, secondary, and higher order visual centers in the cortex, stored and then used by the brain to make up the clear "visions" which we all have about future events? As pointed out by Nauta (1971; cf. Fuster 1980), the large pathways from the secondary and higher order sensory cortices to prefrontal areas are most likely of fundamental importance; so are pathways from superficial and deep temporal structures to the frontal lobes subserving memory, as described by Mishkin (1982). But still, the interaction between the neuronal machineries for past/present/future defy even a crude description. It appears that it is from this interaction that consciousness takes its origin. The brain cannot produce normal conscious awareness without the "self" having a "total" (Granit 1977; Popper and Eccles 1977; Lundh 1983), somehow simultaneous, access to the information in the neuronal systems subserving the experience of a past, a present, and a future. This view dominates in fact, although expressed in other terms, much of the rich neurophysiological, psychological, and philosophical literature on consciousness (cf. Lundh 1983, and references above).

The past/present/future paradigm used to analyze consciousness may, as it seems, have a very direct implication for research on memory. As pointed out above, and emphasized by Tulving (1972, 1985), human memory operates not only with past experiences, but also with alternative, semantically meaningful sequences of events which are located in an anticipated future. These sequences are remembered and can be recalled often in detail, in spite of the fact that the events have not taken place. A systematic study of the cognitive content of the anticipated future of normal individuals would seem to be highly profitable, and so would a closer study of the various forms of defective "memory of the future" which are observed clinically in patients with prefrontal dysfunctions, suffering from organic dementia, frontal lesions, chronic schizophrenia, etc.

"Memory of the future" and perception

On a more general plane, the evidence presented in this essay leads to the following comment concerning sensory perception. The information (from our sensory organs) which reaches conscious awareness about our own body and the surrounding world is principally of two types. The greatest part is of random nature, i.e. *non-serial,* and lacks temporal structure. It is generally agreed that most of such random, non-serial information must be ignored and actively filtered out, so as not to disturb the stream of conscious awareness (Davidson and Davidson 1980). There is evidence that this takes place by active inhibition from mesial and basal prefrontal regions of the cortex (cf. Fuster 1980), as well as from the brain stem and spinal mechanisms. Temporally structured, *serial* information, on the other hand, which carries a "melody" (Luria 1966) or a rhythm (in its widest sense), or a series of symbols, may be perceived and experienced as significant, as having a message, a meaning. In accordance with views discussed elsewhere (Ingvar 1979, 1983c; cf. Hess 1943; Lundh 1983), one may postulate that *it is the temporal structure, the serial nature, of the sensory input which is a prerequisite for the experience of causality and, hence, the production of serial neuronal action plans underlying the anticipatory concepts of the future.*

This argument may be taken one step further. Could it be that the serial concepts, or "memories", of the future, which are handled by the prefrontal cortex, are of fundamental importance for the perception of – as well as for the selection of – meaningful serial afferent messages? Our serial programs and concepts of the future may be used as templates with which the input is compared. If there is a correspondence between the two, the input is understood, its "meaning" is perceived. Such a notion forms, in fact, the basis for the above cited "motor theory of speech perception" (Liberman et al. 1967). Without access to serial action plans for word articulation and sentence production, we cannot perceive the meaning of serial word meassages and speech. Possibly such a notion has general validity: *it is only by access to serial plans for future behaviour and cognition, i.e. access to our "memory of the future", that we can select and perceive meaningful messages in the massive sensory barrage to which our brains are constantly exposed.*

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References

Alavi A, Reivich M, Jones SC, Greenberg JH, Wolf AP (1982) Functional imaging of the brain with positron emission tomography. In: Freeman IM, Weissman HS (eds) Nuclear medicine annual. Raven, New York, pp 319–372

The Confessions of St. Augustine (1945) Translated by Pusey EB, edited by Rhys E, Everyman's Library. JM Dent & Sons, London

Bechterew V (1908–1911) Die Funktionen der Nervencentra. Gustav Fischer, Jena

Bès A, Guell A, Fabre N, Dujurni P, Victor G, Géraud G (1983) Cerebral blood flow studied by Xenon-133 inhalation technique in Parkinsonism: loss of hyperfrontal pattern. J Cereb Blood Flow Metab 3:33–37

Bianchi L (1921) La méchanique du cerveau et la fonction des lobes frontaux. Louis Arnette, Paris

Bindra D (ed) The brain's mind. Gardner, New York

Brådvik B, Hedqvist Ch, Ingvar DH, Johnson K, Ryding E (1984) rCBF studies of hemisphere dominance and language functions. Proc Swed Soc Med (Dec 1982), p 262

Bunge M (1980) The mind-body problem. A psychobiological approach. Pergamon, Oxford

Buser PA, Rougeul-Buser A (eds) (1978) Cerebral correlates of conscious experiences. INSERM symposium 6. Elsevier, Amsterdam

Chase TN, Foster NL, Fedio P, Brooks R, Mansi L, di Chiro G (1984) Regional cortical dysfunction in Alzheimer's disease as determined by positron emissin tomography. Ann Neurol [Suppl] 15:5170–5174

Corning WC, Balabau M (1968) The mind: biological approaches to its functions. Interscience, New York

Davidson JM, Davidson RJ (1980) The psychobiology of consciousness. Plenum, New York

Denny-Brown D (1951) The frontal lobes and their functions. In: Modern trends in neurology (chapter 1). Feiling, London

Descarries L, Jasper HH (eds) (1984) Monoamine innervation of cerebral cortex. Liss, New York

Deutsch JA (ed) (1983) The physiological basis of memory, 2nd edn. Academic, New York

Duara R, Margolin RA, Robertson-Tchabo EA, London ED, Schwartz M, Renfrew JW, Kozicerz BJ, Grady G, Moore AM, Ingvar DH, Sokoloff L, Weingartner H, Kessler RA, Manning R, Channing R, Cutler NR, Rapoport S (1983) Resting cerebral glucose utilization as measured with positron emission tomography in 21 healthy men between the ages of 21 and 83 years. Brain 106:761–775

Edelman GM, Mountcastle VB (1978) The mindful brain. MIT, Cambridge, Massachusetts

Frankenhaeuser M (1959) Estimation of time. Almqvist & Wiksell, Stockholm

Freud S (1915) The unconscious. In: Strachey J (ed) Complete psychological works, vol 14. Hogarth, London, pp 159–215

Fulton JF (1951) Frontal lobotomy and affective behaviour. A neurophysiological analysis. Norton, New York

Fulton JF, Aring CD, Wortir SB (eds) (1948) The frontal lobes. Res Publ Ass Nerv Ment Dis, vol 27. Williams and Wilkins, Baltimore

Fuster JM (1980) The prefrontal cortex. Anatomy, physiology and neuropsychology of the frontal lobe. Raven, New York

Fuster JM (1985) The prefrontal cortex, mediator of cross-temporal contingencies. Human Neurobiol 4:169–179

Gilinsky AS (1984) Mind and brain. Principles of neuropsychology. Praeger, New York

Goldman-Rakic PS (1984) Modular organisation of prefrontal cortex. Trends Neurosci 7:419–424

Granit R (1977) The purposive brain. MIT, Cambridge, Massachusetts

Granit R (1985) Comments on time in action and perception. Human Neurobiol 4:61–62

Gregory RL (1981) Mind in science. Cambridge University Press, Cambridge

Hagberg B, Ingvar DH (1976) Cognitive reduction in presenile dementia related to regional abnormalities of the cerebral blood flow. Br J Psychiatr 128:209–222

Hagstadius S, Risberg J (1984) Hemispheric asymmetries of rCBF in normal subjects during rest. II Scand Neuropsychol Meeting, Lund (Sweden), August 14–18

Hebb DO (1949) The organization of behavior. Wiley, New York

Hess WR (1943) Teleokinetisches und ereismatisches Kräftesystem in der Biomotorik. Helv Physiol Pharmacol Acta 1:662–663

Ingvar DH (1975) Patterns of brain activity revealed by measurements of regional cerebral blood flow. In: Ingvar DH, Lassen NA (eds) Brain work. Munksgaard, Copenhagen, pp 397–413

Ingvar DH (1977) L'ideogramme cérébrale. L'encephale III, pp 5–33

Ingvar DH (1979) "Hyperfrontal" distribution of the cerebral gray matter flow in resting wakefulness; on the functional anatomy of the conscious state. Acta Neurol Scand 60:12–25

Ingvar DH (1980) Abnormalities of activity distribution in the brain of schizophrenics. A neurophysiological interpretation. In: Baxter D, Melnechuk B (eds) Perspectives in schizophrenia research. Raven, New York, pp 73–98

Ingvar DH (1982) Mental illness and regional brain metabolism. Trends Neurosci 5:199–202

Ingvar DH (1983a) Serial aspects of language and speech related to prefrontal cortical activity. A selective review. Human Neurobiol 2:177–190

Ingvar DH (1983b) Brain, time and consciousness (in swedish) Forsk Framsteg (Stockholm) 12:39–45

Ingvar DH (1983c) Functional landscapes of the brain pertaining to mentation. Human Neurobiol 2:1–4

Ingvar DH, Franzén G (1974) Abnormalities of regional cerebral blood flow distribution in patients with chronic schizophrenia. Acta Psychiatr Scand 50:425–462

Ingvar DH, Gadea Ciria M (1975) Assessment of severe damage to the brain by multi-regional measurements of cerebral blood flow. In: Outcome of severe damage to the central nervous system. A Ciba Symposium. Elsevier, Amsterdam, pp 97–120

Ingvar DH, Gustafson L (1970) Regional cerebral blood flow in organic dementia with early onset. Acta Neurol Scand [Suppl 43] 46:42–73

Ingvar DH, Lassen NA (eds) (1975) Brain work. Munksgaard, Copenhagen

Ingvar DH, Philipson L (1977) Distribution of cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. Ann Neurol 2:230–237

Ingvar DH, Risberg J (1965) Influence of mental activity upon regional cerebral blood flow in man. Acta Neurol Scand [Suppl 14], pp 183–186

Ingvar DH, Risberg J (1967) Increase of regional cerebral blood flow during mental effort in normals and in patients with focal brain disorders. Exp Brain Res 3:195–211

Ingvar DH, Risberg J, Schwartz M (1975) Evidence of subnormal function of association cortex in presenile dementia. Neurology 25:964–974

Ingvar DH, Schwartz MS (1974) Blood flow patterns induced in the dominant hemisphere by speech and reading. Brain 97:273–288

Jasper HH, Proclor LD, Knighton RS, Noshay WC, Costello RT (1958) Reticular formation of the brain. Little, Brown, Boston, Massachusetts

Kant I (1781/1919) Kritik der reinen Vernunft, 11th edn. In: Valentiner T (ed) Felix Meiner, Leipzig

Kierkegaard S (1843/1901–1906) (Collected works) (in Danish) Drachman AB, Heiberg JC, Lange HO (eds) Munksgaard, Copenhagen

Kolb B (1984) Functions of the frontal cortex of the rat: a comparative review. Brain Res Rev 8:65–98

Lashley KS (1950) In search of the engram. Symposia Soc Exp Biol 4:454–482

Lashley KS (1960) The problem of serial order in behaviour. In: Beach FA, Hebb DO, Morgan CT, Nissen Nw (eds) The neuropsychology of Lashley, McGraw-Hill, New York

Lassen NA, Ingvar DH (1961) The blood flow of the cerebral cortex determined by radioactive Krypton-85. Experientia 17:42–43

Lassen NA, Hoedt-Rasmussen K, Sörensen SC, Skinhöj E, Cronqvist S, Bodforss B, Ingvar DH (1963) Regional cerebral blood flow in man determined by Krypton-85. Neurology 13:719–727

Lassen NA, Ingvar DH, Skinhöj E (1978) Brain function and blood flow. Sci Am 239:62–71

Lassen NA, Larsen B (1980) Cortical activity in the left and right hemispheres during language-related brain functions. Phonetica 37:27–37

Lhermitte F, Deroulsne J, Signoret JL (1972) Analyse neuropsychologique du syndrome frontal. Rev Neurol 127:415–440

Liberman AM, Cooper FS, Shankweiter DR, Studert-Kennedy M (1967) Perception of the speech code. Psychol Rev 74:431–461

Luria AR (1966) Higher cortical functions in man. Tavistock, London

Lundh L-G (1983) Mind and meaning. Towards a theory of the human mind considered as a system of meaning structures. Acta Univ Upsaliensis Stud Psychol 10, Uppsala

Magoun HW (1963) The waking brain. Charles C Thomas, Springfield, Illinois

Mazziotta JC, Phelps ME, Miller J et al. (1981) Tomographic mapping of human cerebral metabolism: normal unstimulated state. Neurology 31:503–516

Mazziotta JC, Phelps ME, Carson RE, Kuhl DE (1982) Tomographic mapping of human cerebral metabolism: auditory stimulation. Neurology 32:921–937

Melamed E, Larsen B (1979) Cortical activation pattern during psychotic eye movements in humans: localization by focal cerebral blood flow increases. Ann Neurol 5:79–88

Melges FT (1982) Time and the inner future. A temporal approach to psychiatric disorders. Wiley, New York

Miller JG (1976) Living systems. McGraw-Hill, New York

Milner B (1972) Disorders or learning and memory after temporal lobe lesions in man. Clin Neurosurg 19:421–446

Milner B, Petrides M (1984) Behavioural effects of frontal lobe lesions in man. Trends Neurosci 7:403–407

Milner B, Petrides M, Smith ML (1985) Frontal lobes and the temporal organization of memory. Human Neurobiol 4:137–142

Mishkin M (1982) A memory system in the monkey. In: Desmedt DE, Weiskrantz L (eds) Philos Trans Roy Soc Lond 298:85–95

Nauta WJH (1971) The problem of the frontal lobe: a reinterpretation. J Psychiatr Res 8:167–187

Nilsson L-G (ed) (1979) Perspectives on memory research. LEA, Hillsdale, New Jersey

Nishizawa Y, Skyhöj-Olesen T, Lassen B, Lassen NA (1982) Left-right cortical asymmetries of regional cerebral blood flow during listening to words. J Neurophysiol 48:458–466

Ojemann GA (1983) Brain organisation of language from the perspective of electrical stimulation mapping. Behav Brain Sci 6:189–206

Olesen J (1971) Contralateral focal increase of cerebral blood flow in man during arm work. Brain 94:635–646

Ornstein RE (1972) The psychology of consciousness. Viking, New York

Penfield W, Jasper H (1954) Epilepsy and the functional anatomy of the human brain. Little Brown, Boston

Phelps ME, Mazziotta JC, Kuhl DE et al. (1981) Tomographic mapping of human cerebral metabolism: visual stimulation and deprivation. Neurology 31:517–529

Phelps ME, Mazziotta JC, Huang SC (1982) Study of cerebral function with positron computed tomography. J Cereb Blood Flow Metab 2:113–162

Popper KR, Eccles JC (1977) The self and its brain. Springer, Berlin Heidelberg New York

Prinz W, Sanders AF (1984) Cognition and motor processes. Springer, Berlin Heidelberg New York Tokyo

Rasmussen JE (1973) Man in isolation and confinement. Aldine, Chicago

Reisberg B (ed) (1983) Alzheimer's disease. The standard reference Free Press, New York

Reivich M, Alavi A, Greenberg J, Fowler J, Christman D, Wolf A, Rosenberg A, Hand P (1978) Metabolic mapping of functional cerebral activity in man using the 18-F-2-fluoro-2-deoxyglucose technique. J Comput Ass Tomogr 2:656–664

Risberg J (1980) Regional cerebral blood flow measurements by 133-Xe inhalation: methodology and applications in neuropsychology and psychiatry. Brain Lang 9:9–34

Risberg J, Ingvar DH (1973) Patterns of activation in the gray matter of the dominant hemisphere during memorization and reasoning. Brain 96:737–756

Risberg J, Prohovnik I (1983) Cortical processing of visual and tactile stimuli studied by non-invasive rCBF measurements. Human Neurobiol 2:5–10

Roland PE (1982) Cortical regulation of selective attention in man. A regional cerebral blood flow study. J Neurophysiol 48:1059–1078

Roland P (1985) Cortical organization of voluntary behaviour. Human Neurobiol 4:155–167

Roland PE, Larsen B, Lassen NA, Skinhöj E (1980) Supplementary motor area and other cortical areas in organization of voluntary movements in man. J Neurophysiol 43:118–136

Rylander G (1939) Personality changes after operations on the frontal lobes. Munksgaard, Copenhagen

Sechenov IM (1863/1965) Reflexes of the brain (transl) Gibbons G, Gellerstein S (eds) MIT, Cambridge, Massachusetts

Shakow D (1967) Some psychophysiological aspects of schizophrenia. In: Romano J (ed) The origins of schizophrenia. Excerpta Medica,

Amsterdam, pp 54–69
Solomon P (ed) (1961) Sensory deprivation. Harvard University Press, Cambridge, Massachusetts
Stokeley EM, Sveinsdottir E, Lassen NA, Rommer P (1980) A single photon dynamic computerassisted temograph (DCAT) for imaging brain function in multiple cross-sections. J Comput Assist Tomogr 4:230–240
Toulmin S, Goodfield J (1963) The discovery of time. (Swedish translation) Ekstrand, Lund
Tulving E (1972) Episodic and semantic memory. In: Tulving E, Donaldson WD (eds) Organization of memory. Academic, New York, pp 381–403
Tulving E (1985) Memory and consciousness. Canad Psychol 26:1–12
Tysk L (1985) A study of time estimation in psychotic and affective disorders. Acta Univ Upsaliensis 511. Almqvist & Wiksell, Uppsala
Wittgenstein L (1953) Philosophical investigations. Blackwell, Oxford
Wollheim R (1984) The thread of life. Cambridge University Press, Cambridge
Zubeck JP (ed) (1969) Sensory deprivation: fifteen years of research. Appelton-Century-Grofts, New York