Brain Imaging Methods and the Study of Cognitive Processes: Potential and Limits

Rainer M. Bösel

Free University of Berlin, Germany

Author's address:

Arbeitsbereich Kognitive Neuropsychologie

Freie Universität Berlin

Habelschwerdter Allee 45

D-14195 Berlin, Germany

Fon: ++49-30-838-55733

Email: rboesel@zedat.fu-berlin.de

www.fu-berlin.de/kogpsy/Kogpsych/rboesel.html

Abstract

Knowledge about the importance of certain regions of the nervous system for motor action, consciousness, and reasoning arose very slowly during the past centuries. Recent imaging techniques, such as functional magnetic resonance imaging (fMRI), are powerful methods that reveal activations of certain brain regions involved in mental processes. Presently, methods for imaging brain dynamics are being developed. Here, we have to

consider that there is an important time lag between neurological processes and corresponding conscious acts. Voluntary acts are coordinated according to the history of subjective experience and established strategies, and they are delayed to their corresponding brain processes by at least 300 ms.

Introductory and historical remarks

What kind of realization of psychological facts is possible using imaging methods compared to using other psychological methods? The popular literature of the day informs us about such things as brain localization of intelligence or moral conscience. Naturally, questions arise concerning the relationship between the topography of brain processes and the topology of cognitive structures. Behind the scenes, we argue about the usefulness of excessive technology in psychological research and about some deviant goals that biomedical techniques embark on. Given these considerations, the main question to discuss here is how to measure cognition.

Cognition means to realize things, hence to link objective and subjective matters. To elucidate the nature of this link, most researches look at localization within the brain and at the time course of cognitive processes. According to the history of neuropsychology, let us begin with the discussion of the psychological view on localization of cognition.

Long ago, a connection between brain and thought was proposed by Alkmaion (500 BC). Assumptions about a relationship between brain anatomy and individual characteristics and skills, such as the ability of causal thinking, social support, imitation, or cautious planning, were expressed much later in the 18th century by Franz Joseph Gall in Vienna. Gall's theoretical approach was later called phrenology. When in 1796 the Académie française requested a detailed look at Gall's theory, he was cautious enough to present only his anatomical studies and not his functional assumptions.

At this time, empirical data were mostly recorded for single cases. One fruitful observation was made by the British physician John Harlow on his patient Phineas Gage. Gage, who worked as a blaster, was severely injured by an explosion in 1848. An iron pole with a thickness of about 3 cm went through his brain and lesioned his frontal cortex. The injury altered the patient's character: he mainly showed a loss of responsibility, pleasantness, and his sense of fairness. In general, the birth of neuropsychology is associated with the Parisian psychiatrist Pierre Paul Broca. In 1861, he claimed a relationship between aphasias of speech and lesions of the left frontal cortex. In the following years he bolstered this thesis with the description of 12 cases of aphasic patients.

More recently, Sandra Witelson surveyed Einstein's brain (Witelson et al., 1999) and found him to have a partly greater brain volume around the gyrus supramarginalis than can commonly be found in other brains. Similar results were obtained for Karl Friedrich Gauß's brain. However, these findings were met with derision, because the gyrus supramarginalis is known for imagery of motions. Today, we know that reasoning engages in part the same brain resources as imagery of motions. Despite the long history of knowledge about localization of function in the human brain, there are still many unanswered questions. Time has come, once again, to think about the location of mental processes within the brain.

First of all, we have to recognize that scientific measuring of mental processes is a common procedure in psychology. According to the ophthalmologist Donders, it seems to be indisputable for reaction time research to assume that there is a mental course beginning with detection and followed by selection and decision. Simple decisions require less time than multiple-choice reactions. Certainly, we also reach a limit, assuming that reaction is determined by the strongest signal without knowledge about the power behind. Nevertheless, technologies for measuring mental processes seem to be fruitful for psychological theories, and theories about brain functioning may be fruitful for neuropsychological practice.

In the present, we cannot ignore the importance of measuring mental processes by measuring brain activity. But how well can we determine the location of any ongoing mental process within the brain?

Locating mental functions with neuropsychological methods

The basis for measurements on the working brain is the assumption that information processing by nerve cells is related to electrical and metabolic changes within the brain. Measurements of the electrical or magnetic field on the scalp show fluctuations in the frequency range of 0 to 60 Hz. These fluctuations are related to wakefulness and to observable changes of stimuli or motor actions. The source of potential changes within the brain can be computed. However, an exact localization is not easily practicable because this source is only the sum of an unknown number of unknown positions of real dipole generators within the cortex. Nevertheless, we can analyze the time course of brain activation up to a range of milliseconds by the use of electrophysiological methods.

Measurements of the metabolic responses induced by active brain regions are realizable with different methods. A commonly used method is functional magnetic resonance imaging (fMRI), based on the determination of actual oxygen disposal and metabolism in certain brain regions. Here, properties of hydrogen atoms in haemoglobin molecules are measured. These properties can be measured only from a small percentage of molecules and change very slowly within 5 to 6.5 s. Nevertheless, we can analyze the location of activation very precisely up to millimeters. It should be mentioned that recently developed methods such as event-related optical signal processing (Gratton & Fabiani, 2003) promise a resolution up to 25 mm in space and 100 ms in time.

There is, however, a marked trade-off between the measures of locations and times. Besides these uncertainties, different methods seem to produce commensurable results and psychological facts can often be related to the localization of brain activity. Therefore psychologists are called to be open for these methods. Physicians and psychologists use these methods contributing to 50% of publications each, or publishing in teams. Psychologists are requested to design paradigms for testing selected brain regions. Psychological research should be helpful in the realization of imaging-based diagnostics.

At this point in the usefulness discussion, we have to consider three basic restrictions in interpreting local brain activations: (1) anatomical variability, (2) variable distribution of the cognitive structure according to the individual learning history, (3) differing functional significance of activated areas for understanding psychological processes.

Anatomical brain differences between subjects require unsettled allometric interpolations in the determination of brain areas (what does 'unsettled allometric interpolations' mean?). Moreover, conceptual representations seem to be located in wide-spread, distributed ensembles. For instance, the gyrus fusiformis is well known as an area involved in face recognition ("fusiform face recognition area"). Lesions here have long been supposed to cause an inability to recognize faces (so-called prosopagnosia). Also within this area, some nerve modules are activated when buildings are recognized (Haxby et al., 2001). In general, as revealed by neuronal network models, the exact pattern of distribution is determined by the individual learning history. Newer findings give rise to the assumption that prosopagnosia is more often caused by certain lesions in a network involved at an earlier stage in visual processing (cf. Barton et al., 2003). Similar problems occur in dyslexia. Reading skills have to be localized in a wide-spread network. It is very difficult to predict particular symptoms from distinct lesions. In this case, network models are more helpful for a thorough understanding than pure anatomy (Plaut & Shallice, 1993).

Figure 1 about here

An additional problem occurs with the interpretation of parts of activation patterns as representing factors or stages of cognitive processes. Blood and Zatorre (2001) investigated activation patterns in the brain during pleasurable experiences (i.e., listenening to classical music). They found parts of the brain to be active which are usually involved in effort and social behavior, and other parts to be inactive, such as control of avoidance behavior or other executive functions (see figure 1). It remains unclear, however, if the sum of these activations or a part of them represents a true image of aesthetic perception (Bösel, 2003). Indeed, ”The fact that area Ö becomes active during happiness does not imply that happiness is localized to area Ö” (Sarter et al., 1996, p. 20).

Supposing that patterns of coincident activations are representative for a certain mental stage, a lot of methods are used for imaging coherences of electrical brain activity. Highly coherent patterns are indeed strongly related to certain gestalt perceptions (Tallon-Baudry et al., 1996). Synchronous oscillations in the so-called gamma band of the electroencephalographic signal seem to be good candidates for indexing binding of detected features into holistic percepts. Binding processes can be assumed to be correlated to conscious phenomena. Unfortunately, a lot of literature gives rise to the assumption that synchronous oscillations are in fact a necessary but not a sufficient condition for a gestalt experience.

Localizing brain activation is not always instrumental in exploring factors that influence cognitive functioning or mental steps. The reader may remember Leonardo da Vinci’s paintings by the use of the camera obscura. This technique - as perfect as it was - opened a door to distortion, faking, and fiction. Perhaps, we presently have a similar problem of changing technology in cognitive sciences. On the other hand, many psychologists are worried about a loss of traditional psychological research fields. As demonstrated early in the philosophy of science, precise findings cannot prevent being focused on the wrong point (Wind, 1930). Some scientists warn against so-called pseudo-empirical findings; that is the interpretation of empirical results determined by a-priori-assumptions of the measured concept. How useful is it in psychology to know where cognitive processes are localized? The question of usefulness of topographic methods arises in psychology apart from medical applications (neurosurgery, pain research, or diagnosis of cerebral dysfunction). Undoubtedly, there is a relationship between the dynamic of activations over time and the changing patterns of mental states due to the progress of ongoing information processing.

Relationship between brain dynamics and information processing

To understand brain dynamics we usually differentiate between data-driven processes that work bottom-up in encoding, and top-down processes of controlled attention and working memory actions (see fig. 2). Interactions between early processes in perception and higher-level dynamics are in most cases not observable and have to be interpreted post hoc according to a common psychological validity.

Figure 2 about here

The mentioned fundamental problem of reconstructing brain dynamics from imaging data can be discussed in two steps. First, brain areas that are representative for interactions between bottom-up and top-down processing are usually less active than areas activated by mismatch detection or automatic attention. For example, this has been shown in a recognition paradigm. Consider subjects who got familiar with certain abstract geometric figures in a training phase. The following day, a good deal more figures were presented and subjects had to decide whether they have seen these figures before or not. Executive processes were supposed to control reward behavior according to the match between presented figures and memory standards. This match is seen by fMRI halfway between primary sensory area and motor cortex, located in a pathway known for object recognition (Bösel, 2001, fig. 25.4). Unfortunately, this location shows only a small amount of activity because broad memory activations as seen for mismatches (new stimuli) are suppressed in the case of matches (old stimuli). Moreover, the location for recognition changes slightly between subjects according to their subjective memory structure.

Second, another problem is constituted by the partly unknown causes of activity patterns. Consider a subject monitoring a video showing a fast ride through a winding tunnel simulating sliding in a pipe like those found in a water park. In most cases, subjects experience the feeling of bodily locomotion instead of the perception of moving features on a screen. To analyze brain mechanisms of this illusion phenomenon, we imaged cerebral activity using fMRI during film presentation. Two brain areas were active for the comparison between movement perception and perception of a still picture, the supramarginal gyrus and the premotor cortex (see fig. 3). Doubtlessly, the path of information can be interpreted as proceeding from supramarginal to premotor areas, explaining unwilled compensatory movements. However, perceptions of bodily locomotion also occur in cases without automatic compensatory movements. The questions remain: (1) what gives rise to these premotor activations? and (2) is there a retrograde influence on the supramarginal imagery area producing the illusory phenomena? Unfortunately, these questions cannot be answered by brain imaging methods.

Figure 3 about here

It should be mentioned that other neuropsychological methods are more closely related to the assumed underlying mental processes, illustrating the time course of brain activation patterns. In a recent experiment we showed two or more digits of the same digit value on screen. Subjects had to make decisions about the numerical amount of either the digit frequency or the digit value. This condition was compared to a more difficult one, where they had to decide whether the numerical amount was larger for the digit frequency or the digit value. In the harder condition, subjects had to perform at least one additional cognitive operation before response execution compared to the simple condition, namely, the comparison between the former two judgements. We hope to see exactly this in the time course of a certain EEG frequency power obtained from attention controlling parts of the executive cortex (fig. 4). However, evidence for a correspondence between EEG power changes and mental activity has still to be come.

Figure 4 about here

At this point of the discussion we have to ask the question of what level of cognitive dynamics can be mapped by imaging techniques. For this we have to turn to the problem of the time course and the chronometry of mental processes.

Locations and the time course of mental processing

Let us consider that mental phenomena are matters of subjective experience which have to be commensurate with objective facts. Cognition is determined by the architecture of the brain. But how do we find out the best parameters of mapping cognitive dynamics?

Cognitive dynamics can be illustrated by considering a fact, which could be described verbally by 3 to 5 sentences each, containing about 10 words. Verbal description takes about 10 s, given a speech speed with 3-5 words per second. But mental dynamics is considerably faster. To feature the mental dynamics representing the same fact, we may consider a complex choice reaction upon this fact, lasting about 500 to 1000 ms. Subtracting the encoding time, we can assume a time course lasting about at least 300 to 350 ms to build up a mental image of the fact. This process is called the microgenesis in cognition, resulting in a mental state.

Brain dynamics is essentially faster. Each cortical neuron is connected to another one by at least three to four synapses. Given the synaptic delay of some ms plus the nerve conductance speed of 25 to 50 m/s, we can assume a resulting delay of more than 300 ms between the starting point of the brain process and the beginning of conscious mental events.

The negative time lag between mental states and the rise of the related physiological process of at least 300 ms can be observed by certain methods. In event-related potential research a positive deflection of the derived signal occurring more than 300 ms after stimulus onset (P300) gives reference to a conscious perception of the stimulus. Libet (1985, 1999) found voluntary acts to be delayed in comparison to the related unconscious cerebral activities by about 350 ms.

We cannot know exactly to what extent this negative time delay determines the degree of freedom for intentional thoughts (in the sense of will). Intentional thoughts depend on ongoing working memory processes and it is very hard to predict subjective associative connections and their related activity within the individual memory. This remains an open question, especially in the planning phase of convergent thinking (after having ‘crossed the rubicon’ according to Heckhausen’s model, 1989). Nevertheless, there is a strong determination by brain processes for voluntary acts (Bieri, 2001). Potentials for acts are matters of objective fact, while potentials for thoughts are matters of social judgements, revealed by reasoning and predictions against the background of common norms.

Critique and Outlook

Most of our concepts of human behavior and subjective experience are highly abstract and are derived from a myriad of features. Social constructs such as creativity, qualia, or reality filters do not exist within the brain, while things like concept formation or episodic reconstruction do.

An anecdote may illustrate the problem of social judgements about cognition and cognitive abilities in neuropsychology. The British neurologist John Lorber (1915-1996) reported on a young student at his university. This student had an IQ of 126, had gained a first-class honors degree in mathematics, and was socially completely normal. And yet the boy had virtually no brain. When Lorber did a brain scan on him, he saw that instead of the normal 4.5 millimeter-thick brain tissue between the ventricles and the cerebral surface, there was just a thin layer of mantle measuring a millimeter or so. The cranium of the student was mainly filled with cerebrospinal fluid (Lewin, 1980).

To bridge the gaps between subjective experience, cognitive psychology, and neurology we urgently need more data derived from self-report in neuropsychological research. In psychology, we need concepts with a good perspective for a possible implementation in the real neural networks of the brain. In using biomedical methods, we have to develop better methods for mental chronometry, particularly for induced (non phase-locked) brain processes. In general, we do not only need a peaceful coexistence of different methods within psychological research. In fact, we also need a fruitful cooperation between traditional and biomedical research, controlling one another for research goals and theoretical implications. In the end, it should be possible to describe human behavior and consciousness based on the functioning of about 20 billions of cortical neurons.

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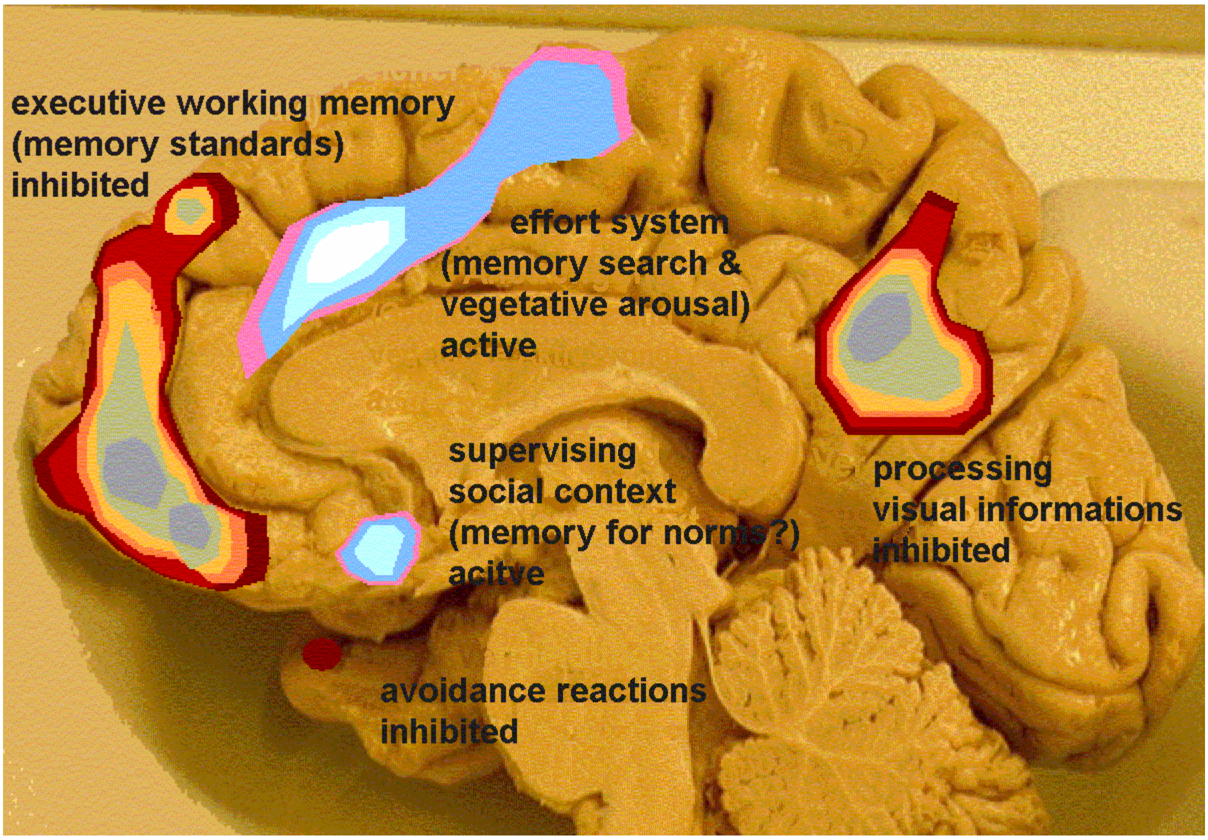
Figure Captions

Figure 1. Example for an imaging pattern representing a complex brain state in aesthetic perception. Is the state of aesthetic experience equal to the sum of shown activated and inhibited parts of the processing structure? (Adapted from Bösel, 2003; data in accordance with Blood & Zatorre, 2001).

Figure 2. Brain dynamics is composed by an interaction of bottom up and top down processes. Time course of dynamics and involvement of brain structures depends on the actual setting demands as well as on the individual cognitive set determined by the learning history, and habitual or instructed strategies. (Adapted from Desimone et.al, 1995).

Figure 3. Activated brain structures in monitoring a video showing a ride through a winding tunnel as revealed by fMRI. Subjective experience is dominated by the illusory perception of locomotory movement. A region below in the right hemisphere is activated within the gyrus supramarginalis, an important part in mental imagery of movements. The activation in the middle of the right hemisphere shows participation of the premotor cortex, commonly active in movement performance. What kind of interaction between these brain parts may produce the occuring illusory phenomenon? (Data presented with permission of Mareike Heß).

Figure 4. Brain dynamics in decision making: time course of EEG power of 8 Hz frequency value at frontal sites (F3), indicating mental concentration. Stimuli consisted of two or more digits of the same value (such as: **4 4**). Two response conditions are compared: (INS) find out the numerical amount the digit value/frequency, (SEL) find out the greater/smaller amount of digit value/frequency. A one-step decision as in INS, e.g. deciding amount of value or frequency, corresponds to one phase of brain activation. Decisions requiring two mental steps as in SEL, e.g. deciding amount of value and frequency and comparing them, at least correspond to two phases of brain activation. Here, activation of selected brain areas are less informative than the time course. (Data with permission of Sascha Tamm).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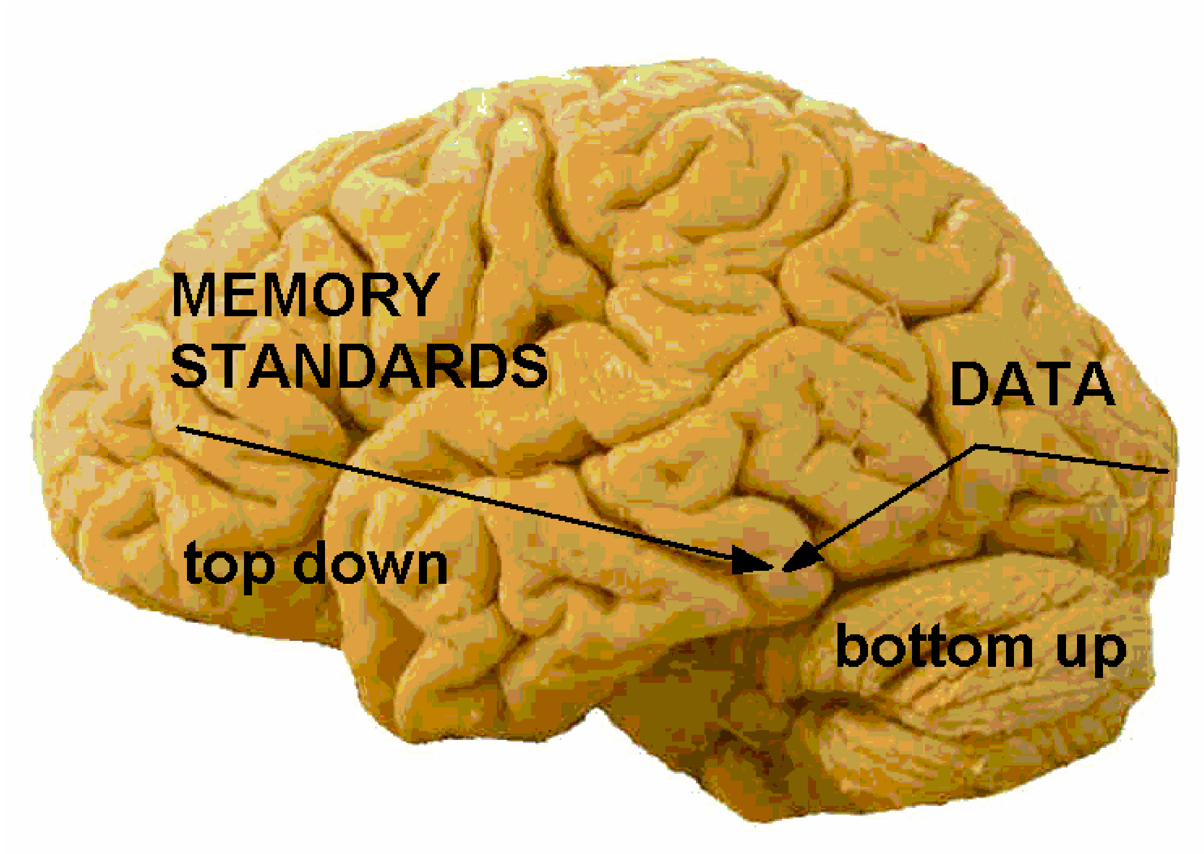
MEMORY
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