NEUROBIOLOGICAL BASES FOR PSYCHOLOGICAL FUNCTIONING

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Contents

Summary

The present article introduces the neurobiological basis of psychological functioning. It focuses on the neural system although other body systems such as the endocrine system are also important. It stresses that psychological functioning is not possible without its neurobiological basis but also that the relations between psychological and neurobiological levels are bi-directional in a continuous cycle of mind-body interactions. Three major approaches are used in the study of these mind-body relationships: psychological effects of neural alteration, neural effects of psychological change, and mind-brain correlations. The study of mind and brain take different perspectives, each having its specific levels of analysis. Mind-brain relations are reciprocal in continuous cycles. Mental processes induce neural change, altering the brain and thus affecting subsequent mental functioning. Correlational studies are employed whenever it is not intended or not possible to establish mind-brain relation in causal terms. A synopsis of the neural substrate follows. The neurobiological levels of

analysis, from the organ level to the molecular level, and their relevance for assessing and theorizing about psychological functions are briefly introduced. The cognitive neurosciences use a wide variety of methods that can be classified in terms of temporal and spatial resolution and with respect to their degree of invasiveness. Contemporary methods of non-invasive human neural imaging are introduced in some detail. The electrophysiology of mind is considered the most important neurobiological technique for answering psychological questions. Of the set of mental functions, aspects of three functions—perception, attentional selection, and language—are discussed in some detail. The conclusions draw on the relevance of knowledge about the interplay between neurobiological and psychological levels for psychological theorizing in particular, for the sustainable development for life on earth in general, and provide a perspective on future developments in the neurobiologically informed modeling of mental functions.

1. Introduction

Neural structures underlie mental functioning. Peripheral neurons gather sensory information, specialized brain areas and distributed neural networks construct perception and recognition, compute solutions to problems, or complex plans for action, and motor neurons send commands to peripheral effectors—the brain enables the mind. In the last two decades of the twentieth century, cognitive neuroscience made rapid progress in mapping mental functioning onto the brain's complex functional architecture. A number of modern techniques are available for imaging brain activity non-invasively. Nevertheless, to date, a complete function-to-brain mapping is not yet available.

This article first presents general principles and considerations concerning the mind-brain-relation. Then, neurobiological bases are introduced followed by an introduction to the methods available for investigating the mind/brain. A selection of mental functions and their neural implementations is subsequently described. The article concludes with an outlook on future perspectives.

2. Principles

As scientific working principles, three approaches to relate mind and brain, on the one hand, and two perspectives—mind and brain—that both comprise various levels of psychological and neurobiological analysis, on the other hand, are distinguished. Modern neurobiology of mind or cognitive neuroscience is a highly interdisciplinary endeavor that increasingly brings together scientists from various fields who are concerned with the study of a particular mental function and its neural implementation at different levels of analysis. Knowledge from all relevant scientific areas is acquired in the quest for a unified theory of the function at hand.

2.1. Approaches to Relating Mind and Brain/Body

Assessing psychological effects of neural alterations, neural effects of psychological changes, and correlating mind and brain are the three fundamental approaches to the study of the mind/brain (see Figure 1). The first two imply causal relations, whereas the last does not. The relations between the body, neural structures in particular, and the mind are reciprocal. Both affect each other in a continuous cycle of bodily and mental interactions. Experience physically alters neural structure and therefore affects future mental functioning. Bodily changes have an effect on the mind, which in turn leads to somatic alterations.

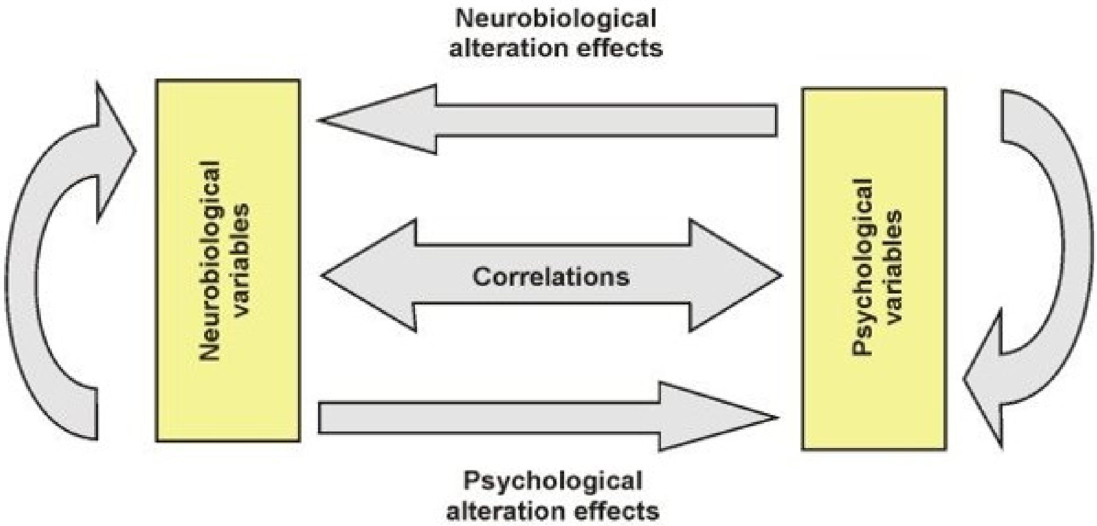

Figure 1. Three major approaches in the study of mind-body relations. Psychological effects of neural alteration, neural effects of psychological alteration, and mind-brain correlations are investigated.

2.1.1. Psychological Effects of Neural Alteration

Neural changes occur for a number of reasons. In scientific research, somatic intervention is used in humans and other animals to establish causal relationships between mind and brain. Measures may range from minor reversible interventions (e.g. the application of a small dose of alcohol to a healthy adult) to major irreversible experimental lesions of neural structures in animals. In all these cases, investigators are interested in resultant effects on some dependent measure of psychological functioning.
Outside the laboratory and independent of planned intervention, long-term impairment of mental functions occurs also as a consequence of neurobiological damage for a number of reasons. Neurological conditions that involve damage of neural tissue, for instance cancer, stroke, head trauma, or degenerative diseases of the nervous system, affect the mind. Use and abuse of psychotropic substances (e.g. alcohol, crack cocaine, or ecstasy) can also lead to impairment of mental functions. The characteristics of the neural damage determine the nature of the contingent impairment of psychological functioning. These may range from a feeling of numbness in a small, clearly circumscribed area of skin that is due to a severed sensory nerve to a progressive decrease in general academic intelligence measures caused by large-scale neural cell death in the brain due to abuse of alcohol or a degenerative disease like Alzheimer's. Again, investigators are interested in resultant effects on a dependent measure of psychological functioning.

In addition to effects of acquired neural damage, there are a number of other reasons for neural changes. The nervous system develops, there is neural maturation and aging, and regular physiological processes are subject to changes. All these neural processes also affect psychological functioning.

2.1.2. Neural Effects of Psychological Alterations/Change

Scientists use psychological intervention in the mental processes of individuals and record resultant changes in neural processes or structure. Psychological intervention comprises a broad spectrum of events, ranging from the application of a simple peripheral tactile stimulus to the fabrication of a complex social situation of considerable duration. The neural effects of these interventions also form a broad spectrum that is investigated using a wide variety of methods **(see *Section 4. Methods*).** These effects range from transient changes in a neuron's membrane potential to long-term training effects affecting large neural populations and lasting a lifetime. Investigators use the dependent neural measures to infer aspects of mental architecture as well as to gather knowledge about the neural system. In psychophysiology, for example, usually non-invasive physiological measures are employed to pursue this venue **(see *Section 4. Methods*).**

In everyday life, a variety of somatic effects of mental processes occur. Of these, processes that lead to bodily dysfunction and illness are of particular importance and are thus especially attended to. For example, somatic effects of stress or anxiety can lead to severe impairments. These interactions of mental functions with endocrine information systems of the body or with the immune system are investigated by psychoneuroendocrinology and psychoneuroimmunology respectively **(see *Experimentation in Psychology: Rationale, Concepts, and Issues* and *Methods in Psychological Research*).**

2.1.3. Correlating Mind and Brain

Correlational studies consist of establishing the extent to which psychological measures vary with neural measures. They establish a link between mental and bodily variables that are not intended to or cannot be interpreted in causal terms. Correlational studies might comprise variables too far apart on the levels of analysis of neurobiology and psychology to be investigated experimentally. For example, how do certain hormone levels link to the strength of specific complex behaviors or does mere brain size vary with academic intelligence measures? Also, correlational studies often are a precursor of intervention studies and serve in hypothesis generation.

Neuropsychological studies are considered to be correlational, if the extent of neural damage is extensive and direct effects of the neural change on psychological variables cannot be investigated **(see *Statistics and Its Role in Psychological Research* and *Methods in Psychological Research*).**

2.2. Mind and Body: Two Perspectives

Psychology describes and explains experience and behavior at various hierarchical levels of analysis while neurobiology does the same for neural structures. Both sciences regularly constitute different perspectives on one mental/neural event (see Figure 2). As a consequence, two accounts may result that cannot easily be merged. Depending on the respective levels of analysis, descriptions of one process from both perspectives might merge: For example, the work of edge detectors in early cortical visual processing can be described in detail in neural science terms. This account can be merged with one implemented in an artificially intelligent computer program that simulates the information processing function (i.e. the mental function) of these edge detectors. Such a merge is more difficult or impossible if distant levels of analysis are at issue (e.g. social systems and synaptic change). Merges of this kind—the description and explanation of human information processing, psychological functioning, in terms of neural computations—become increasingly possible. Successful merges provide a neural machine account of a mental function. This progress has been referred to as racing the ghost back into the machine—the ghost of non-bodily, mental processes into the neural machinery

The issue of aligning psychological and neurobiological approaches should not be intermixed with the difficulties of aligning psychological insights obtained from the first-person inner perspective or the third-person outer perspective. This problem is even more severe and may be regarded as irresolvable for reasons of principle. This type of mind-body problem arises from the apparent discrepancy between subjective, individual experience and objective description of underlying neural structures and processes. For instance, subjective experience of a mental event and the neurobiological processes underlying this event occur simultaneously and cannot be fused by an individual **(see *Cognitive Psychology*).**

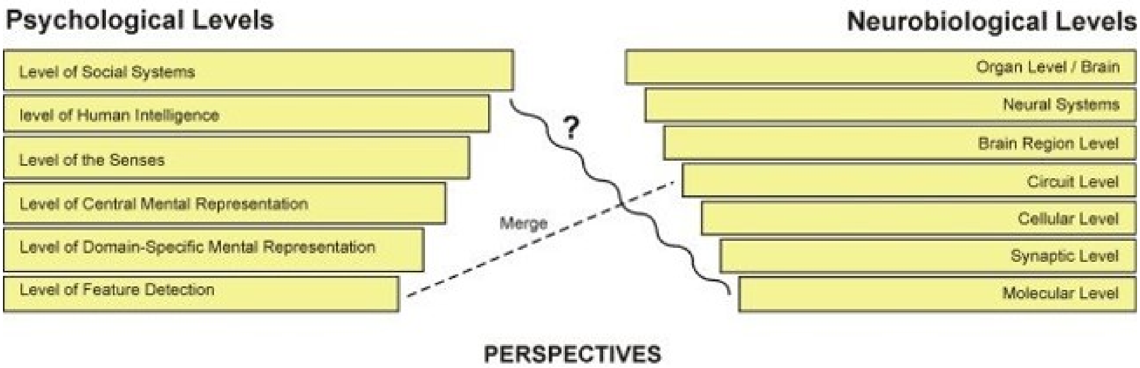

Figure 2. Psychological levels of analysis (mind), neurobiological levels of analysis (body), and examples of interrelations. Neurobiological levels are introduced in ***Section 3. The Neural Substrate***. There are topics that allow a merging of both perspectives (dashed line example) and others where a merge is very difficult, not desirable, or impossible (curved line example).

3. The Neural Substrate

This section introduces the relevant neurobiological levels of analysis and illustrates which kinds of mind-brain relations are drawn using these levels. For reasons of brevity, this section cannot provide a comprehensive introduction to neurobiology. The following levels of analysis are distinguished: organ level, neural systems level, networks level, circuit level, cellular level, synaptic level, and molecular level (see also Figure 2).

At the organ level, first, the central nervous system is distinguished from the peripheral nervous system. The former consists of the brain and the spinal cord. Also, the nervous system is distinguished from other organs (such as the heart). Results obtained at this level assert, for example, that the functional neuroanatomy responsible for the patella extension reflex is located in the spinal cord, not in the brain. Also, psychologically relevant neurobiological functions of the peripheral nervous system are distinguished from central functions.

The next lower level is the neural systems level. Here, functional networks of neural structures are characterized. Distributed networks underlie more complex functions. Object recognition, for instance, is achieved via the contribution of a number of specialized brain regions, rather than by one brain structure alone.

Neuroanatomy distinguishes brain structures and brain regions at the next level. The brain is composed of the medulla oblongata, the metencephalon (consisting of cerebellum and pons), the midbrain, the diencephalon (consisting of thalamus and hypothalamus), and the telencephalon or cerebral hemispheres. These are composed of the neocortex, the basal ganglia, and the limbic system. The neocortex of the two hemispheres consists of folded sheets of layered neurons. The cortical layers are about three mm thick and feature a specific architecture. In addition, infoldings (sulci) and crowns of the folded tissue (gyri) serve the purpose of volume reduction. The hemispheres are interconnected mainly by a neural fiber tract, the corpus callosum. Each hemisphere consists of four lobes: the frontal, parietal, temporal, and occipital lobes. In a more fine-grained subdivision, different regions of cerebral cortex are demarcated on the basis of cytoarchitectonics. There are in the order of 50 cortical areas, known as Brodmann areas (B.A.). These different brain regions might underlie distinguished mental functions, aspects of functions, subfunctions. Depending on the complexity of such a function, brain regions are connected into networks distributed over various parts of the brain (see above) to realize a function. On the other hand, the functioning of a given brain region can be mandatory for the production of various different functions.

These aspects can be considered one of the main venues of analysis in contemporary cognitive neuroscience. From a functional point of view, cognitive theories are augmented by adding neural localizations. The latter might reciprocally aid selecting one functional theory over the other by providing crucial additional evidence. From the perspective of neuroscience, on the other hand, psychological research contributes to functionally mapping the human brain.

The next level of analysis is concerned with local neural circuits. The connectivity of neurons is analyzed. This comprises cellular architecture as well as processing specifics. One central goal is to illuminate the regularities or even algorithms of neural computations. Hence one of the main concerns is how the brain processes information.

On the following level, investigations are concerned with the cellular units of the nervous system. Neurons show two different ways of information processing. On the one hand, an electric potential between the intra- and the extra-cellular milieu is maintained. This membrane potential changes as a function of neural interaction.

Negative and positive potential changes are summed up spatially and temporally and thus constitute analog information processing. On the other hand, digital information processing is achieved via action potentials that travel down a neuron's axon. Each neuron is a separate information-processing device. Different types of neurons show distinct characteristics that render them well suited for special types of computations and information processing.

Inter-neuronal transmission of information takes place via synapses. At the synaptic level of analysis, types of synapses, types of synaptic receptors, changes in synaptic connectivity, characteristics as well as dysfunctions of synaptic transmission, etc. are investigated. Synaptic functioning changes with maturation, aging, illness-related processes, and under the influence of certain drugs. It also changes as a regular function of learning processes.

Finally, at the molecular level, processing aspects that can be traced to the chemical properties of individual molecules are investigated. The mechanisms of membrane receptors and relevant neurotransmitters are investigated. This knowledge can be applied to the study of pharmacological interventions and drug effects.

A comprehensive theory of a psychological function needs to compile knowledge at various levels of neurobiological analysis. For example, knowledge acquisition can be investigated and described not only at different levels of psychological analysis but also at various neurobiological levels. At the neural systems level, networks of brain regions realizing a given memory function are described. Individual brain regions that contribute specialized processes or subprocesses are characterized at the next lower level. In order to specify the how in addition to the where, neural computation procedures and architectures are accounted for at the local circuit level. Memory also results in long-term as well as short-term cellular and synaptic changes. These are ultimately characterized by analyzing the underlying neurochemical processes. In essence, a complete, unified theory of knowledge acquisition would specify structures and processes at every level of analysis in close correspondence to psychological specifications.

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