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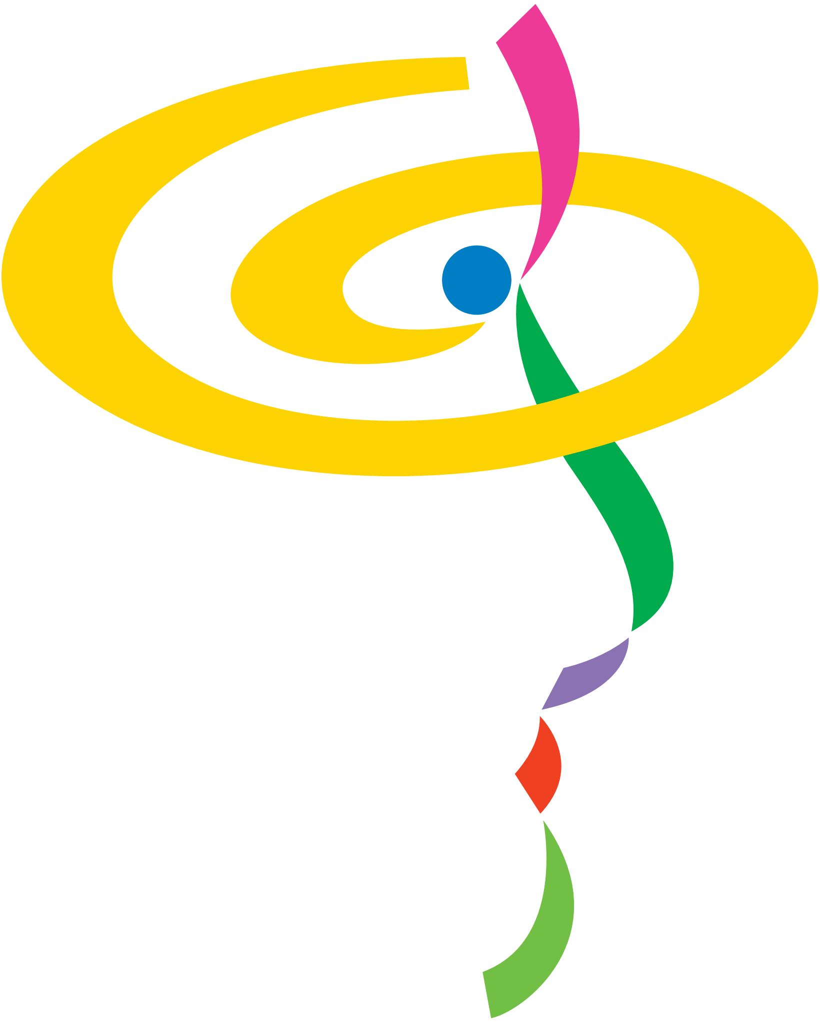

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Educational Research and Neurosciences – Expectations, Evidence and Research Prospects

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1. Objective of this expertise and chapter overview

1.1 Starting point

Since methods such as EEG, PET, and fMRI allow insights into the neurophysiology of human information processing, scientists and laypersons are fascinated by pictures of the thinking and learning brain. Studies on the human brain are currently the focus of international research and, in Germany, public interest in research on human thinking and learning has also risen, but for another reason. The problems of Germany's educational institutions uncovered by the PISA study immediately demand professional solutions. It is increasingly being realised that Germany has wasted too much time on ideological debates concerning the educational system while other countries have already redesigned their educational institutions according to the demands of a post-industrial knowledge society. Since such a rethinking process has also begun in Germany, many found it reasonable to concentrate on the very latest line of research, viz. educational neuroscience. This trend, however, is met with scepticism and worries by several researchers on learning and instruction – and not only by them. Currently available evidence from educational neuroscience cannot often be interpreted unequivocally and, if it can be done, only rather general conclusions can be drawn, imparting the delusive impression that improvement of school learning can be achieved without great efforts. In order to improve education in Germany in the medium-term it is necessary to specifically implement tested and proved measures in teachers' education. In this vein, teachers can acquire pedagogical content knowledge that is indispensable in the development and design of learning opportunities and in the interaction with students.

Beyond the practical applicability of educational neuroscience, the time is ready for the question of how we can further our understanding of educational processes with the aid of neuroimaging methods. At present, we can measure learning outcomes only by means of performance tests. But exactly this restriction hampers the investigation of learning by sense-making and insight as this type of learning takes a certain time and the insight (the „AHA!" experience) usually emerges unexpectedly, thus, it often cannot be examined. Insightful learning results from the integration and reorganisation of knowledge. Which brain activities precede insight is one of the most exciting research questions for the future. The objective of this expertise is to review neuroscientific studies and paradigms that are relevant for school learning and, based on this, to discuss future research questions. It should be noted that the extensive research on dyslexia and dyscalculia is not explicitly dealt with in this expertise. Of course, it is undoubted that some children cannot benefit from instruction in school due to deviant brain functions, but what these deviant brain functions exactly look like is currently being examined by several research groups around the world. Reviewing these findings would fill volumes and is far beyond the scope of this expertise.[1]

1.2 Chapter overview

Chapter 2: What are we searching for and what can we find in brain research? Prospects and limitations of educational neuroscience

Important keywords:

- Dynamics in children's brain development.
- Early brain development does not place high demands on the environment but is very susceptible to artificial interventions and interferences.
- Atypical cortical development in the first years of life usually results from sensory dysfunctions rather than environmental influences.
- The examination of children's sensory functions in preventive medical checkups in the first year is more important than providing sophisticated learning opportunities.
- It must be the aim of early education to establish a basis for knowledge acquisition in content areas where no privileged learning can be expected.

Even if brain research provides fascinating findings on human information processing, only rather general conclusions on the design of learning opportunities in preschool and school can be drawn. Educational institutions have been established to have children, within a few years, to acquire and apply knowledge that took centuries and millennia to evolve. To make this feasible, teachers must acquire pedagogical content knowledge and apply it in the design of learning opportunities. Findings from science history and cognitive psychology can aid teachers in establishing this type of knowledge.

Chapter 3: What are the relations between explanations from neuroscience, psychology and pedagogy?

Important keywords:

- Psychological and pedagogical explanations cannot be reduced to neuroscientific explanations.
- Distinction between privileged and non-privileged learning.
- Although neuroscientific studies describe the general conditions in which successful learning can occur, they are as a matter of principle too underdetermined to provide specific instructions for improving learning conditions at school.

This chapter addresses the question of which implications can be drawn from neuroscientific studies of the human brain for psychological and pedagogical theories. In the framework of contemporary theory of science, it is argued that

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[1] Gratitude shall be expressed to Rainer Bösel, Gerald Hüther, Andrea Rodenbeck, and Frank Rösler for their helpful comments on earlier versions of this expertise.

neuroscientific studies can describe the general conditions in which successful learning can occur, but they are as a matter of principle too underdetermined to offer specific instructions for improving learning conditions at school. In the first section it is outlined why psychological and pedagogical theories are autonomous levels of explanation which cannot be reduced to neurophysiological explanations. In this context, the supervenience model is described and used to characterise the relation between mental states (beliefs, intentions, etc.) and brain states (neuronal activation patterns, neuronal connections, etc.). The second section focuses on the relevance of neurophysiological studies for psychology and pedagogy. Since cognitive processes are always realised by processes in the brain, certain kinds of explanations and instructions can be derived from neuroscientific investigations which are thus of psychological and pedagogical significance. For instance, it may be possible in principle to diagnose cognitive developmental disorders by means of neurophysiological evidence before they become salient at the behavioural level later in development. In this vein, brain research can contribute to the early diagnosis of specific cognitive developmental disorders. In these cases, neuroscientific investigations can inform us about the neurophysiological conditions indicating a need for special treatments. But they do not provide any specific information about what exactly has to be done in order to remediate these deficits. How such treatments should be designed, in contrast, can only be elaborated in the framework of psychological and pedagogical theories. In the third section, it is argued that neurophysiological investigations are always underdetermined with regard to pedagogical research because they do not consider other aspects that are important in the design of learning environments, such as the learners' prior knowledge and cultural factors. In this context, it is necessary to distinguish privileged and non-privileged learning. Privileged learning occurs if biological programmes determine which learning processes are initiated by which environmental influences, at which developmental stage, and how these learning processes are executed. Non-privileged learning, in contrast, concerns all contents and abilities that we have not been prepared for by evolution and that are taught in school – such as reading, writing, and mathematics. In order to know how to design learning opportunities in school and, consequently, to improve the conditions for non-privileged learning, the learner's prior knowledge has to be considered and to be related to learning goals and demands. Since neither prior knowledge nor learning demands and goals can be captured in neurophysiological descriptions of the brain, brain research is as a matter of principle too underdetermined to provide specific instructions for designing learning opportunities. In non-privileged learning, the human brain represents just one factor within a larger cultural context. Therefore, the description of the cultural preconditions of non-privileged learning must go beyond descriptions of the brain and include further factors such as the learner's prior knowledge.

Chapter 4: Brain imaging methods in cognitive neuroscience

Important keywords:

- PET, MRI, and fMRI are not suitable in research on school-related learning because they are not – or only with restrictions – applicable in children due to exposure to ionising radiation, or noisiness.
- Neuroimaging methods can be reasonably applied in shielded laboratories only, but not in school settings.

The identification of neuronal correlates of cognitive functions requires neuroimaging methods which can measure the brain's structure and function in vivo. This chapter provides an overview of the most frequently used brain imaging methods, viz. (1) Positron Emission Tomography (PET), (2) Magnetic Resonance Imaging (MRI), (3) functional Magnetic Resonance Imaging (fMRI), (4) transcranial Near-Infrared-Spectroscopy (NIRS), (5) Electroencephalography (EEG), and (6) Magnetoencephalography (MEG). The description of these methods is divided into the following sections: Basic principles (type and source of the measured biosignal, fundamentals of measurement), spatial and temporal resolution, application, significance (validity of measurements), and a concluding discussion on advantages and disadvantages. At the end of the chapter the most important characteristics are summarised in a table.

PET, MRI, and fMRI cannot be applied (or only with restrictions) in children (and in research on learning and instruction, respectively) due to the exposure to ionising radiation or their noisiness. Other methods such as NIRS, EEG, and MEG are applicable in children and allow the administration of several cognitive demands, but they have the disadvantage that they are either under development (NIRS), provide a comparably poor spatial resolution (EEG), or are very expensive (MEG). In addition, neurophysiological measurements have to be conducted in shielded rooms, which puts the obtained findings' generalisability to school or school-related learning environments into question. At the end of the chapter, it is argued that it does not suffice to „look into the brains" of children or adults during cognitive performance. These methods can only then provide significant findings if carefully planned experimental paradigms are administered.

Chapter 5: Brain development

Important keywords:

- Brain development comprises both the establishment of new synaptic connections and elimination of redundant ones.
- Experience-expectant and experience-dependent plasticity of the brain.
- Critical or sensitive periods in brain development are only to be expected in genetically controlled developmental processes.
- Stimuli required in critical and sensitive periods are universal and available in any normal environment.

This chapter describes brain developmental processes that are relevant in the education of the developing human. At the beginning, a general overview of basic neuronal processes in brain development is given. The second section deals with the development of two cortical regions, viz. the primary visual cortex and the middle frontal gyrus. Both regions, being among the best investigated human brain areas, illustrate important differences in developmental trajectories between brain regions. While the developmental stage of both areas is similar at birth, synaptic density decreases much slower in the frontal than in the visual cortex. It is also emphasised in this context that human brain development not only consists in establishing new synaptic connections between neurons but also in the elimination of unused connections. Moreover, brain development includes the strengthening of important synaptic connections by myelination. In the third and fourth sections, external factors affecting brain development are addressed and the distinction between experience-expectant and experience-dependent plasticity of the brain is outlined. Experience-expectant plasticity refers to genetic developmental mechanisms requiring external stimuli to be initiated. This is exemplified by mechanisms involved in the development of the visual cortex. These mechanisms are only activated upon the input of certain visual stimuli; otherwise, they fail to occur. Thus, experience-expectant plasticity is characterised by its age-dependency and irreversibility. Only if the brain receives stimulation according to a genetic programme, certain developmental processes take place. Depending on how strongly these processes are affected by age and how irreversible they are, they are either called „critical" or „sensitive" periods: If certain developmental deficits cannot be made up at a later time, we speak of critical periods. However, if brain development is only favoured within a certain time window, and thus, can be caught up later – even if taking more efforts – these time windows are termed sensitive periods. Two important aspects of critical periods should be highlighted in this context: (1) Critical periods can only be expected in genetically controlled development. Therefore, critical phases exclusively occur in the development of basic functions such as the ability to discriminate speech sounds and faces or stereoscopic vision. Thus, critical periods only concern privileged learning where the necessary input and the execution of the learning process are biologically determined. Non-privileged learning that is important in school, in contrast, is generally not affected. Evolution has not prepared our brains for the acquisition of school-related knowledge (e.g., reading, writing, and arithmetic) as these cultural skills have – from an evolutionary perspective – come into existence only very recently. (2) Stimuli required to trigger developmental mechanisms in critical time periods are universal and available in every normal environment. These stimuli are only absent if organisms are kept under extremely deprived conditions, such as in an experiment in which the visual cortex of kittens did not develop normally because their eyes were covered up. Because of the universal availability of these stimuli, one does not need to provide children with a great many of specific stimuli during critical or sensitive periods. Nevertheless, the availability of such stimuli should still be taken into consideration. Otherwise, irreversible aberrations can occur, for instance, if infants' eyes are – due to surgery – covered up for a longer time during the development of the visual cortex, or if inflammations of the middle ear go unnoticed during the development of auditory brain areas. Contrary to the genetically controlled experience-expectant plasticity, experience-dependent plasticity is not restricted to specific time windows. At the end of this chapter, a number of animal experiments are presented demonstrating how neuronal organisation changes depending on different experiences.

Chapter 6: Central executive and frontal lobe

Important keywords:

- Tripartite working memory model.
- Individual differences in cognitive ability are accounted for by differences in working memory capacity.
- Working memory capacity is the best predictor of intelligence.
- The central executive resides in the frontal lobe.

How information processing has to be modelled in the brain in order to account for cognitive achievements as well as for performance impairments represents a central research question in cognitive psychology. The best theory currently available to answer this question is the tripartite model of working memory which describes the temporary maintenance and processing of information. Accordingly, working memory consists of a central executive and two subsidiary systems, viz. the phonological loop and the visuo-spatial sketchpad. While the phonological loop enables storing and processing of speech-based (phonological) information, the visuo-spatial sketchpad refers to visual and spatial input. The central executive is the main control system, inter alia managing the interplay of both subsidiary systems and supervising the efficiency of mental operations for goal achievement. Therefore, the central executive is regarded as the basis of complex cognitive performance. This model also accounts for individual differences in cognitive performance by referring to individual differences in working memory capacity. Behavioural studies have revealed a strong correlation between working memory capacity and cognitive abilities (both assessed by means of psychometric tests), for instance, reading and language comprehension, mathematical thinking, reasoning, learning of vocabulary, and spatial imagery. Therefore, working memory capacity is also the best predictor of intelligence. Brain research has made great efforts to identify the neuronal correlates of working memory functions. Studies on patients with brain lesions, for instance, could show that short-term and long-term memories reside in different brain areas, and that the phonological loop is subserved by left-hemispheric cortices. The central executive is localised in the frontal lobe, because frontal lesions are associated with the following cognitive deficits: attention, motor control, spatial orientation, short-term memory, learning, creativity, reasoning, and goal-directed behaviour. Furthermore, neuroimaging studies have revealed that the frontal lobe lights up in these cognitive activities.

Chapter 7: Pinpointing cognitive functions in the human brain

Important keywords:

- Differences regarding the localisability of basic functions and higher-order cognitive functions.
- In higher-order cognitive functions, overlaps in brain activation argue against assigning cognitive functions to specific brain areas.
- Higher-order cognitive functions that are distinguishable at the psychological level do not have clear-cut neuronal correlates.
- One and the same brain state can take over different functions depending on the other activated areas within the same network.
- Neurophysiological indicators of different problem solving strategies and learning processes.

This chapter addresses the question of whether or not only working memory but also qualitatively distinguishable cognitive functions – such as mathematical performance – can be pinpointed in the human brain. Are different brain areas involved in mathematics compared to text comprehension? The answer to this question may be highly relevant for research on learning and instruction. If this were the case, neurophysiological examinations could reveal whether a student already applies „appropriate" solution strategies or whether he or she is still trying to solve a problem by suboptimal means. The precondition for such an examination is, of course, that each (complex) cognitive function or process must correspond to a specific neuronal activation pattern which can be used as a marker of the applied solution strategies. Several investigations, however, call the notion that every psychological process and function can be assigned to a specific brain area into question. There are considerable differences between basic functions (e.g., colour perception, motor processes, etc.) and higher-order cognitive activities in the brain. This holds true regardless of whether the activities are classified by content (verbal, numerical, figural, spatial) or by the involved cognitive processes (attention, memory, reasoning etc.). In contrast to basic functions, higher-order cognitive activities cannot be unequivocally attributed to specific brain regions. Thus, neurophysiological evidence stands in contrast to a „cupboard model" of the brain where every function is located in a specific „drawer". Furthermore, localising basic cognitive processes in the brain only means that an area is systematically activated during this process, but does not implicate that only this area is involved. Especially in light of the strong interconnectedness in the brain, it appears highly plausible that every complex cognitive achievement requires the coordinated interplay of different brain areas.

Studies on attention, perception, imagery, and language show that only rather coarse topographical localisations are attainable. For instance, performance of attention and working memory tasks are accompanied by activations in the prefrontal and parietal cortices. Findings of topographical activation overlaps during different cognitive tasks additionally challenge the reasonableness of the aforementioned „cupboard" model. For instance, Broca's area is not only activated during the production and comprehension of speech but also during the processing of musical syntax, the imaging of movement trajectories, and during visuo-spatial performance. Recapitulating, it can be stated that cognitive functions distinguishable at the psychological level do not have equivocal neuronal correlates. Moreover, one and the same brain state can even take over different functions depending on the other activated areas within the same network. Nevertheless, the comparably clear-cut distinction between verbal and visuo-spatial information processing can be taken as a starting point in the application of neuroimaging methods in research on learning and instruction. In this vein, it may be possible, for instance, to neurophysiologically identify different strategies in solving arithmetic problems, even if they cannot be differentiated at the behavioural level. Moreover, as brain activation patterns change through learning, searching for neurophysiological indicators of learning progress appears feasible.

Chapter 8: Activation changes accompanying learning

Important keywords:

- In general, learning results in brain activation decreases.
- In some cases, learning is accompanied by activation shifts.
- The extent of activation decrease following learning is positively correlated with cognitive performance improvement.

A central characteristic of learning is the transition from controlled to automatic information processing. How is this transition reflected at the neurophysiological level? The question for neurophysiological correlates of learning can be divided into the following parts: (1) How does the level of activation change through learning? (2) In which ways do the topographical activation patterns change through learning? (3) What are the correlates of the activation changes? The first question can be answered quite well based on current neurophysiological studies. In general, learning results in a decrease in brain activation. The finding that better performance is accomplished with lower activation is usually explained in terms of an increase of neural efficiency, which means that only task-relevant brain regions are activated. With respect to the second question, in some studies an activation shift was observed, for instance, from prefrontal to (posterior) task-relevant brain regions. Concerning the third question, some studies have revealed a positive relationship between the extent of activation decrease and the performance improvement. Those individuals with the largest performance improvements displayed the strongest activation decreases. Activation changes are not only a neurophysiological correlate of learning but also an indicator of individual differences in learning progress. Can these findings which primarily derive from investigations of short-term training of simple cognitive processes also be generalised to longer learning phases? As school-related learning covers comparably long time periods, this question is highly relevant for research on learning and instruction. However, there are currently only a few studies on neurophysiological effects of long-term learning. Hence, research on the neuronal correlates of (school-related) learning is still in its infancy. A noteworthy exception is a brain imaging study in which illiterates and literates had to repeat nonsense words. It was found that differences in their ability to perform well on this task are also reflected in different brain activation patterns.

Chapter 9: The dopamine system

Important keywords:

- Dopamine is a neurotransmitter, which is, inter alia, important in memory consolidation.
- Dopaminergic neurons are activated by reward stimuli.
- Previous studies on the role of dopamine in learning refer to animal experiments; therefore, the results cannot be generalised to human learning offhand.

Dopamine is a neurotransmitter associated predominantly with motor functions as well as with motivation and memory processes. Animal studies have revealed that dopaminergic neurons are activated if reward stimuli are presented. If, in contrast, a reward fails to occur, activation in dopaminergic neurons is inhibited. These reactions have turned out to influence memory consolidation. However, most findings corroborating the role of the dopamine system in learning and memory are based on animal studies in which „learning" is equated with conditioning. Thus, it is questionable, whether and in what ways these findings can be transferred to school-related learning. At present, virtually no conclusions for research on learning and instruction can be drawn from previous investigations of animals.

Chapter 10: Direct brain-computer communication and neurofeedback: On the application of modern neurofeedback technology in educational research

Important keywords:

- Modern neurofeedback technology allows controlling machines (e.g., robots, wheelchairs or computers) by thought via brain-computer interfaces.
- This technology is used in individuals with pathological disorders to remediate abnormal brain activation patterns by learned self-regulation.
- It is an interesting (but nevertheless unresolved) research question whether cognitive performance can be enhanced, for instance, by EEG neurofeedback.

This chapter deals with modern neurofeedback technology that allows controlling machines (e.g., robots, wheelchairs or computers) by thought via brain-computer interfaces. In particular, the question is addressed whether brain activation can be influenced to facilitate learning. If this were possible, the brain could be prepared for learning in an unspecific way. The neurofeedback technology is based on the finding that individuals can alter their own brain activity if it is continuously measured and fed back by visual or acoustic signals. By this means, for instance, a computer cursor can be controlled via EEG signals. This technology is applied in the therapy of pathological diseases such as epilepsy, attention deficit disorders or hyperactivity. Here, individuals are trained to elicit „normal" activation patterns by self-regulation whenever first symptoms emerge. Even though only a few studies on the effect of EEG neurofeedback on cognitive performance exist, it seems feasible to enhance performance even in healthy individuals. Hence, it appears highly interesting to examine whether direct brain-computer interfaces enable a new way of learning which could be offered complementary to instruction in school.

Chapter 11: Results of the workshop „Educational research from a neuroscientific perspective"

In the preparation of this expertise, a workshop with scientists from different research fields took place from 19th to 20th November 2004 in Berlin (Germany). The participating scientists were invited to outline and discuss neuroscientific project proposals with implications for instruction in school. Among the participants were: (a) brain researchers possessing extensive experience concerning the interpretation of neuroimaging data, (b) cognitive scientists dealing with the acquisition and application of knowledge, and (c) researchers specialised in didactics[2] and educational scientists dealing with the design of learning opportunities in central subject domains. The goal of this workshop was to elaborate the research projects of educational and brain scientists and to constitute potential interdisciplinary research groups. This chapter provides a brief summary of all proposed research projects. A list of the participating researchers and the materials used in the workshop can be found in the appendix.

Chapter 12: Conclusions and outlook: What can educational research and brain research expect from each other?

Important keywords:

- The neuronal correlates of conditioned learning are currently investigated in animal studies, and it can be assumed that many findings can be transferred to conditioned learning in humans.
- However, in scientific examinations of learning in school, the focus does not lie on conditioning but on insightful learning and learning by sense-making with the aid of symbolic systems. Only little is known about the neuronal basis of this typical human form of learning.
- Empirical educational research has provided well-established findings on basic conditions of insightful learning and good instruction practice. These have to be implemented in school for different subject domains.

This chapter discusses several fundamental questions, but in spite of referring to the preceding chapters, it can also be read on its own. First, it is emphasised that neurophysiological animal studies merely investigate conditioned learning. Of course, this type of learning also occurs in humans, in general, and in pupils,

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[2] These are educational researchers specialised on the didactics of certain subjects (e.g., mathematics educators, physics educators, biology educators).

in particular, but the aim of schooling is not conditioned, but insightful learning. Therefore, findings on the neurophysiological basis of conditioning play only a subordinate role in research on learning and instruction. Learning in school refers to the acquisition of cultural knowledge, which requires symbol systems like language, script, pictures and mathematical symbols. The neurophysiological basis of this type of learning, however, is not well understood. Even though neuroimaging methods enable insights into the brain while reading, calculating or deliberating on laws of nature, such data has only little explanatory power. At the same time, empirical educational research has provided several findings concerning the design and improvement of instruction in school. In contrast to some other statements, there is no fundamental debate among empirical educational researchers on conditions of insightful learning and good instructional practice. The often expressed notion that brain research can contribute to the clarification of theoretical controversies in education is simply not true. The basic conditions of insightful learning are already well-established; but there is need for research on how to implement these basic conditions in the design of content-oriented learning opportunities and their transfer in school. This question, however, cannot be answered by brain research.

Chapter 13: Beyond immediate applicability: Potential research questions where cooperation of neuroscience and educational research is desirable

Important keywords:

- If neuroscience aims at a deeper understanding of typically human brain functions, cooperation with empirical research on learning and instruction should be established.
- Even if neuroscience cannot tell us what good instructional practice looks like, educational research can, in medium-term, gain important insights into how learning in school is reflected in the brain by applying neuroimaging methods.

Although an improvement of learning in school cannot be expected from neuroscientific findings in the near-term, a dialogue between neuroscience and educational research is desirable. If neuroscience addresses brain functions in typical human types of learning, learning in school downright inflicts itself as an object of investigation. The manifold experimental paradigms and tasks that were devised in educational research in the last years may provide important cues on interesting brain processes to neuroscientists. In turn, by looking at an individual's brain while coping with school-related demands, educational researchers can gain new insights into potential obstacles in specific subjects. Ten potential research questions are outlined where cooperation between neuroscience and educational research may prove seminal. Finally, organisational suggestions regarding the implementation of a research fund are put forward.

2. What are we searching for and what can we find in brain research? Prospects and limitations of educational neuroscience

2.1 Learning processes in the brain – a fascinating perspective

It is undoubtedly very fascinating to see by means of neuroimaging methods how the brain responds to certain information. Some novel neuroscientific findings are also reassuring in so far as they impart an optimistic picture regarding the brain's flexibility and plasticity throughout the lifespan. In fact, the localisation of specific mental functions in the brain seems to be rather flexible. Brain lesions due to diseases or trauma do not necessarily involve permanent and irreversible impairments in cognitive functioning. Likewise, the functional dichotomy of the two hemispheres (left hemisphere for language, right hemisphere for visuo-spatial processes) is far less strongly determined than has been assumed for a long time. Blakemore and Frith (2005) provide an excellent overview of neuroscientific evidence that is also relevant for educational scientists. But, they also explicitly state that currently no conclusions about the design of learning opportunities or classroom instruction can be drawn from such findings.

An example for an interesting neuroscientific finding is that we must not confine ourselves to cortical grey matter in the investigation of higher-order cognitive processes typical for human beings. The cerebellum, for instance, does not only control balance and posture but is also involved in higher-order learning and thinking processes. Psychological research on learning has similarly uncovered strong associations between body movements and thinking, e.g., in gesticulation. New findings on how the brain controls motor processes will also further our understanding of the relationship between mind and behaviour. Moreover, novel findings on the role of sleep in memory consolidation are also of interest in research on learning and instruction (Wagner et al., 2004). Which type of information should be learned at what time of day and how rest periods could be integrated into the learning process, are of immediate practical relevance. Thus, bringing together findings from psychology and brain research will presumably lead to the development of integrative theories of mind and behaviour in medium-term.

Brain research – in particular the work by Peter Huttenlocher – has also provided interesting findings on child development within the first months and years. The dynamics of brain development are indeed quite impressive (e.g., Huttenlocher & Dabholkar, 1997). Several changes occur in the human brain according to inherent programmes as long as children's basic physical and emotional needs are satisfied and their sensory functions are intact. For instance, during the first year the number of synaptic connections in the baby's brain dramatically increases. This is followed by a rapid decrease starting in the third year of life and continuing until adolescence in attenuated form. A popular fallacy in the last century was to equate an increase in synaptic density with higher learning ability and to interpret the subsequent elimination of synaptic connections as first signs of cognitive decline. In fact, the described changes in synaptic density are not necessarily bound to specific stimulation. The type of stimulation that is needed for normal development is universal and available practically everywhere, in a Mongolian yurt, in an African hut, in a concrete slab in Berlin, or in a mansion in Beverly Hills. From previous research we know that a child's ability to recognise and discriminate speech sounds of its mother tongue develops from the verbal input within the first year of life. In Western cultures, for instance, this verbal input consists of ample talk directed at the infant, being aware that it does not understand anything. But even if no direct communication takes place, e.g., in other cultures, the child learns to speak. Hence, listening to others' verbal interactions appears to suffice for language development.

Although early child development does not place high demands on environmental input, it reacts sensitively to artificial interventions and interferences. For instance, if eggs of chicks are opened prior to maturity, the early light input results in improved vision. However, the birds' auditory functions are permanently impaired in this case (Lickliter, 1990). This is typically explained by referring to predefined neurons of the auditory system which are now occupied by the visual system. Such findings impressively demonstrate the dynamics of normal brain development.

Provided that basic physical and emotional needs of the infant are satisfied, atypical cortical development is more frequently due to sensory dysfunctions than due to environmental factors. Infant squint is more than a blemish, and an inflammation of the middle ear in the first year of life is more than only painful. If the eyes are not well coordinated, neuronal asymmetries in the visual cortex can occur which, in turn, may produce permanent visual deficits. If hearing is impaired, the ability to discriminate sounds could be harmed in a way that also learning literacy is affected.

Such neuroscientific findings are highly relevant in caring for infants and children. Optimal child development in the first year is not facilitated by confronting them with complex and sophisticated learning environments – which at best do no harm – but rather by having examined their sensory functions in preventive medical checkups. Visual and auditory impairments have to be diagnosed and treated early. In case such disorders are incurable, e.g., the child remains blind and/or deaf, compensation measures have to be taken, such as the acquisition of sign language. Research has revealed that deaf children communicating with their deaf parents in sign language right from the start develop better than deaf children with hearing parents. Unless there are indicators of impaired visual or auditory functions in children one does not have to worry about the learning opportunities of infants. If the opportunity presents itself – e.g., because family members have different mother tongues – the child could acquire different languages if each family member uses its mother tongue when addressing the child. Second language acquisition is one of the few subject domains with a sensitive time period. Neuroimaging studies comparing adults with early (i.e., within the first 3 years) and late second language acquisition have found differences in language comprehension in the brain, even though both groups did not differ at the performance level.

The outlined findings on second language acquisition moreover underline the domain specificity of learning. In fact, there are competencies and content domains whose foundations are innate – they are referred to as *start-up* mechanisms, suggesting that learning is privileged in these domains. Among these are, for example, speaking and walking, visual pattern recognition and also basic forms of quantification and social interaction (e.g., empathy and aggression).

Probably the most interesting result in this context comes from Castelli et al. (2002). The brains of autistic individuals who meanwhile were able to master tasks drawing on their theory of mind displayed slower processing of social information than mentally retarded individuals. Non-autistic individuals do possess start-up mechanisms that enable fast processing of social information. Autistic individuals, however, lack these start-up mechanisms, thus, they have to acquire knowledge about social interaction by other, more effortful means.

The fact that privileged and non-privileged learning can also be distinguished in the brain is of particular significance for learning in school since the „institution school" aims at enabling and supporting the non-privileged kind of learning.

2.2 The content matters: Analysis of knowledge domains as the main task in educational research

The genetic endowment of humans has not considerably changed in the past 40,000 years, but the available knowledge has increased profoundly. About 35,000 years had passed before letters and number symbols emerged providing the basis for the later development of mathematics (just think of the importance of the number zero in arithmetic), science and engineering. Analytical geometry or Newton's law of mechanisms, both central parts of the secondary school curriculum, belong to the human cultural assets for only a few centuries. School children are expected to learn within a few years what took ingenious characters and millennia to evolve. Nevertheless this is made possible by providing professional learning and exercise opportunities in which knowledge is presented in portions and acquired over several years (Stern & Schumacher, 2004).

Non-privileged learning is time-consuming; therefore, early education is necessary. But it is neither the case that the child's brain generally learns more effectively, nor should the learning material be simply presented earlier. For instance, learning to read and write is not facilitated by drilling letters into three-year olds. Instead, the handling of pens can be practised and specific singing along or talking activities may be used to enhance phonological awareness, which has turned out to facilitate learning literacy. A reasonable preparation for mathematics does not consist in the presentation of arithmetic problems but rather in the children's sensitisation to mathematical patterns in their environment. By these means, the disastrous tendency towards equating mathematics with the correct execution of arithmetic routines is also countered. Likewise, children's scientific understanding can be fostered by making them experience, for instance, that the water level in a glass rises if an object is immersed in it. Science instruction in elementary school can refer to such experiences, e.g., when explanations for floating and sinking of objects are worked out which, in turn, facilitate later comprehension of physical concepts like density and buoyancy force.

Thus, early education must aim at providing the foundations for knowledge acquisition in domains where privileged learning cannot be expected.

2.3 Teachers doing a good job know how students learn

Proponents of brain research often claim that teachers have to know how learning takes place. In fact, research on learning and instruction makes the same request. In this context, educational research has been referring to the concept of *pedagogical content knowledge* for many years. It delineates the integration of content knowledge and pedagogical knowledge (Staub & Stern, 2002). Teachers doing a good job know about and appropriately consider the students' prior knowledge. They also anticipate which misconceptions underlie learners' mistakes and they can appropriately respond to mistakes and deficits with specific exercises or explanations. Knowledge about neurotransmitters or the function of the hippocampus and the amygdala in information processing does not suffice to understand the students' obstacles. Instead, pedagogical content knowledge has to be established for each subject domain, and teachers can actually benefit more from the history of science and from developmental psychology than from brain research.

Even though parallels between scientists discovering a law of nature and learning children should not be taken too literally, there are indeed some similarities between scientific fallacies and children's misconceptions. An example hereof is the impetus theory, referred to by scientists for the explanation of moving objects before Newton's law of mechanics revolutionised physics. That the impetus of moving objects continuously dissipates represents a popular view of many children as well as adult laypersons. Similar parallels exist concerning chemical reactions in combustion. For a rather long time in the history of science, it was assumed that a new substance (phlogiston) is produced – a theory that is still present in the minds of many laypersons. When teachers are informed about the scientific history of the respective subject domain, they will be more aware of the circumstance that children cannot catch up 200 years of science within two hours of classroom instruction.

But also, recent concepts from developmental psychology can help teachers to understand why students encounter problems in specific subjects. Domain-general developmental theories such as the one by Piaget have taken a back seat. The question for the cognitive differences between children and adults is today answered by „knowing differently" rather than by „thinking better". Children often use the same terms as adults, but they frequently assign a different meaning to them. This may be best illustrated with the following example. Children affirm the question of whether a heap of rice weighs anything but negate the question of whether a single rice grain has any weight. Although this may be incomprehensible for educated adults, it makes sense from the child's perspective. Children equate „having weight" with „feeling heavy" and, thus, also hold the opinion that a rice grain has weight for an ant. This misconception of weight cannot be explained by an underdevelopment of the child's brain but rather reflects a learning deficit as Boedeker (2004) demonstrated recently: Uneducated adults living on the pacific isle Trobriand likewise did not possess a concept of weight that is independent of subjective experience. The precondition for the development of the physical concept of weight is the availability of the concept of „measurement" and of the corresponding metrics. Only the integration of mathematical knowledge and knowledge about objects yields a physical concept of weight.

Difficulties in mathematical comprehension can be explained as well by developmental psychology. Like language learning, the learning of numbers is guided by genetic programmes. Preschool children learn to count without formal instruction – they inherently know that larger numbers refer to larger quantities. Of course, they sometimes mix up number names but they never assign the same number name to two different quantities. Culturally developed mathematics, however, is not intuitively comprehensible. Children who learned that 8 is larger than 7 have to accept in fractional arithmetic that $6/7 > 6/8$. Moreover, that multiplication means increasing and that division means decreasing numbers is again intuitively insightful. However, this is not the case in multiplication with numbers smaller than 1 which produces smaller results and the division by such a number which yields larger results. Teachers who are aware of the difference between intuitive and cultural knowledge can better handle their students' difficulties.

2.4 Stimulating learning environments

The question of how to get students to learn multiplication tables, the binomial formula, the Pythagoras theorem, a poem, lists of vocabulary and grammar rules of a foreign language, the capitals of European countries or the formula for buoyancy force may be similarly answered by teachers and psychologists. Learning and memory psychology suggests that we should learn in small steps and that learning and practice time should be distributed over the day. Reinforcements in the form of reward or punishment will result in a higher frequency of desired answers and a lower frequency of undesired answers. But answering the question of how students can learn to apply second language vocabulary and correct grammar rules in writing an essay is by far more difficult. Under which conditions can children learn to refer to their knowledge about the buoyancy force in explaining why their legs are feeling weighty when they get out of a swimming pool?

Brain research does not provide an answer to the question of how learning opportunities have to be designed in order that acquired knowledge is drawn upon in mastering novel tasks. Fun and good temper alone it is not everything.

German students' deficits in autonomous and flexible application of knowledge acquired in school (uncovered in TIMSS and PISA) cannot be attributed to disorders in the dopamine system but rather to poorly stimulating classroom instruction.

International studies and experiments in school have revealed how to arrest students' attention and how to keep them at it: They are confronted with demands that they cannot master at first go but they already possess useful prior knowledge to solve the problem. Their prior knowledge can be activated by offering specific exercises and discussions. Misconceptions and mistakes are allowed and are constructively incorporated by the teacher. In this vein, students can extend, revise and adjust their knowledge to the specific demands. How such learning opportunities can be designed has to be answered for each subject domain and requires equal cooperation of teachers, researchers specialised in didactics, and cognitive scientists.

3. What are the relations between explanations from neuroscience, psychology and pedagogy?

3.1 Introduction

Which implications can be drawn from neuroscientific studies for psychological and pedagogical theories? Can neuroscientific evidence provide specific instructions for improving learning conditions at school? Or are these studies as a matter of principle too underdetermined with respect to psychological and pedagogical explanations in order to be able to offer such instructions? To answer these questions, I am going to outline some thoughts, based on contemporary theory of science, about the difference and autonomy of distinct levels of explanation.

3.2 The difference and autonomy of distinct levels of explanation

One and the same phenomenon can always be described from different theoretical perspectives. Let us consider, for instance, a chess computer. Such a device can be described at a *physical*, *functional*, and *intentional* level. Due to the different explanatory purposes that characterize these levels, each level of explanation describes its own kinds of objects, properties and relations.

If a chess computer is described at a physical level of explanation, *causal* relations between different physical states are examined in order to explain, for example, which natural laws underlie certain successions of electrically charged states. At a functional level, however, completely different kinds of objects, properties and relations are addressed. This level is not about electrons and causal relations between different physical states. In contrast, at the functional level of explanation objects are individuated by functional criteria, for instance, as an „AND” switch, and *functional* relations, like, e.g., *logical* relations among them are investigated. The intentional level of explanation, in turn, focuses on entirely different objects, i.e., on intentional states like beliefs and intentions, and describes *cognitive* relations among them. Hence, distinct levels of explanation are not only characterized by specific kinds of entities, but also by specific explanatory aims and models of explanation. Whereas at the physical level we are looking for causal explanations, at the intentional level we are looking for reasons to explain certain kinds of behaviour.

Which of these different levels of explanation we chose depends entirely on our aim of explanation. If we intend to examine which materials are suitable for the construction of a chess computer, it would be appropriate to select the physical level. But if we intend to design the chess computer’s wiring system, the functional level of explanation has to be chosen at which the computer’s components are functionally individuated, for instance, as resistors and amplifiers. However, if I am interested in learning how to beat the chess computer, knowledge about its physical and functional configuration is useless, because it would be by far too complicated to predict the computer's actions on the basis of knowledge about its physical or functional structure. Hence, it would be much more efficient in this case to focus on the intentional level and to consider the computer's objectives and strategies. It is important to note that none of these levels of explanation is, on its own, better or more appropriate than any other. In contrast, it entirely depends on our aims of explanation which level to chose. In this context, of course, simplicity should by an important guiding principle of our decisions, as is, for instance, emphasized by the contemporary American philosopher Daniel Dennett (1987). It may indeed be possible to calculate the chess computer's moves based on our knowledge about its physical or functional properties. But this strategy is much more costly and time consuming than making such predictions at the intentional level.

Every higher-level state or property can be realised by several different states or properties at a more basic level of explanation. The functional property of being an amplifier, for instance, can be realised by completely different physical devices such as transistor tubes or microchips. Likewise, an „AND" switch can be realised by different electric, hydraulic and pneumatic systems. Furthermore, one and the same intentional state such as knowledge about a certain chess rule can be realised, for example, by different programming languages or by different brain states of distinct individual persons. Hence, higher-level states and properties are capable of *multiple realisation* by different lower-level states and properties.

In order to account for the possibility of the multiple realisation of higher-level states and properties, their relationship to lower-level states and properties is characterised by an asymmetric relation which is called '*supervenience*' in contemporary philosophy of mind (see Kim, 1993, 2005). Accordingly, a state or property M supervenes on a state or property P under the following three conditions:

(1) M belongs to a higher level of explanation than P.
(2) The occurrence of P is sufficient for the occurrence of M.
(3) But the occurrence of M is *not* sufficient for the occurrence of P because M cannot only be realised by the lower-level state or property P, but also by other lower-level states or properties.

Therefore, for each difference between higher-level states or properties there exists a corresponding difference between lower-level states or properties. For example, corresponding to the distinction between autism and schizophrenia at the psychological level there is a specific difference between brain states at the neurophysiological level. Furthermore, due to the asymmetry of the supervenience relation, *not every* difference between lower-level states or properties corresponds to a difference between higher-level states or properties. This can be illustrated by the fact that dyslexia, i.e., reading and writing difficulties, may have different neurophysiological causes: It can be due to disorders in the visual system as well as to disorders in the auditory system. In the first case, the affected persons have difficulties in recognising letters. In the second case they have difficulties in understanding speech sounds. In this example, we find a difference at the neurophysiological level, but none at the psychological one, because both neurophysiological disorders result in the same cognitive and learning deficits.

In order to establish relationships between phenomena described at different levels of explanation, it is necessary to start with the concepts of the respective higher-level descriptions. For instance, in order to be able to identify certain physical states as realisations of an „AND" switch, one has to possess knowledge of the relevant functional concepts. Likewise, one must already understand cognitive concepts in order to be able to find out associations between certain brain activities and visuo-spatial information processing or memory processes. *Hence, these relationships can only be established in a top-down direction.* Consequently, higher-level concepts enable classifications at lower levels of explanation which would not have been possible with the concepts of the lower levels only. This can be illustrated by the following examples:

- No physical description suffices in defining the property of being a chair, because the property of being a chair is a functional property which can in principle be realised by an *indefinite* number of physical objects. However, if one aims at defining this property in terms of physical concepts, a *finite* number of concrete physical realisations would be privileged and, consequently, the possibility of multiple realisation by an indefinite number of physical objects would get lost. Therefore, if only physical concepts were available for the description of reality, the discrimination of chairs and non-chairs, reflecting functional concepts, would not be possible.
- Likewise, neurophysiological descriptions are not sufficient for defining what it means to be in a certain cognitive state. In addition, if only neurophysiological concepts were available to us, we would never form the idea that those particular brain states that are associated with a certain cognitive state have something in common, and, therefore, are substantially different from other brain states which are not associated with this particular cognitive state. Again, this can be illustrated by the example of dyslexia: We do need psychological concepts in order to be able to describe the characteristic cognitive and learning deficits of dyslexia at the psychological level of explanation. Starting from this cognitive characterisation, we can subsequently identify neuronal correlates of this cognitive and learning deficit, namely disorders in the visual or auditory system. Neurophysiological concepts alone, however, could not explain why just these two neuronal correlates and no others are subsumed under this particular concept.

Since concepts of the physical or neurophysiological level of explanation are not suited to provide the aforementioned classifications, higher-order concepts thus cannot be reduced to concepts of lower levels of explanation. This holds generally true for *all* levels of explanation. Similarly as historical, legal and economic categories cannot be reduced to physical concepts, psychological and pedagogical concepts cannot be reduced to neurophysiological concepts. Consequently, distinct levels of explanation are not only different, because they focus on different kinds of entities and have specific explanatory aims and models of explanation. In addition, they are also autonomous.

3.3 The significance of neuroscientific studies for psychology and pedagogy

The crucial advantage of the above described supervenience model lies in the combination of the following two ideas: First, it accounts for the fact that higher-level explanations are irreducible to lower-level explanations. Second, this model also takes into regard that higher-level states and properties are always realised by lower-level states and properties. Hence, conditions can be formulated at lower levels of explanation which have to be fulfilled by objects in order to possess higher-level properties. This may again be illustrated by the chair example: Although the property of being a chair is essentially a functional property, an object has to fulfil certain physical conditions in order to be a chair. Therefore, at the physical level of explanation requirements concerning shape, size and stability can be indicated that objects have to fulfil in order to be considered as appropriate candidates for the property of being a chair.

This view can be transferred to the relationship between the neurophysiological, psychological and pedagogical levels of explanation. Since cognitive processes are always realised by processes in the brain, certain kinds of explanations and instructions can be derived from neuroscientific investigations which are thus of psychological and pedagogical significance. This holds particularly true for the diagnosis and explanation of cognitive deficits based on neurophysiological examinations. In the following, I am going to illustrate the psychological and pedagogical importance of neuroscientific studies by six examples.

(1) Neurophysiological explanations of developmental cognitive deficits

Neurophysiological studies can provide novel explanations for phenomena that are already well-known at the psychological level. A current example is a study by Judy DeLoache (2004) who investigated the inability of 18 to 30 months-old infants to identify small models of chairs, slides, cars, etc. as small models and to act accordingly („scaling error"). DeLoache related the toddlers' inability to neurophysiological evidence that visual information is processed in two distinct systems in the brain, i.e. in the ventral and the dorsal system, which are not sufficiently connected at this stage of their cognitive development.

(2) Neurophysiological explanations of cognitive and learning deficits

Neurophysiological studies can provide explanations of cognitive and learning deficits. This may again be illustrated by the example of dyslexia. Most dyslexic children have an impaired phonological awareness. This means, they have difficulties in recognising and producing compound speech sounds in words. Children with such phonological deficits usually have less neuronal activity in temperoparietal areas whilst working on tasks that require a decision whether certain letters and syllables rhyme (see, e.g., Simos et al., 2002). Since activation in these areas increases with improving reading ability, dyslexia may be explained by diminished brain activity in these particular areas (see also Shaywitz et al., 2002). Hence, neuroscientific studies may be of psychological and pedagogical importance because they can provide evidence for the neuronal causes of certain cognitive and learning deficits. For instance, it has been shown that dyslexia is not due to a *deviate* development of the phonological system. Instead, it is rather caused by a *delayed* development of this system (Goswami, 2004). Since delayed developments may require other treatments than deviate developments, such neuroscientific insights may also help to find the adequate treatment of cognitive deficits.

(3) Different causes of cognitive deficits

A given cognitive deficit can have different neuronal causes. While no differences are observable at the behavioural level, neurophysiological studies may identify different causes of a particular cognitive deficit in different individuals. This is again the case in dyslexia, which may be due to both, disorders in the visual or in the auditory system. Accordingly, different treatments have to be applied in these different cases to remediate this cognitive and learning deficit. In this way, neurophysiological studies may have practical consequences for treatments, even though they do not give us detailed information about the specific kinds of treatments which are required to remediate a certain cognitive deficit. Instead, we just learn from such studies that *different* treatments have to be applied.

(4) Early diagnosis of cognitive developmental disorders by neurophysiological evidence

It may be possible in principle to diagnose cognitive developmental disorders by means of neurophysiological evidence before they become salient at the behavioural level. This would imply that there is clear evidence for a reliable relationship between certain brain states at a given developmental stage and the later emergence of specific cognitive developmental disorders. At present, however, neurophysiological methods do not allow this kind of reliable early diagnosis of cognitive developmental disorders at an individual level.

(5) Decisions between competing psychological explanations

Neuroscientific evidence may be considered in order to find out which of two competing psychological explanations is more adequate. For instance, if theory A explains dyslexia by disorders in visual perception, whereas theory B explains the same cognitive deficit by disorders in language comprehension, neurophysiological research about the respective brain areas may help to determine which of these theories is the best explanation (Goswami, 2004).

(6) Training of precursor skills

Neurophysiological investigations have shown that brain areas which are activated during the mathematical reasoning of adults are also activated during

> children's finger counting (Dehaene, 1997). This finding is consistent with the assumption that finger counting is a mathematical precursor skill whose promotion may be beneficial for later competence acquisition. If this prediction were confirmed in longitudinal training studies, neurophysiological insights could provide information about the design of educational instructions.

These examples illustrate that neuroscientific investigations are of significance for psychological and pedagogical explanations because they can uncover differences that are not observable at the behavioural level. However, it must be kept in mind that this is subject to the condition that the association between cognitive performance and brain states is empirically proved so that the presence of a specific neuronal state can be regarded as precondition of a specific cognitive ability. Therefore, it must be ruled out that the cognitive abilities in question emerge without respective brain states. Moreover, it is important to take into regard that the aforementioned examples mainly refer to the diagnosis and explanation of cognitive and learning deficits. Even though neurophysiology is definitely capable of diagnosing and explaining *pathological cases*, one must not jump to the conclusion that it holds similar competences regarding the design of learning opportunities in school. In addition, neurophysiological investigations do not tell us anything about the specific content of treatments and trainings to remediate cognitive and learning deficits. They tell us something about the conditions under which certain cognitive abilities are absent and, thus, provide some information about *when* treatments are needed. But they do not provide any specific information about *what* exactly has to be done in order to remediate these deficits. In contrast, how such treatments should be designed, can only be elaborated in the framework of psychological and pedagogical theories.

This even holds true if neurophysiological studies identify specific brain areas activated during certain tasks like, for instance, finger counting. Simply from the finding that finger counting in children activates brain areas which are associated with mathematical reasoning in adults, one cannot draw the conclusion that later mathematical performance can be deliberately improved by practising finger counting in childhood. Likewise, from the fact that our hands are used for eating and writing, the conclusion that eating is a deliberate practice for writing cannot be drawn. *The fact that similar physiological bases contribute to the emergence of two competencies is not sufficient for drawing conclusions about treatments or trainings to improve these competencies.* In particular, with respect to the development of mathematical thinking it may be assumed that it depends on additional context variables not considered in the description of the human brain. In the following, I am going to analyse these context factors and argue that neurophysiological studies are in principle too underdetermined to provide specific instructions about the improvement of learning opportunities in school.

3.4 The underdetermination of neuroscientific studies with regard to research on learning and instruction

The previous considerations refer to the ideal case of one and the same object being examined at different levels of explanation. This precondition, however, is not met if we address questions about on the optimal design of learning opportunities in school, because in this context the human brain is only part of a larger system. This part is, of course, indispensable, but as it represents only one factor in a much larger cultural context, its description cannot cover all aspects that are relevant for improving learning opportunities in school.

This is mainly due to the fact that instruction in school concerns the acquisition of kinds of knowledge for which no *privileged learning* can be expected. Privileged learning occurs if biological programmes determine which learning processes are initiated by which environmental influences, at which developmental stage, and how these learning processes are executed. Speech as well as many motor skills like, for instance, walking are learned in this way. However, in *non-privileged learning* it is not biologically determined which factors initiate learning processes, and what the course of learning processes looks like. This distinction between privileged and non-privileged learning corresponds to the differentiation between „fast route learning" and „slow route learning" suggested by Uta Frith (2001). While learning processes are controlled through specific biological „start-up mechanisms" in fast route learning, slow route learning follows more general learning principles. The evolutionary psychologist David Geary (1996) describes the same phenomenon in terms of „primary and secondary abilities". Non-privileged learning concerns all contents and abilities that are taught in school – such as reading, writing, and mathematics. Evolution has not prepared our brain for the acquisition of these contents and abilities, because these cultural skills have – from an evolutionary perspective – come into existence only very recently. As a consequence, the description of the preconditions of this type of learning has to go beyond descriptions of preconditions to be met by the human brain. In addition, further external, i.e. cultural factors have to be considered that are relevant for successful non-privileged learning.

Preconditions of non-privileged learning are primarily *knowledge preconditions*. For instance, in order to acquire the physical concept of density, children already have to know other physical concepts like weight and volume. This also holds true in case of the explanation that whales are not fish but mammals. In order to understand that animals are not classified according to their habitat but to their type of reproduction requires that children already have the right kind of knowledge about animals' reproduction. Likewise, children, who have learned that 7 is smaller than 8, can only understand that 2/7 is larger than 2/8 if they have made the experience that numbers can refer to different units. *The description of such knowledge preconditions cannot be reduced to descriptions of neurophysiological states.* In the same way as the property of being a chair cannot be defined by physical concepts alone, it also cannot be defined in purely neuroscientific terms what it means to possess knowledge about the reproduction of mammals. *For this reason, we need psychological concepts to describe these knowledge preconditions.*

A further important prerequisite for non-privileged learning is that the respective knowledge base is *well-organised.* What a well-organised knowledge base is can only be described and explained by reference to the demands and learning goals that are assigned to a person. The property of being well-organised is not an intrinsic property of a knowledge base irrespective of specific demands and learning goals. In contrast, it rather represents a *relational* property which can only be assigned to a knowledge base if we also explicate in relation to which specific demands and learning goals the knowledge base should be regarded as being well-organised. It is important to note, that the terminology to describe these demands and learning goals cannot be reduced to neurophysiological concepts, because these demands and learning goals are *cultural factors outside our brains.* Hence, there cannot be purely neurophysiological criteria for a knowledge base's being well-established. Instead, we need psychological concepts in order to be able to describe the demands and learning goals we have to refer to in order to qualify the organisation of a person's knowledge base.

This may be illustrated by the following example: What do I have to know to win a regatta? Well, first of all I have to know the physical properties of my sailing boat – for instance, its draught, and the size of its keel or skeg – to predict its behaviour under certain wind and water conditions. Without this knowledge I would not be in a position to predict what I can demand from my boat. Moreover, I need this information to know which functions will fail if certain physical preconditions are not fulfilled – for instance, if the mast is broken. In addition, for successful participation in a regatta I also need knowledge about the traffic rules in sailing, for example, about the right of way as well as knowledge about strategies for successful sailing, and about the intentions and skills of my opponents. These requirements represent knowledge that cannot be reduced to knowledge about the physical properties of my sailing boat, because this knowledge refers to factors *outside* my boat.

In this sense, I am suggesting the following analogy: Just as the sailing boat in the regatta is one factor in a larger cultural context, the brain is also just one factor in a larger cultural context with regard to non-privileged learning. Moreover, in the same way as knowledge about the physical properties of a sailing boat is not sufficient for providing instructions about successful participation in a regatta, neurophysiological knowledge about the human brain is also not sufficient for providing specific instructions for improving learning opportunities in school. With respect to these instructions, both kinds of knowledge are *principally underdetermined.* For this reason, brain research cannot be for educational research what physics is for engineering.

Let us a look at another example. Take the case of a certain farmer who knows practically everything about the biology of wheat. Now he ponders about the further handling of this year's wheat harvest. These are his most important options:

(1) Should he make whisky of it?
(2) Should he preserve it as seeds?

(3) Should he make fodder of it?
(4) Or should he sell it to an agrarian company?

His knowledge about the biological properties of wheat is not sufficient to provide a concrete instruction for his decision. Like the sailing boat in a regatta, the wheat is also just one factor in a larger context. For this reason, mere biological knowledge is by far too underdetermined to provide instructions for the farmer's decision. Instead, several other aspects such as economic factors, for instance, whose description goes beyond that of wheat, have to be taken into consideration.

An interesting illustration of this idea can also be found in an article by John Morton and Uta Frith (2001). They emphasise that in the description of dyslexia we must not confine ourselves to the neurophysiological level of explanation, but that we also have to take into regard the psychological level in order to be able to explain the influence of cultural factors: In particular, dyslexia is less frequently found in children with Italian as mother-tongue as compared to children with English as mother-tongue – and this fact can be explained by the rules of grapheme-phoneme correspondence which are easier in Italian than in English!

3.5 Concluding remarks

For optimising learning opportunities in school, educators have to know the following:

(1) Which concepts do children already have to understand, and how does their knowledge base have to be organised, in order to be able to solve certain problems and to reach certain learning objectives?
(2) Which prior knowledge do children actually possess? For instance, which intuitive concepts and explanations do they already understand? And which misunderstandings and mistakes must be expected if children with this knowledge try to cope with certain tasks?
(3) What exactly is the learning objective? How should the children's knowledge base be organised after this learning objective has been achieved?

This kind of information is the precondition of answering the question of how learning opportunities and instructions in school should be designed so that prior knowledge can be applied in solving novel problems. Brain research alone cannot provide such information because it is in principle too underdetermined for the following two reasons:

(1) Since psychological and pedagogical theories belong to higher levels of explanation than neurophysiological theories, it is in principle not possible to reduce psychological and pedagogical explanations to neurophysiological explanations.
(2) In non-privileged learning, the human brain represents just one factor within a larger cultural context. Therefore, the description of the cultural preconditions of non-privileged learning must go beyond descriptions of the

> brain and include further factors such as the learner's prior knowledge. Among other reasons, we do need psychological concepts in order to evaluate whether a person's knowledge is appropriate for coping with certain novel tasks.

However, the underdetermination of neuroscience with regard to the design of learning opportunities in school does not diminish its general importance – likewise as the importance of physics is not diminished by the fact that legal, economic and historical categories cannot be reduced to physical concepts. This underdetermination is rather an expression of the fundamental autonomy of the distinct levels of explanation. In addition, irrespective of its underdetermination with regard to instructions for improving knowledge acquisition in school, brain research is relevant for psychological and pedagogical theories, because it contributes to the diagnosis and explanation of cognitive and learning deficits like, for instance, dyslexia and perhaps helps to identify cognitive precursor skills. Hence, neuroscience provides important insights for psychological and educational research by describing the general neurophysiological preconditions of successful learning.

4. Brain imaging methods in cognitive neuroscience

Neuroscientific methods have in the last years, primarily due to exceptional technical advancements, found their way into a number of traditional psychological research fields and have even constituted new research branches (e.g., the „cognitive neurosciences"; Raichle, 1998, 2003; Savoy, 2001). Of particular interest in this context are neuroimaging methods that enable the in-vivo imaging of the brain's structure and function. The application of the latter, functional methods that enable to „watch" the brain during thinking have resulted in a great number of studies addressing a broad spectrum of psychological processes, ranging from perception to memory and other intellectual functions (cf. the review of Cabeza & Nyberg, 2000). As neuroimaging methods play a role of increasing importance in the investigation of mental performance, understanding their basic principles is inevitable in evaluating their significance as well as their range of applications. This chapter aims at providing an overview of the most frequently used methods at present:

- Positron Emission Tomography (PET)
- Magnetic Resonance Imaging (MRI)
- functional Magnetic Resonance Imaging (fMRI)
- transcranial Near-Infrared Spectroscopy (NIRS)
- Electroencephalography (EEG)
- Magnetoencephalography (MEG)

The description of the methods is divided into the following sections: In *basic principles* the type and source of the measured biosignal as well as the fundamentals of measurement are depicted. The *spatial and temporal resolution* is described separately as far it is important for the evaluation of applicability and significance. In the subsequent section on *applications* practical application aspects, experimental designs, and restrictions in applicability are outlined. In the section on *significance* questions for the validity of the method and the related experimental designs are addressed. Finally, the *advantages and disadvantages* of each method are listed as far as they have not already been discussed in the other sections. It should be explicitly mentioned that the methods' description in this chapter is not exhaustive. In addition, the basic principles are presented in a simplified way for reasons of comprehensibility. More detailed descriptions are available, for instance, by Jäncke (2005) and Toga and Mazziotta (2002).

4.1 Positron Emission Tomography (PET)

Positron emission tomography (PET; cf. Posner & Raichle, 1994) is one of the earliest methods devised for functional neuroimaging. This method measures brain activation by means of indirect parameters (e.g., changes in cerebral blood flow or glucose metabolism); until the mid 1990s PET was the prevailing neuroimaging method in the cognitive neurosciences. With the advent and increasing availability of functional magnetic resonance imaging (fMRI), PET is now applied considerably less often which is primarily due to the fact that fMRI provides a comparably significant but non-invasive method. Nonetheless, it is still an interesting method in cognitive neuroscience as recent technical advancements even allow the measurement of neurochemical parameters.

Basic principles

If a given brain area is activated, for instance while performing cognitive tasks, local energy and oxygen consumption increases. To compensate for this increased demand, glucose and oxygen is carried into the brain through the bloodstream which is achieved by expansion of blood vessels (vasodilatation) followed by increases in regional cerebral blood flow (rCBF) and blood volume (rCBV). Hence, the activation distribution can be assessed indirectly by measuring the glucose and oxygen concentration in the brain. However, organic molecules like glucose or oxygen do not emit measurable signals and, therefore, have to be radioactively labelled. To this end, organic substances (e.g., glucose or oxygen) are combined with artificially produced (radioactive) isotopes (radionuclides) to so-called „tracers" (radiotracers). The employed isotopes are produced in cyclotrons and are short-living, i.e. they continuously emit positrons in random directions (positron emission) during decay. After injecting the tracer (into the arteria carotis) or uptake through inhalation, the tracer is carried into the brain and distributed according to energy and oxygen demands. In human tissues the emitted positrons collide with surrounding electrons, producing a pair of annihilation photons (gamma photons) moving in opposite directions (180°). The thereby emitted energy is so strong that the photons move through the skull virtually unaffected by tissue and bones until they are recorded by radio detectors in the PET scanner (consisting of a cushioned examination table and a concentric tube). The emission direction (annihilation photons are always emitted 180° apart) and the temporal coincidence enable the source localisation of positron emission and, consequently, of activated brain areas.

As energy supply for the brain is almost exclusively provided by glucose metabolism, measurement of the regional cerebral glucose metabolism has turned out particularly suitable for the investigation of brain activation during cognitive processes. For this purpose, radioactively labelled glucose (^{18}Fluorodeoxyglucose, FDG) is administered which, like normal glucose, is carried into the cells and absorbed. However, the degradation of this artificially produced glucose analogue takes places rather slowly and, thus, it is accumulated in the cells of the respective brain area. In this way, the spatial distribution of energy consumption – and of the accompanying neuronal activity – can be determined for a specific time period.

Spatial and temporal resolution

The spatial resolution of PET primarily depends on the technical specifications of the scanner (size and number of detectors) – but the spatial resolution cannot be improved infinitely by technical means as the type of the employed isotope also matters. Depending on the isotope, emitted positrons can travel up to a few millimetres until they annihilate with an electron and produce gamma photons. Therefore, the spatial resolution is often estimated to be about 1 cm^3 which is considerably worse than in fMRI. The temporal resolution is determined by the half-lives of the isotopes which range from a few minutes (e.g., 2 minutes in ^{15}O labelled oxygen) up to hours (e.g., 110 minutes in FDG). The lower limit is often estimated to lie between 45 and 60 seconds.

Application

In contrast to other neuroimaging methods, PET requires an injection (or inhalation) of radioactively labelled chemicals which (a) exposes the participant to ionising radiation, and (b) is often an unpleasant experience, especially if the tracer is administered intra-arterially. In fact, the use of tracers imposes several restrictions to this method: For ethical and medical reasons only a limited number of PET scans are to be conducted in healthy adults per year. Its application in children and women of childbearing age is entirely prohibited (except for medical indications), which hardly allows the investigation of developmental trajectories or sex differences. Besides the exposure to ionising radiation, it is the unpleasant procedure of tracer injection that may result in samples of rather „tough" volunteers whose representativeness for the population may be called into question.

The experimental procedure in PET studies strongly depends on the employed tasks and the measured parameters (or tracer features, respectively) and comprises single scans after a longer phase of cognitive activity (e.g., 30 min in FDG) as well as multiple scans with repeated tracer injection or inhalation (e.g., up to 30 scans in radioactively labelled oxygen). All experimental designs, however, require that the assessed time period captures the (cognitive) target activity in order to draw conclusions about the involved brain areas and their activation level. To isolate the brain activity of interest, subtraction designs are frequently applied. This means that an experimental condition is compared with a control condition regarding the distribution of energy or oxygen consumption (cf. the section on fMRI for a more detailed description of the underlying rationale and criticism of this approach).

Significance

Similar to fMRI (see section 4.3), conclusions on the underlying neuronal activity are indirectly drawn either via hemodynamic changes or via glucose metabolism. In general, empirical findings suggest a strong coupling of neuronal activity and regional changes in blood flow, even though the molecular principles are not fully understood yet (Heeger & Ress, 2002; Kim, 2003; Raichle, 1998). The significance of PET studies is additionally restricted due to a rather poor spatial and temporal resolution; time intervals of 30-45 seconds do not allow the measurement of time courses in cognitive processes which usually occur within periods of some hundred milliseconds. If the accumulated activity over a certain time period is to be analysed, e.g., over some minutes, the differentiation of the interesting cognitive processes from other activities could prove to be rather difficult.

Advantages and Disadvantages

The declining application of PET as compared to fMRI can predominantly be attributed to the fact that (a) PET is an invasive method which (b) implies exposure to ionising radiation. Its poorer spatial and temporal resolution also contributes to the notion of PET as an outdated imaging method. Another disadvantage lies in the need for cost-intensive tracers which have to be produced on-site by means of cyclotrons as the positron emission begins immediately after production.

Nevertheless the advantages of this method also should be mentioned. In contrast to fMRI, PET scans are rather quiet which allows the presentation of auditory material and creates a more pleasant (and ecologically more valid) experimental situation for the participants. Moreover, by employing appropriate designs, a broad range of psychological tests can be administered which cannot be presented in an MRI scanner. This holds particularly true if the PET scan is conducted *after* participants have solved cognitive tasks during which the radioactively labelled glucose was accumulated in active brain areas. At a gross level, PET is also more sensitive than fMRI as nearly every positron emission or every gamma photon emission, respectively, can be detected. The broad application of this method, in particular the opportunity to investigate distributions of neurotransmitters (such as dopamine or serotonine) and their receptors will presumably prevent that PET becomes outdated too soon.

4.2 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) or magnetic resonance tomography (MRT) enables three-dimensional imaging of brain structures. This method builds on the effect of nuclear magnetic resonance which has been used in organic chemistry since the 1950s. The technical device required for structural imaging was introduced by Lautenbur in 1973 in the international journal *Nature* and, to date, has revolutionised medical diagnostics. Since the 1980s MRI belongs to the standard diagnostic methods in medicine. However, beyond medicine the use of MRI in cognitive neuroscience has turned out to be a particularly well-suited method for imaging and measuring anatomical characteristics in the human brain, such as brain volume, grey and white matter or distinct anatomical structures. The application of MRI also contributed to the evolvement of the neuroscientific research field of cognitive neuroanatomy which deals with relations between structure and functions in the human brain.

Basic principles

Atomic nuclei with an odd number of protons and neutrons show a permanent spin on their own axis. This spin produces a weak magnetic field around the nuclei. In organic tissue, however, the spins are randomly oriented in space and may even compensate one another; thus, no magnetic field is detectable. Hence, the first precondition for utilising magnetic resonance signals is the alignment of the spins according to an external static magnetic field which either results in parallel or antiparallel alignment. Nuclei aligned parallel to the direction of the field are in a lower energy state than nuclei aligned antiparallel. After initial fluctuations of single nuclei between both orientations most of them are in the lower energy state which produces a static net magnetisation parallel to the external magnetic field. But the nuclei never align exactly with the magnetic field; they are tilted somewhat and wobble around the vector of the static field; this phenomenon is called precession.

Aligning the nuclei with an external static magnetic field is only the first step in MRI as the dynamic balance between the two energy states (i.e., more nuclei oriented parallel than antiparallel) represents a state of equilibrium where no signal is emitted. An MR signal is produced only if the magnetic vector of the nuclei is temporarily shifted and the magnetisation returns to equilibrium afterwards. This temporary shift is achieved by applying high-frequency magnetic pulses (radio frequency, RF pulses) whereupon the longitudinal magnetisation passes into a transversal (in the optimal case 90°) magnetisation. In addition, the nuclei now precess in phase, i.e. they point in the same direction at the same time. After the RF pulse is switched off, the nuclei again align with the static magnetic field whereupon an electromagnetic resonance signal (FID, Free Induction Decay) is produced. This FID is detected by receiver coils in the MR scanner and provides the basis for MR data collection.

The decay of transversal magnetisation is due to two independent processes: (1) The spin-lattice relaxation time (T1) is the exchange of energy between the nuclear spins and the lattice. (2) The spin-spin relaxation time (T2), in contrast, signifies the loss of phase coherence (synchronous precession) of the nuclei. Both times depend on the tissue (e.g., the T1 and T2 times are shorter for white as compared to grey matter). This specificity allows the differentiation of organic tissues and anatomical structures. Additionally, the contrast of the MR image can be varied by different T1 and T2 weightings.

Even though most, if not all atomic nuclei with a spin could be used for MRI, hydrogen is the most frequently imaged nucleus in MRI. This is due to the fact that hydrogen nuclei are present in great abundance in the human body and that they give the most intense magnetic signal.

Spatial and temporal resolution

MR signals are detected sequentially for slices of tissue which are then added to a three-dimensional image of the human brain. Each slice has to be scanned repeatedly to obtain a high-resolution MR image. Typically, the thickness of the slices ranges from 1 to 10 mm with each slice containing a matrix of individual measuring points, so-called voxels. The larger and more fine-grained this matrix is, the higher is the spatial resolution – usually matrices of 256 x 256 voxel are applied. The signal strength of each measuring point depends on the number of nuclei per voxel. The larger a voxel is, the more nuclei contribute to the MR signal and, thus, its intensity increases. The spatial resolution is not only a question of technical parameters, but also the acquisition time has to be extended to gain higher resolutions at a given signal-to-noise ratio. For instance, the spatial resolution is about 1.25 x 1.25 x 5 mm for an acquisition time of 1-2 seconds. As MRI, in contrast to fMRI, aims at detecting structural information of the human brain, its temporal resolution is not relevant. In any case, the atomic nuclei have to be repeatedly stimulated by RF pulses to collect enough data for an exact neuroanatomical image of the brain.

Application

Similar to PET, an MRI scan always has to be conducted in the laboratory. The participant is lying in the MR scanner, a tube with a diameter of about 60 cm. During the scan, which usually takes between 20 and 40 minutes, the participant has to keep his head still to prevent scan artefacts. Since such movement artefacts can cause considerable problems in data analysis, several devices were proposed to immobilise the head. Besides bite-bars or head shells, the participant's head is in most cases immobilised by means of soft foam pads. As the MRI scan itself is accompanied by loud noise (produced by magnetic gradients interacting with the main magnetic field), ear protection (headphones and/or ear plugs) is essential. The restricting and noisy environment inside the scanner may also provoke anxiety which sometimes necessitates the application of tranquilisers. This is especially the case in (young) children. Children under five usually have to be sedated or even narcotised for medical MRI scans in order to prevent movement artefacts.

Significance

At present, MRI is considered state-of-the art in imaging and measurement of structural properties in the human brain. What was only feasible by post-mortem studies of the brain in the 1970s is now realisable anytime and with high resolution.

Advantages and disadvantages

Disadvantages of this method are the high costs for acquisition, operation and service as well as potential (albeit improbable) health risks. Aspects concerning the latter two factors are relevant. First, participants are exposed to a strong static magnetic field which is assumed to be safe up to an intensity of 4 Tesla (most frequently MRI scanners with 1.5 Tesla are used). Second, minimal intracranial warming due to the RF pulses can be observed. If reviewing current literature, however, no health risks are evident but due to a lack of longitudinal studies this cannot be said for certain. The successful and unproblematic application of MRI since the 1980s, though, makes health risks appear very unlikely. As already mentioned in the introduction, MRI nowadays plays an important role in the investigation of links between brain structures and cognitive functions. Differences in the size of anatomical structures can be measured in the range of millimetres and can be related to cognitive variables. Haier et al. (2004), for instance, found significant correlations between frontal grey matter and participants' intelligence. Other studies provide evidence that learning processes are also reflected in macrostructural changes which was shown, for example, in taxi drivers (Maguire et al., 2000) or musicians (Gaser & Schlaug, 2003).

4.3 Functional Magnetic Resonance Imaging (fMRI)

Functional magnetic resonance imaging (fMRI) can be regarded as an extension of MRI in order to measure functional parameters of the nervous system. Neuronal or brain activity can hereby be assessed with a similar spatial resolution as in MRI. The introduction of fMRI can be dated back to the early 1990s where first endeavours were made to draw conclusions on neuronal activity from hemodynamic changes in the brain (cf. Aine, 1995; Raichle, 1998).

Basic principles

The BOLD (blood oxygen level dependent) signal provides the basic signal in measuring cerebral activity. This signal was first described by Ogawa and coworkers in 1990 who observed that blood vessels can be mapped differently well by means of MRI depending on their oxygenation. This phenomenon derives from the fact that oxygenated blood (with high concentration of oxyhaemoglobin) has other magnetic properties than deoxygenated blood (with high concentration of deoxy-haemoglobin).

If a certain brain area is activated (e.g., during cognitive activity), local energy and oxygen consumption increases. This causes vasodilatation and, consequently, an increase of regional cerebral blood flow (rCBF) and blood volume (rCBV). The supply of oxygenated blood, however, exceeds the local oxygen demand; hence, blood in activated brain areas contains more oxy-haemoglobin and less deoxy-haemoglobin. Deoxy-haemoglobin is paramagnetic (it distorts the surrounding magnetic field and has a higher magnetic susceptibility), whereas oxy-haemoglobin is diamagnetic and does not display these effects. The different magnetic properties are reflected in the MR signal in that an increase of deoxy-haemoglobin is accompanied by a decrease of the signal whereas a decrease of deoxy-haemoglobin leads to signal increase. The concentration change of oxy- and deoxy-haemoglobin due to neuronal activity represents the BOLD signal which can be detected by means of MR scanners.

Spatial and temporal resolution

The spatial resolution is about 5 mm^3 in 1.5 Tesla scanners and is generally better in scanners with high field intensity (e.g., 4 Tesla and above). A principal disadvantage of this method consists in its restricted temporal resolution. This, however, is not primarily due to technical features – new scanners can collect images every 100 ms – but rather to the detected physiological changes. If a certain brain area is activated, the BOLD signal shows a characteristic time course which reflects different physiological processes. Prior to the large signal increase (following increased blood flow) a short-lasting signal drop is often observed expressing the increased local oxygen consumption (increase in deoxy- and decrease in oxy-haemoglobin). After a delay of about 2 seconds, the regional blood flow is augmented and the supply with oxygenated blood exceeds the demand resulting in the aforementioned concentration change and the emergence of the BOLD signal. Even though it is sometimes assumed that the first signal (the drop before blood flow increase) is more strongly associated with neuronal activity, it is the second signal change (increase in blood flow) that is used as a reliable and valid measure for brain activation. This might be attributed to inconsistent evidence concerning the first signal change and the need for high-intensity MR scanners to detect it. If the delayed BOLD response is considered, however, the problem arises that this method can only determine where in the brain the neuronal activity is but not when it occurs and how long it lasts. This temporal aspect, though, is of particular relevance in the investigation of cognitive information processing since MEG and EEG studies demonstrate a decay of neuronal responses within a short time (300-800 ms) after stimulus onset. The low temporal resolution of fMRI also seems problematic for the study of processes during the performance of elementary-cognitive tasks (tasks that can be solved within one or a few seconds).

Application

FMRI scans are conducted in the same laboratory environment as MRI scans (the participant has to lie in the scanner), which hampers the administration of several experimental paradigms. Visual stimuli cannot be, as usual, presented on a computer monitor but have to be reflected on a mirror installed above the participant's eyes. Responses can only be given by means of a keypad which is not in the participant's field of view as the head is immobilised during the scan. Hence, the participant has to memorise the position of the response keys beforehand (e.g., which finger is placed on which key). The loud noise in the scanner and movement artefacts make vocal answers often impossible. But also the presentation modality of stimuli is restricted by the noisy environment. For instance, special presentation devices are required to present auditory material in a way that even subtle differences (in pitch or, especially relevant in language studies, slight differences in speech melody and intonation) can be perceived. Another restriction consists in the small BOLD signal strength following a single stimulus and the necessity of aggregation which might be problematic if only a limited number of stimuli is available.

To compensate for the rather small BOLD signal strength for each stimulus several scans (or images) have to be aggregated to reliably detect changes in blood flow. To this end, typically two types of designs are applied: block designs and event-related designs. Since the advent of fMRI research, block designs have been administered in which different conditions are presented alternately in blocks. Either different experimental conditions are compared with each other (e.g., cognitive tasks of the same type but with different levels of complexity) or an experimental condition is compared with a control condition (e.g., a resting period). In the statistical analysis, the BOLD signal of the different conditions is contrasted. Besides the block design event-related designs are increasingly gaining importance. Contrary to the block design, stimuli (or tasks) of different experimental conditions are not presented in blocks but in a predefined sequence. The BOLD responses related to single stimuli (or events, respectively) are aggregated afterwards and – similarly to the block design – contrasted between different experimental conditions. A central advantage of this design is the possibility to aggregate the signals of each stimuli following either predefined (e.g., tasks of the same type) or post-hoc defined criteria (e.g., successfully learned vs. unlearned stimuli). Hence, this design provides a wider scope in the analysis of brain activation accompanying cognitive processes. The problem of this design – the slow BOLD response (declining after 10-12 s following a stimulus) – has meanwhile been solved by means of advanced statistical analyses and, thus, even short inter-stimulus intervals of 1-4 seconds are feasible (Savoy, 2001).

Significance

Probably the most important question concerning the significance of fMRI studies concerns the relationship between neuronal activity and the BOLD signal reflecting changes in local blood flow. Only if the assumption – based on empirical evidence – can be made that both physiological phenomena are strongly associated and that the BOLD signal reliably depicts them, this method can show its advantages. Recent reviews on the couplings between neuronal activity, changes in cerebral blood flow and hemodynamic parameters generally substantiate the validity of this method (e.g., Logothetis et al., 2001), even if the underlying mechanisms are not entirely understood yet (cf. Heeger & Ress, 2002; Kim, 2003; Raichle, 1998). This can be partially ascribed to the lack of evidence concerning the relationship between different indicators of neuronal activity (local field potentials, firing rates, synaptic activity etc.; Heeger & Ress, 2002).

The significance of fMRI studies moreover depends on the quality of the employed experimental design. Both block and event-related designs aim at investigating the neuronal bases of cognitive processes and functions. As the human brain is permanently active, a comparison between different experimental conditions (or an experimental with a control condition) is required. It is essential that both conditions only differ in the interesting cognitive function and not in irrelevant aspects. Stated differently, the experimental conditions have to be constructed in such a way that activation differences between them can unambiguously be attributed to the process or function of interest. As the activation during one condition is often (also statistically) subtracted from the activation during another condition, this approach is called the subtraction method (cf. Raichle, 1998). This method, however, has frequently been criticised (e.g., Poldrack, 2000; Sergent, 1994), as complex cognitive processes are often no simple addition of elementary processes. Problems especially arise in comparing a condition of cognitive activity and a resting period. As it is not known which cognitive processes take place during the resting condition, it is also unknown what is subtracted from the cognitive task condition – both, at the cognitive and neurophysiological level. Binder et al. (1999), for instance, found that language regions are active during a resting period which was attributed to „mental soliloquising" of the participants.

Advantages and disadvantages

The advantages and disadvantages of fMRI are largely similar to those of MRI. As fMRI is non-invasive, less expensive than PET, widely applied, and measures brain activation with high spatial resolution during different cognitive demands, it is the method of choice for many researchers in cognitive neuroscience. Despite its many advantages, the disadvantages and restrictions regarding application and significance should also be kept in mind; this makes the combined application with alternative methods essential for understanding the time course and localisation of cognitive processes and functions.

4.4 Transcranial Near-Infrared Spectroscopy (NIRS)

Transcranial near-infrared spectroscopy (NIRS) is among the most recent achievements in neuroimaging techniques. Although near-infrared light was discovered about 200 years ago (for a historical overview, cf. McClure, 2003), its first application in functional neuroimaging can be dated back as late as to 1977 (a study on cats by Jöbsis). At the beginning of the 1990s, four independent research groups reported on the possibility to investigate human brain activation with this method; in the year 1995 the first study dealing with motor brain activity was published (cf. Koizumi et al., 1999). At present, this method appears to be a seminal candidate for future cognitive neuroscientific research (cf. Boas, 2004).

Basic principles

NIRS enables the measurement of cortical activity and the accompanying physiological changes through optical methods. Light with a wave-length between 700 and 1000 nm (near-infrared light) penetrates biological tissue (the scalp), thus, changes in light absorption and reflection in the cortex due to neuronal activity can be detected. In particular, two types of signals associated with cortical activity can be measured: (1) Intracellular changes: If neurons fire, the absorption characteristics of their neuronal membranes change (Stepnoski et al., 1991). This signal emerges very fast after stimulus onset (within milliseconds) and is similar to event-related potentials (ERPs; cf. section 4.5 on EEG). However, these responses are rather weak, which is why event-related optical signals can only be detected if a number of trials (e.g., 1000) is averaged. (2) Intravascular changes. As already outlined above, an increase in brain activation results in regionally increased blood flow and volume and in concentration changes of oxy- and deoxy-haemoglobin. This physiological response is far slower and emerges after about 2 seconds. Oxy- and deoxy-haemoglobin not only have different magnetic characteristics but also distinct reflection and absorption properties of visible and near-infrared light, which provides the fundamentals for the NIRS signal.

Near-infrared light is emitted via optical fibres (light injectors) at an angle of 45° into the scalp, whereupon the reflected light is detected by means of optodes (detectors) located next to the injectors. If several measurement locations (e.g., several light injectors and detectors) are used, the different light sources are distinguished by frequency modulation. In consideration of the strong difference in the absorption and reflection rate of oxy- and deoxy-haemoglobin, usually the slower hemodynamic response is taken as measure of cortical activity.

Spatial and temporal resolution

Its spatial resolution depends on the number of applied light injectors and detectors and is in the cm range. The largest contribution to the NIRS signal is made by grey matter, in particular its surface areas (up to about 20 mm below the scalp). Therefore, this method is presently restricted to the measurement of cortical activity. The temporal resolution depends on the physiological response under investigation. If hemodynamic changes due to neuronal activity are assessed, its temporal resolution equals that of fMRI and PET in the range of seconds; if event-related signals are measured its spatial resolution is in the range of milliseconds.

Application

In current devices, light injectors and detectors are located in distances of 2-3 cm within a matrix; between each injector and detector lies a measuring point. The light is emitted via optical fibres with diameters between 1 and 3 mm, the reflected light is detected by the neighbouring optodes. In most cases, fibres and optodes are incorporated in a flexible cap which ensures permanent contact with the scalp surface. The major problem of NIRS is artefacts due to the light absorption of hair (absorption rates between 20 and 50 %). Hence, it is essential to place the injectors and detectors between hairs, directly on the scalp.

If successfully applied, the detection of cortical activity via NIRS is, in general, not subject to any notable restrictions. Movement artefacts do not play a role; even measurements while walking or running should be feasible in future. Also studies on children of different age have been conducted successfully (e.g., Baird et al., 2002). There is neither need for sedation (as in fMRI) nor are they exposed to potentially noxious ionising radiation (as in PET). On the whole, this method may open up new vistas in future cognitive neuroscience.

Significance

Most of the NIRS signal originates in grey matter. Studies employing simultaneous NIRS and PET or fMRI measurements found good correspondence between the detected signals (Villringer et al., 1997; Strangman et al., 2002); also multi-method measurements with EEG have provided evidence for this method's reliability and validity (e.g., Kennan et al., 2002). Besides artefacts due to hair, there is currently still some doubt whether and to what extent blood vessels in the scalp may affect the signal and produce distorted results. Hence, further studies on the sources of the NIRS signal are needed.

Advantages and disadvantages

Most advantages of NIRS have already been listed in the section on application. Among them are the non-invasiveness and innocuousness of this method, the high temporal resolution, the opportunity to measure different parameters of cortical activation, the simple applicability, the robustness to movement (muscle) artefacts, the comparably low costs and a broad scope of application. The spatial resolution, though, is presently restricted to cortical areas; moreover, artefacts are produced by hair. NIRS is currently being further developed, even though some systems are already purchasable whose performance (and price) covers a broad range. In near future, however, this method could be similarly widely available and applied as electroencephalography (EEG).

4.5 Electroencephalography (EEG)

The development of electroencephalography (EEG) can be traced back to Hans Berger (1929) who successfully measured voltage fluctuations („brainwaves") on the human scalp for the first time. At present, this method has a rich developmental history contributing to its establishment as a standard method in medical research and practice as well as in psychophysiological research.

Basic principles

Electrical signals on the scalp are caused by activations of neuronal assemblies. These are mainly assemblies of pyramidal cells oriented vertically to the cortical surface (axons downwards and apical dendrites upwards into the top cortical layer). If a neuron (in this case a pyramidal cell) fires, an extra-cellular current is produced which is closed intra-cellularly (by means of EEG both, the intra- as well as the extra-cellular current flow is detected). If all neurons fired randomly, no detectable EEG signal would emerge on the scalp surface as the electrical potentials produced by single cells are too weak to be detected. Therefore, thousands of neurons have to fire in synchrony to elicit EEG signals. Moreover, these potentials oscillate in certain frequencies, which are usually traced back to the influence of subcortical structures (e.g., the alpha rhythm is caused by the thalamus).

In contrast to magnetoencephalography (MEG, see below) EEG electrodes can only detect voltage or electrical potential differences between two locations on the scalp; thus, they are reference-dependent. In this context, bipolar and monopolar recordings (montages) are distinguished. While bipolar montages detect voltage differences between two active electrodes (both are placed at electrically active areas on the scalp), in monopolar recordings, an active electrode is recorded against a reference electrode placed at an (presumably) electrically inactive location (e.g., earlobes, nose). Even though it has been shown that no point of the body is electrically inactive (Nunez, 1995), the reference problem is no longer problematic in current EEG systems as the recorded signals can be converted post-hoc to different references (e.g., the average of all active or of the surrounding electrodes) depending on the research question.

Spatial and temporal resolution

The general advantage of EEG and MEG over traditional neuroimaging techniques such as PET or fMRI undoubtedly lies in its high temporal resolution. Electrophysiological processes can be detected within milliseconds, which is particularly relevant in the investigation of time courses of cognitive processes. Time resolution, in turn, depends on the experimental design and the assessed parameters (see the section on application). The question for its spatial resolution, though, cannot be answered as clear-cut. Although the number of applied electrodes (from about 19 in classical 10-20 systems according to Jasper, 1958, to configurations of 128) and the topographic resolution are inter-related, the sources of the detected potentials as well as their spatial localisation are still a controversial problem (see section on significance). In general, it is assumed that electrode distances of less than 2.5 cm (or more than 128 electrodes, respectively) do not enhance the spatial resolution further. Another influencing variable is the signal quality (extent of artefact contamination, signal-to-noise ratio).

Application

In EEG studies, electrodes are placed on the prepared scalp, a conductive gel additionally improves the contact between electrode and scalp surface. The detected electrical signals (in the range of μV) are amplified and digitally recorded. The number of applied electrodes depends on the research question and ranges from two electrodes up to high-resolution configurations of 128 positions; but usually between 20 and 60 electrodes are applied. A central advantage of EEG lies in the fact that it can also be used outside the laboratory. Mobile EEG systems in handheld size (of course with a smaller number of electrodes) open up various opportunities to measure electrophysiological activity in different environments. However, a major problem of this method is artefacts from different sources. As the detected electrical signals are very weak (in the range from 1 to 200 μV), both external electrical fields and (internal) biosignals can contaminate the data. Whereas a notch filter attenuates noise interference generated by power lines, no optimal procedure exists for removing muscle artefacts as they affect a broad frequency range and produce larger amplitudes than the EEG signal. Simple eye movements (such as blinking), though, can (a) be localised quite well and (b) sufficiently distinguished from the EEG signal by means of specific analyses (via statistical regression or via independent component analysis, ICA). With respect to the applicability of the EEG it may thus be concluded that – despite mobile EEG systems which enable field studies – high data quality can only be achieved in controlled settings (the participant should not move during recording). This holds particularly true for the investigation of cognitive processes requiring advanced analyses of electrophysiological signals.

Different parameters can be extracted from the EEG signals which, in turn, require appropriate experimental paradigms. Here, only the basic distinction between event-related potentials and oscillatory activity is outlined to illustrate the required research designs and the parameter's functional significance.

1. Event-related potentials (ERPs; or evoked potentials; EPs) are brain responses to internal or external events which occur within a time period of approximately 500 to 1000 ms. They are not visually detectable as they have very small amplitudes (1-40 µV) and are superposed by the stronger background (oscillatory) EEG activity. Thus, several trials have to be averaged to detect the potential. This procedure bases on the observation that event-related potentials always occur at a specific time point after the event and show a constant and characteristic time course. If an event (e.g., a visual stimulus) is repeatedly presented (e.g., 100 times), and the event-related EEG sequences are averaged, the background activity is cancelled out allowing the ERP to stand out clearly. The characteristic time course (curve) of the ERP consists of positive and negative components (amplitude deflections) which can be associated with different neurophysiological processes (cf. Rösler & Heil, 1998). While early components (before 100 ms) rather reflect initial stimulus processing and predominantly depend on physical stimulus properties, later components (from 100 ms onwards) are related to cognitive functions (language, memory, attention; e.g., studies on the significance of the N400 component in language processing; Kutas & Federmeier, 2000). Latencies and amplitudes allow a quantification of the components.
2. In investigating oscillatory brain activity, EEG rhythms are analysed which can be divided into different frequency bands. Generally, the lower the frequency (approximately between 0.5 and 40 Hz) is, the larger are the amplitudes (between 1 and 200 µV). A visual inspection of an EEG recording already reveals different frequencies depending on the participants' level of alertness. Relaxed wakefulness is usually accompanied by oscillations in the alpha frequency range (about 8-13 Hz), whereas cognitive or physical activity goes along with higher frequencies (about 14-30 Hz, beta band). During sleep, frequencies slow down and delta activity between 0.5 and 4 Hz emerges. As an example, the proportion of specific frequency components in the EEG may be analysed, with the power (relative proportion) of a certain frequency band being expressed in the bandpower value. Different frequency bands have turned out to be differentially sensitive to specific cognitive processes and functions. Changes in theta bandpower (4-7 Hz) are associated with memory processes (e.g., Bastiaansen & Hagoort, 2003), the alpha band sensitively reacts to attention and information processing (e.g., Klimesch, 1999), but also beta (14-30 Hz) and gamma rhythms (around 40 Hz) are discussed in the context of various cognitive functions (e.g., Başar-Eroglu et al., 1996). The quantification of bandpower changes accompanying events or cognitive demands has increasingly gained importance. In these analyses, the bandpower prior to an event (e.g., before a cognitive task is presented) is related to the bandpower during the event (e.g., during cognitive

processing; cf. the method of event-related desynchronisation by Pfurtscheller & Aranibar, 1977). Bandpower changes in different frequency bands can thus be used as indicators for cortical activation or specific cognitive processes. This holds particularly true for the alpha band as bandpower decreases reflect a valid measure of cortical activation (see also Laufs et al., 2003, on the relation between alpha activity and hemodynamic changes). Alternatively, synchronies between cortical areas can be analysed to reveal which cortical regions are functionally coupled. These analyses range from simple EEG signal correlations (coherences; Rosenberg et al., 1998) over associations between different frequency bands (Tallon-Baudry, 2003) up to analyses of the direction of information transfer (Varela et al., 2001).

Significance

EEG measures the sum of electrical events on the scalp. Thus, it detects not only electrical activity of neurons in the brain but also other physiological signals (such as muscle tension). The physiological bases of the EEG are not yet fully understood but there are powerful models derived from detected EEG signals. This is also relevant for the functional significance of the EEG parameters. While, for instance, plausible models on the function of oscillatory alpha activity exist (for bandpower changes in the alpha frequency, cf. Lopes da Silva & Pfurtscheller, 1999), the role of beta and gamma activity in cognitive processes is still a matter of debate (Tallon-Baudry & Bertrand, 1999). In addition to the question for the functional significance of EEG signals, the question for the sources of the neuronal activity is still unresolved. Although a number of mathematical algorithms exist for solving this (inverse) problem (e.g., Low Resolution Brain Electromagnetic Tomography, LORETA; Pascual-Marqui et al., 1999), in interpreting the herewith obtained results it has to be kept in mind that there are always multiple solutions whose number is only reduced by means of theoretical assumptions. Topographical EEG analyses or EEG mappings have to be distinguished from these algorithms as they only map the topographical distribution of EEG parameters on the scalp without referring to the underlying anatomical sources. Nevertheless, they are frequently applied as a tool to gain a quick impression of the topographic distribution of different parameters (such as bandpower changes). The recorded signals may not necessarily derive from the underlying cortical structures, but topographic differences may suggest that different neuronal assemblies are involved in a cognitive process (e.g., Jost et al., 2004).

Advantages and disadvantages

An obvious advantage of the EEG (as compared to other neuroimaging techniques) undoubtedly lies in its high temporal resolution. In addition, there is no health risk since neither radioactively labelled chemicals have to be introduced into the body nor artificial external magnetic fields are applied. Therefore, repeated as well as long-lasting recordings are feasible. The wide availability of EEG systems, the low costs of purchase and operation as well as the opportunity to conduct EEG investigations outside the laboratory with mobile systems also represent notable advantages. Moreover, in contrast to PET and fMRI, EEG (and MEG) can detect oscillatory brain activity which is discussed to be of paramount importance in cognitive information processing (Başar et al., 2001). Disadvantages of this method are the poor spatial resolution, the source localisation problem, and the susceptibility to artefacts (especially outside the laboratory). Finally, the restriction to cortical activity can be listed as another disadvantage as no affirmed conclusions on subcortical signals (e.g., limbic system, hippocampus) can be drawn.

4.6 Magnetoencephalography (MEG)

Compared with EEG, MEG is a rather young technology which can be attributed to the recent development of SQUID detectors (Clarke, 1993). MEG allows the measurement of neuronal activity with the same temporal resolution as EEG but with higher spatial resolution. Hence, this method is predestined for the investigation of event-related activity.

Basic principles

This method detects magnetic fields which are induced by electrical currents in the active neurons (cf. the basic principles of EEG). The magnetic field strength is considerably smaller than that of the earth's magnetic field (< 1 picoTesla = < 10^{-12} Tesla). Therefore, extremely sensitive devices (SQUIDs, Superconductive QUantum Interference Devices) are necessary to detect them. The device's high sensitivity derives from (a) the superconductive property of the coils which is achieved by extreme cooling with liquid helium (at -269 °C, i.e. -452 °F), and (b) from the application of powerful amplifiers. The induced current is proportional to the density of the line of magnetic flux and allows conclusions on the spatial distance of the source. It is noteworthy that organic tissue is quasi transparent for magnetic fields; in contrast to the EEG signal there are no distortions due to different electrical conductivities of brain tissue (e.g., bone, liquor). Furthermore, magnetic fields can be detected reference-free, whereas the EEG signal always represents a voltage difference.

Spatial and temporal resolution

Because of the undistorted magnetic radiation MEG allows a more accurate localisation of activity by means of mathematical algorithms. Spatial resolutions in the range of a few millimetres are frequently reported which even outperforms traditional neuroimaging methods such as PET. To achieve such a high resolution, of course, systems with many channels (for instance, 256) are required. As already outlined, its temporal resolution is similar to the EEG.

Application

Although MEG offers non-invasive and contactless registration of brain activity, its practical application is far more expensive than EEG. This is firstly due to the large device resembling an „oversized hair dryer", and secondly, due to different artefacts (movement artefacts and external magnetic fields) which can severely impair the recording. The necessary prevention of movement artefacts (e.g., head movements) restricts its universal application and, moreover, MEG recordings have to be shielded from external magnetic fields (e.g., caused by lamps, lifts, trams, motors) by appropriate magnetically shielded rooms (such a room weighs between 7 to 12 tons; therefore, it must already be considered in the construction of buildings). With respect to the experimental paradigms and the calculable parameters, MEG is largely comparable to EEG. Likewise, event-related parameters (event-related magnetic fields; ERF) as well as changes in bandpower can be analysed.

Albeit being tied to enormous efforts, combined MEG and EEG measurements appear to be particularly powerful in the investigation of cognitive processes. As both methods complement each other with regard to their advantages and disadvantages, an integrative application enables a more accurate localisation of activation sources (in the range of about 2 mm) and, thus, a more comprehensive registration of neuronal activity (Jäncke, 2005).

Significance

The basic principles of MEG are largely similar as in EEG. However, in comparison with electrical potentials, magnetic fields have better propagation properties as the lines of magnetic flux arrive at the surface of the scalp almost unaffected by the different tissues of the brain. The intensity of the magnetic field or the induced current in the coils, respectively, predominantly depends on the distance of the source: the deeper (more inferior) the neuronal activity, the weaker is the signal – a fact that can be considered in spatial source localisation (e.g., in LORETA). But, as a major restriction to this method, only a part of the magnetic field can be detected by MEG. More precisely, only those lines of magnetic flux can be detected which are perpendicular to the surface of the scalp. This is only the case if the activation source (or the current, respectively) is aligned in tangential direction, like in the pyramidal cells in the brain fissures (sulci). In subcortical areas (e.g., in the thalamus) the effects cancel out each other due to different neuronal orientations. Therefore, it is assumed that this method is restricted to cortical activity whereas the EEG signal also picks up thalamic activity and activity from other subcortical areas (Jäncke, 2005).

Advantages and disadvantages

MEG offers completely contactless registration of cortical activation. As the detected magnetic fields arrive at the scalp undistorted by organic tissue, highly accurate source localisation can be attained. Similar to EEG, another advantage consists in the fact that neuronal activity that is not accompanied by hemodynamic or metabolic phenomena (e.g., changes in rCBF or glucose metabolism) can also be detected. Despite the advantages of MEG, its application is very effortful and expensive, both in purchase (besides the system also a magnetically shielded room is necessary) and in operation (fluid helium for cooling). Consequently, like PET or fMRI also MEG recordings are restricted to the laboratory.

4.7 Concluding remarks

This overview of frequently employed neuroimaging methods in cognitive neuroscience aimed at providing an impression of which methods could be applied in different areas of educational research and what kinds of conclusions may principally be drawn. In addition, this outline sought to point out restrictions which are often unnoticed in the occasionally arising euphoria over „colourful images" of the brain at work. Finally, the question can be addressed which of these methods can be successfully applied in educational research (see also Table 1). With respect to the sample of interest, comprising children and adolescents, PET already drops out due to the potentially noxious exposure to ionising radiation. FMRI as well as MRI are only feasible from a certain age level onwards as children cannot be expected to lie motionless in the scanner for a long time. For investigating learning outside the laboratory only EEG and, in future also NIRS remain, though both offer comparably poor spatial resolution. The general trend towards combining different techniques in fundamental research to complement a high spatial by a high temporal resolution (e.g., by combining fMRI and EEG; Goldman et al., 2000) appears to tap educational research only marginally. Nonetheless, besides the development of novel techniques such as NIRS, this multi-method approach has the greatest potential to help us gain a deeper understanding of the neuronal bases of cognitive functions and processes. A comprehensive picture of these relations can only be achieved if different dimensions are analysed simultaneously. The trend is supplemented by the general tendency not only to localise functions in the brain but also to investigate the interplay of different brain areas in cognitive processes (Aine, 1995; Lloyd, 2000; Raichle, 1998). „Functional integration" seems to be the keyword of the next decade, transcending the often stated criticism that cognitive neuroscience is nothing more than phrenology with more advanced methods (Ramnani et al., 2004).

This chapter should also have made clear that it is not sufficient to „look into the brains" of children or adults during cognitive activity. On the contrary, significant findings can only be obtained if carefully planned experimental designs are applied which allow the attribution of brain activation changes to different (experimental) conditions. This holds particularly true for the investigation of learning processes (cf. Poldrack, 2000) where the following questions are (still) a matter of research: Do changes in activation patterns following learning suggest that information is now processed differently? Or do they simply reflect changes in effort or in the involvement of attentional and control processes? Is the most strongly activated brain area across individuals indeed the „place of processing" or are the functionally specialised brain regions less strongly (more efficiently) activated? In an impressive study, Sidtis et al. (2005), for instance, could demonstrate for simple language tasks that the performance level was not predicted best by the activation in regions with the strongest signal. Actually, even negative correlations between activation and performance were observed – a finding that nicely corresponds to the neural efficiency hypothesis relating individual ability differences to differences in brain efficiency (e.g., Haier et al., 1988; Neubauer et al., 1995). The authors could moreover show that the activation difference between an experimental and a control condition may not be the optimal measure to isolate the task-relevant brain areas (for further criticism on the subtraction method see Sarter et al., 1996; Sergent, 1994).

In order to realise explanatory and powerful studies, not only an adequate research design but also an appropriate experimental situation is required. Imaging learning in school may not shed much light on how learning occurs in the brain and how it can be improved. Even the comparison of brain activation in two different learning environments may not allow conclusions on which of the learning environments should be recommended from a neuroscientific perspective. The investigation of such research questions rather requires standardised experimental designs where it can be controlled (or at least registered) at what time which kind of information is presented in which form. An interesting alternative to traditional experimental settings seem to be the currently popular computer-aided learning environments. Such an („e-learning") environment offers a number of advantages compared to situations in school: information can be presented by means of different media, participants' responses can be exactly registered, immediate feedback can be provided, and the cognitive demands can be continuously adapted to the individual performance level or the learning progress. Furthermore, such an environment can easily be installed in the laboratory which means that a broad range of neuroimaging methods are applicable. Even though, at present, only a few neurophysiological „e-learning" studies exist, this learning environment might hold the potential to bridge (ecologically less valid) laboratory research and applied field research.

Table 1 *Overview of the most important characteristics of the outlined neuroimaging methods*

Method	Basic principle and significance	Practical resolution		bound to laboratory	Advantages	Disadvantages and restrictions
		spatial	temporal			
PET	Detection of concentration of radioactively labelled chemicals (tracers); brain activity is indirectly assessed by hemodynamic or metabolic changes	cm	min	yes	+ quiet environment + many different cognitive tasks can be administered	– invasive – exposure to ionising radiation – high costs – inapplicable to children
MRI	Detection of nuclear magnetic resonance of brain tissue; Imaging and measurement of structural (anatomical) brain parameters.	mm	-	yes	+ widely available + high accuracy	– loud environment – high costs – restricted applicability to children
fMRI	Detection of nuclear magnetic resonance of hemodynamic parameters; brain activity is indirectly measured by hemodynamic changes	mm	sec	yes	+ widely available	– loud environment – high costs – restricted application of cognitive tasks – restricted applicability to children
NIRS	Detection of absorption and reflection of near-infrared light in the cortex; cortical activity is indirectly measured by intracellular and vascular (hemodynamic) changes	cm	msec - sec	no	+ no movement artefacts + low costs + many different cognitive tasks can be administered + applicable to children	– still under development – only cortical activity is detectable
EEG	Detection of electrical potentials on the scalp; cortical activity is measured by different electrical (oscillatory) parameters	cm	msec	no	+ widely available + low costs + many different cognitive tasks can be administered + applicable to children + oscillatory activity measurable	– movement artefacts – problem of source localisation
MEG	Detection of magnetic fields on the scalp; cortical activity is measured by different magnetic (oscillatory) parameters	mm	msec	yes	+ contactless + applicable to children + oscillatory activity measurable + good source localisation	– movement artefacts – high costs

5. Brain development

In humans as in many other species, brain development consists of progressive and regressive changes. There is enormous growth and degeneration of axons, dendrites, synapses and neurons resulting in structural reorganisation. Phases of increased reorganisation are regarded as time windows in which environmental influences considerably impact on cortical development. These impacts may, however, occur at different times in different neuronal systems, i.e. they show different developmental trajectories. In the following, all of these aspects of brain development are outlined (for reviews, cf. Andersen, 2003; Byrnes, 2001; Cowan, 1983; Goswami, 2003; Johnson, Munakata, & Gilmore, 2001; Pauen, 2004). Attention is particularly paid to those processes and time periods that could be relevant with regard to educational aspects.

At the beginning, a short overview of brain structures that are referred to in the following chapter should be given. In addition to a topographic organisation, the cortex is also organised in different layers. Four to six horizontal layers can be distinguished with respect to morphology, density and function of the therein enclosed neurons. Brain cells can be divided into two large classes: glial cells and neurons. Neurons are responsible for information processing. They differ in shape (e.g., pyramidal cells, stellate cells, etc.), in their connectivity with other neurons (excitatory and inhibitory neurons), and in the neurotransmitter they use (e.g., dopamine, GABA, serotonin). Glial cells are also important in information processing and provide far more than mere physical support and nutrition to neurons. They participate in the transmission of bioelectric signals at the synapses by regulating the internal environment of the brain, by supporting the synapses metabolically and by facilitating the reuptake of surplus transmitters and thus, enabling further signal transmission. In addition, glial cells form the myelin sheath, guide (nerve-) cell migration and protect the brain and spinal cord from intruding microorganisms such as viruses, bacteria or extraneous cells (Deitner, 2000).

5.1 Main processes in brain development

During the intrauterine period the brain grows from nothing to about 350 g (about 12 oz). It is also then that most of the neurons of the central nervous system (CNS) are produced. However, after birth the brain continues to grow, reaching a weight of about 1,350 g (about 47 oz) in 20 year-olds. Most of the postnatal growth takes place within the first three or four years, but changes in myelination and other measures (e.g., cortical surface area, number of glial cells, etc.) may even occur 70 to 80 years after birth.

A general principle in brain development is that development occurs in the form of a cascade of events and that each event may impact following but not preceding events. The earlier a certain event occurs in development, the larger is its potential influence on subsequent events and the more likely is its influence on adult brain structure.

The prenatal development can generally be described in structural phases. This means that the beginning and the end of a specific phase is described by structural or anatomic changes. For instance, the zygote phase begins with fertilisation and ends with the development of the blastula (blastosphere) produced by cleavage of the fertilised ovum. Then the gastrula phase starts in which the gastrula is produced.

The stages of brain development can be described in terms of the four most important cellular processes: cell proliferation, cell migration, cell differentiation and cell death. The life history of any neuron or glial cell may best be traced by considering these processes as steps through which each cell has to pass.

5.1.1 Cell proliferation (production of neuronal stem cells)

After gastrulation the cells on the gastrula are translocated and form the neural plate. In a next step the growing neural plate folds in upon itself to form the neural tube, which looks like the tubular nerve system in simple animals such as worms. The anterior portions of the neural tube will later on form the forebrain and midbrain, the remaining portions the spinal cord. There are two regions (proliferative zones) in the neural tube where neurons grow by means of mitosis (cell division into two identical daughter cells). Some neurons can have up to 10,000 offspring cells. Proliferation ends in the seventh prenatal month. At this time, the brain contains more than 10^{11} cells. Thus, on average 250,000 cells are produced per minute in the proliferative zones.

5.1.2 Cell migration

As cell proliferation occurs only in two regions of the neural tube, the young neurons have to move from the site of their proliferation to their final position after mitosis. The neural tube is extended as the cells migrate into outer layers.

There are two ways how the cells can accomplish this location change. Some neurons move only a bit away from the border of the proliferative zone and are subsequently displaced outward away by newly produced cells. As this type of cell movement requires only minimal active locomotor activity by the migrating cells it is referred to as *passive cell displacement.* In areas of this type of cell movement, the neurons that are generated earliest are located farthest away from the proliferative zone. The correlation between the distribution of neurons and their time of origin is termed „outside-to-inside" spatiotemporal gradient. „Outside" and „inside" delineate the position of the cells in relation to the proliferative zone.

In several other parts of the developing CNS, the migrating cells play a more active role in moving to their final position. The young neurons move a far greater distance, and each cell generation bypasses the earlier one. Thus, the cells move away from the inner wall and the cells at the outer wall (farthest from the proliferative zone) are those that were produced last. This active process is frequently termed neuronal migration and results in an „inside-to-outside" spatiotemporal gradient. This pattern of migration is found in most portions of the cortex and in several subcortical structures. In contrast to „passively" migrated cells, these areas have well-laminated structures.

During the migration to their final position the young neurons of the cerebral cortex are guided by radial glial fibres. This interplay represents one of the best documented interactions between cells in the developing CNS.

5.1.3 Cell differentiation

Once a neuron has reached its final position, it enters the final phase of its life, viz. the differentiation into distinct cell types. Each neuron grows out axon and dendrites forming a characteristic pattern of arborisation. Each neuron must also express specific enzymes required in producing the neurotransmitters it will use. In addition, each postsynaptic site has to grow receptors, which are required in receiving signals from its presynaptic partner. Simultaneously, glial cells also differentiate into myelin producing ones (oligodendrocytes) and those performing other functions (astrocytes).

Cell differentiation involves two fundamental processes: First, cells can be differentiated into the „correct" type by genetic transcription processes in the proliferative zone immediately after their production. Hence, the cells would already „know" before migration which type of neuron they would become. Second, the differentiation could be detained until the cell has reached its correct position in the cortex. In this case, neighbouring cells chemically „inform" the migrated cell into which cell type it should differentiate. A number of studies have proved that both processes may occur in the development of different types of neurons.

During development, neurons build projections in a highly specific way. Animal experiments have uncovered that axons are able to find the respective neuron even if the target cell was transplanted to atypical sites. In contrast to synaptic connections which are based on experience, the stereotypical laminar connections are predominantly determined by genes. Once a projected neuron is close to another neuron, the synchronous activity of both neurons fosters the production of synapses. Stated differently, if two neurons are repeatedly active at the same time it is very likely that they produce a synaptic connection between them.

5.1.4 Cell death and transient connections

In an adult human brain, each of the 10^{11} neurons has more than 1,000 synaptic connections to other neurons. In early development, however, neurons even produce more synapses than are necessary to develop the functional circuits for information processing. Therefore, neurons in children have synapses practically everywhere, whereas the synaptic connections are reduced to a specific pattern in adults. One possibility of reducing redundant synapses is cell death, another one is the retraction of the axon by the presynaptic cell.

Numerous researchers assume that cell death and retraction of axons are due to the neurons' competition for a specific substance, the so-called trophic factor, which is released by active postsynaptic neurons. Only few axons connected with the target neuron will get sufficient trophic factor to survive. Other neurons, in contrast, receive enough substance from one side but not from the other. Instead of dying, they retract their axons from the deprived areas.

Indeed, it is of great interest and also somewhat ironic that the development of the nervous system – often considered as a sequence of progressive events – also comprises regressive processes such as retraction of axons and cell death. Actually, it is undoubted that cell death is an essential developmental feature. For instance, „knockout" mice with mutant genes preventing cell death show severe developmental abnormities. It is assumed that the initial oversupply of neurons and synapses has phylogenetically developed as an evolutionary adaptation mechanism to protect the brain from potential problems in its development. This aspect is more thoroughly addressed below.

5.2 The development of two regions of the cerebral cortex: primary visual cortex and middle frontal gyrus

So far, only the general cellular developmental processes occurring everywhere in the human brain have been addressed. It is nowadays widely accepted that brain development is heterochronous, i.e. the developmental time courses differ across brain regions. Changes in cortical neurons before and after birth, however, have been satisfactorily described only for a few brain regions. Among these are the primary visual cortex and the middle frontal gyrus, a region of the frontal lobe.

The visual cortex grows rather early and reaches its maximum volume approximately at the age of four months. This finding is somewhat surprising as the brain size in a four month-olds is only about half that of an adult. Cortical association areas, especially the frontal lobe, grow considerably slower. But the later gain in brain weight could also be attributed to the formation of white matter (myelination) which continues throughout the childhood years. Myelination refers to the sheathing of axons with an „insulating layer" in order to increase the speed of information processing. Myelin notably contributes to the gain in brain weight. Once brain development is largely completed in late adolescence, the brain weight is four-times larger than at birth.

Synaptic profiles can already be detected in the fetal brain from the 28th gestational week onwards – the synaptic density is still very low but increases during late fetal life and early childhood. Between the second and fourth month, synaptic density jumps up and almost doubles. Eventually, at about one year of age synaptic density begins to decline until the age of eleven when it reaches the adult value, i.e. 60 % of the maximum. These results point to a considerable loss of synapses in the postnatal development of the cerebral cortex.

Evidence of the development of other cortical regions is restricted, except for the middle frontal gyrus. In fact, the development of this brain area is quite different from the visual cortex. While the neuronal density is quite similar in both areas at birth, it declines much slower in the frontal cortex afterwards.

Neuronal density in the visual cortex reaches the adult value at the age of five months whereas the density in the frontal cortex still exceeds the adult value by 55 % at age two years and by 10 % at the age of seven. The available evidence on the frontal cortex also suggests a prolonged growth of neuronal structures, especially dendrites, as compared to the visual cortex. This may reflect some form of compensational mechanism for neuronal loss in older age.

Data on the synaptic density in the middle frontal gyrus is limited. However, it reflected a slower postnatal increase in synaptic density as compared to the visual cortex. Maximum density is reached at one year of age. This contrasts with the developmental trajectory of the visual cortex where the maximum density is reached four months after birth. The subsequent synapse elimination also occurs at a slower rate in the frontal cortex – it does not show up before age seven. At this age the visual cortex has almost reached adult level of synaptic density. In the frontal cortex, however, adult synaptic density is met by the age of 16 years. Thus, present evidence demonstrates considerable regional differences in human synaptogenesis.

The number of synapses per neuron decreases in the frontal cortex between late childhood and the age of 16, likewise does the number of synapses per 100 μm^3 (1 μm^3 equals one millionth mm^3) dendrites until it has reached the adult level at 50 % of the maximum synaptic density at two years of age. The fact that synaptic density decreases after neuronal density has stabilised (at the age of seven) reflects a loss of synapses in the frontal cortex. In fact, its extent is similar to the loss in the visual cortex, but the process takes place at a later time.

The quantitative anatomy approach to cortical development is clearly limited in its significance as only averages are reported conveying the impression of a static rather than a dynamic system. Growth and regressive changes can simultaneously occur and may outbalance each other. It is very likely that synapses are constantly produced while old connections are eliminated. These processes cannot be distinguished by stating only absolute numbers of synapses.

Nevertheless, some important information could be gained from the quantitative anatomy approach. For instance, it has been shown that synapse elimination is an important feature of human brain development. In particular, it is assumed that the genetic program for synaptic connections is imperfect and, thus, a complete specification of all synaptic connections is not possible. Therefore, many redundant and labile connections emerge, but only some stabilise as part of functional systems. Stabile synaptic connections remain whereas labile connections – not being part of functional systems – disappear. These postnatal changes are of great interest as they suggest that anatomical changes and cognitive development (e.g., in learning, memory, and language) are related.

This becomes especially apparent in the visual cortex in which functions are quite well-understood. At birth, when visual alertness and visual fixation are not well developed comparably few synaptic connections (about 10 % of the maximum) exist. At the age of four months, though, a rapid increase in the number of synapses is observable, which is accompanied by a sudden improvement in visual alertness.

Synaptic density and, consequently, also the number of unspecific and labile synaptic connections remain at a quite high level until the age of four years. These labile synapses may reflect the biological substrate of neuronal plasticity in the child. Therefore, it may be concluded that the plasticity in the middle frontal gyrus is prolonged as synapse elimination does not emerge before the age of seven. In fact, there is evidence that a high degree of neuronal plasticity for some functions is maintained until late childhood, for instance, the ability to recover language functions following large-scale lesions in the dominant hemisphere. This seems to be possible until the age of eight and apparently depends on changes in the functional organisation of the non-dominant hemisphere.

5.3 Genes and brain development

The most important variable in explaining brain size differences across species is the duration of the proliferation phase. But how does the developing brain know when to stop producing new cells? For instance, it would be plausible that the exact number of mitotic divisions is stored in the DNA of precursor cells. Another possibility is that the division of the precursor cells continues until they receive information that enough cells have migrated to the different parts of the brain. Whichever possibility applies, it is clear that the duration of the proliferation phase is under genetic control.

The same holds true for cell differentiation and cell migration, although it is rather probabilistic for the latter. During migration cells interact with each other in a complex manner. Consequently, the final position of the cells cannot be accurately determined. Thus, genetic information cannot be regarded as an exact construction plan. Brains with identical genes such as in monozygotic twins can still differ significantly.

The importance of genes in brain development is evident in hereditary diseases such as Down Syndrome (DS) where a connection between specific genes and neurological pathology exists. Individuals with DS usually have smaller and less developed brains than their healthy counterparts. The number of cortical neurons is reduced by about a third, their connection patterns are less complex, there is less myelin, and the form of the dendrites is abnormal. In short, the additional genetic material interferes with processes of proliferation, synaptogenesis, and myelination.

5.4 Brain development and experience

In order to adapt to the environment, animals have to be capable of forming mental representations of their experiences. They must be able to recognise their conspecifics or to store the experience that fire is hot. Many animals are already prepared at birth to learn such things by drawing on an innate circuitry (or prewired circuitry) which is closely connected to the sensory system. This innate circuitry consists of cortical neurons receiving, processing and storing inputs from the environment, and afferent neurons transmitting the input signals from the sense organs to different sensory systems in the brain.

Surgical animal studies could demonstrate that atypical cortical maps emerge if the input from the thalamus is redirected. Similar plasticity was observed in infants who have had brain injuries or in whom brain parts had been removed due to epilepsy. In normally developed right-handers, language regions are located in the left hemisphere. In children whose left hemisphere had been removed, language regions developed in the remaining right hemisphere. Hence, it may be concluded that while the laminar cortical organisation is mainly under genetic control, the topographic organisation of brain areas is determined by both innate circuitry as well as environmental influences.

Effects of environmental input depend on when they occur in the developmental course. For example, animals can permanently go blind if they are kept in darkness for the first two weeks after birth. However, if they are deprived of light later in their development, their visual ability develops normally. Two types of neuronal plasticity are proposed to describe such effects in mammalian brain development: experience-expectant and experience dependent plasticity.

Experience-expectant plasticity, which is the basis for assumptions concerning critical or sensitive periods in brain development, refers to the initial internally regulated synaptic overproduction and the subsequent decline. As already outlined, the number of synapses declines as neurons compete for the limited supply of trophic factors.

While experience-expectant plasticity is – from an evolutionary perspective – a very old mechanism which proceeds interindividually similar, experience-dependent plasticity is involved in the storage of information that is unique to the individual and may be vital for survival (e.g., information on food sources or retreats). Experience-dependent plasticity allows animals to build representations of environmental features. Its basic principle is not the elimination of redundant synapses but rather the generation of new synaptic connections and the synaptic reorganisation, respectively.

5.4.1 Experience-expectant plasticity

Experience-expectant plasticity has been demonstrated in animal experiments employing stimulus deprivation. For instance, a few weeks after kittens first opened their eyes almost all neurons of the primary visual cortex selectively respond to stimulus orientation. If they are deprived of such visual input, the neurons begin to lose this function. A complete recovery is no longer possible after a long phase of deprivation. However, recent findings suggest that lacking visual input during early development extends the critical period of synapse elimination. Visual functions that develop rather late (e.g., stereopsis) are more strongly impaired by early deprivation than those which are already well-developed at birth (e.g., colour perception). Total pattern deprivation causes considerable changes in neuronal structures. Deprived animals show a notably lower number of dendritic spines (the main contact areas) in the visual cortex.

Why experience-expectant plasticity and sensitive periods exist is quite an important question. Does it make sense from an evolutionary perspective to develop an organism whose sensory functions are irreversibly impaired in the absence of specific environmental input during a certain time period? It does indeed. Resources of the sensory systems are thus used more efficiently as they can adapt to the expectant experience in the specific environment. Therefore, several species have emerged whose neuronal connections in the sensory systems are only roughly outlined so details can be determined by the interaction of the organism with the environment.

The most important characteristic of this type of plasticity is that the organisation of neural patterns depends on external input (e.g., motor activity or visual stimulation) during a rather narrow time window. Its neuronal basis is the overproduction of synapses and the subsequent preservation of frequently used connections. In the visual cortex, the neurotransmitters norepinephrine and acetylcholine participate in the regulation of the developmental time window. These „neuromodulators" may be involved in initiating or maintaining neural sensitivity to experience.

Another important point refers to the extent to which the developing system follows the pattern imposed upon it by incoming inputs. Stated differently: Does every input cause similar structural changes?

At birth, sensory systems have strong predispositions in input processing leading to a rudimentary organisation of input. Prior experiences determine how strongly the neuronal structure is influenced by incoming inputs. As an example, the auditory cortex increases in size in visually deprived or blind animals. As auditory stimulation is equivalent in deprived and sighted animals, the larger auditory cortex may reflect their greater reliance on auditory information necessary in the absence of visual input. Hence, it can be assumed that individual differences could be preserved even in light of identical environmental experience.

Plasticity in early development is strongly age-dependent and subsequently irreversible. With increasing age, infants lose their sensitivity to phonemic boundaries which are not used in their environment. An example regarding the visual system is provided by recent research on face recognition. In some respects, infants' recognition performance is superior to that of adults, especially if faces of apes are presented. By the end of the first year their performance advantage disappears. Older children and adults even have difficulties in discriminating human faces from other ethnic groups. The underlying neuronal process of this phenomenon is associated with the initial burst of synaptogenesis as well as with the subsequent decline. The extent and time course of these processes depend on both, the type of experience and internal factors such as the neurochemical system.

Findings of a prolonged development and organisation of the prefrontal cortex throughout childhood and adolescence indicate an important parallel between brain and cognitive development. In fact, the gradual decrease of synapse density in childhood and adolescence parallels the development of cognitive abilities. In other words, increasing cognitive abilities are accompanied by the loss of synapses and the stabilisation of the remaining connections but not by the production of new synapses. Repeated stimulus presentation results in faster reactions and stronger associations between event and reaction. At the physiological level, this phenomenon is reflected in the wiring of concurrently active neurons („neurons that fire together wire together"). Competing and irrelevant behaviour, in contrast, is inhibited. The myelination of connection fibres throughout childhood and adolescence additionally contributes to the increase of the speed of information processing.

5.4.2 Experience-dependent plasticity

Experience affects performance not only within certain time windows and during the early development of sensory systems. This is also an important fact from an evolutionary perspective. We cannot count on certain important experiences to occur at particular points in our lifespan. Another reason for prolonged plasticity is that humans and animals constantly have to adapt to specific characteristics of the environment.

Such an important characteristic might be environmental complexity. Already in the middle of the 20th century, an experimental paradigm was developed to show that variations in the (social) environment can cause structural changes in the brain. Rats were reared in three different environments: in a complex environment with many conspecifics, in standard laboratory cages with another conspecific, and in individual cages by themselves. It was found that the rats reared in the complex environment had up to 20 % more dendrites per neuron in the visual cortex as compared to the rats housed alone. Dendrites provide the basis for synaptic connections; the more dendrites, the more synapses. Even though these differences are largest in the visual cortex, similar differences can be observed in other areas of the cerebral cortex, e.g., in auditory areas or regions which are functionally comparable to the human frontal cortex.

Training studies also revealed interesting findings. Young adult rats trained in different mazes for almost one month had more dendrites than untrained animals. Structural changes depending on environmental influences can be observed even in humans. For instance, the posterior part of the hippocampus is larger in London taxi drivers than in controls. The hippocampus is a small brain area in which is related to spatial orientation and navigation. Hence, the taxi drivers' daily work may have caused an enlargement of this neuronal structure.

In adults, the production of synaptic connections in certain brain areas following experiences in complex environments and learning depends on experience-associated neuronal activity. Connections are produced if the activation of different neurons is correlated. In contrast to early synaptogenesis, later experience-dependent production of synaptic connections is restricted to regions subserving information processing. But also this late structural change takes place in a rather unspecific way. Only the cumulative effect of individual experiences leads to the stabilisation of some of the new synaptic connections.

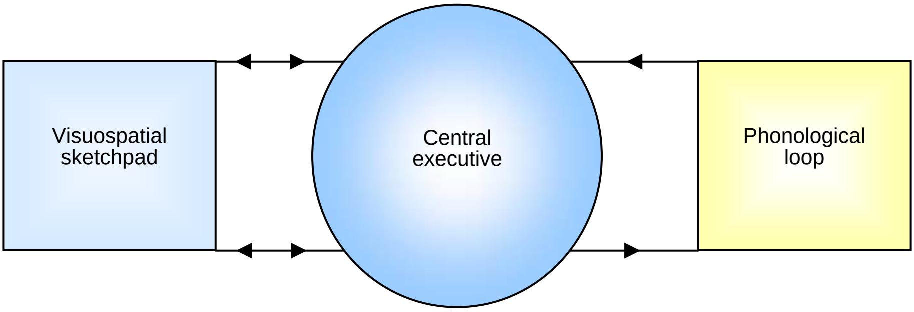
Experience-dependent formation of synaptic connections is accompanied by changes in the brains' blood supply and in astrocytes. These glial cells metabolically support neurons and their synapses. For instance, blood vessel density is extremely high in young rats reared in complex environments. This also holds true for capillaries which are blood vessels that mediate transfer of nutrients from the blood to the brain and also for astrocytes. Given that synapses require a very large amounts of metabolic energy, the number of astroctyes is of great importance for the developing brain. The ability to produce new blood vessels in the brain, however, rapidly declines with increasing age. Consequently, newly produced synapses cannot be sufficiently supplied in later years.

If practical implications should be drawn from the findings on human brain development, it is important to keep in mind that brain development proceeds heterochronously across different regions. While the prefrontal cortex grows during the first six years, the visual cortex already stabilises at the age of two. This heterochronous development, however, is highly advantageous as it allows the developmental system to provide a suitable framework for a subsequent, experience-dependent system. This is an important aspect in human development. Early social and communicative skills could provide a basis for the later acquisition of 'proper' language or help the infant master spatial and causal relations. The infant's active participation in acquiring and organising experience and knowledge becomes essential if a specific process sets the stage for a subsequent, experience-dependent process. Thus, sensitive periods must be characterised in terms of their time course, the involved brain regions, the underlying mechanisms and the organism's experience.

6. Central executive and frontal lobe

Each complex cognitive performance requires goal-directed manipulation of information. We can daily observe this circumstance in different situations. Children solving a mental arithmetic problem have to relate the given numbers according to certain calculation rules. If they have to write an essay about a specific topic they have to handpick adequate contents from their knowledge base and put these together in a meaningful way. A basic conversation between two people already requires that one interlocutor remembers what he and the other person have said to be able to respond appropriately. This list of examples can certainly be continued, comprising a wide range from simple everyday activities to complex cognitive tasks in intelligence or other ability tests. In the first instance, these examples should make clear that (goal-directed) information processing requires at least two functions: (a) controlled manipulation and (b) availability of information. Information can only be manipulated if it is, at least temporarily, available or activated. For a long time, cognitive psychology has been dealing with the question of how information processing can be modelled in order to provide explanations for cognitive performance differences as well as performance impairments. At present, in different areas of psychology one model prevails that has been related to manifold cognitive functions, viz. the working memory model. The term working memory (WM) was introduced in the book „Plans and the Structure of Behavior" by Miller et al. (1960) and has subsequently entered animal research where it describes the temporary maintenance of information and action goals (Baddeley, 2002). In cognitive psychology it was to extend the classical concept of short-term memory (STM; Hebb, 1949; Atkinson & Shiffrin, 1968) from the 1970s and to cover not only memory but also information processing functions.

Figure 1: Tripartite model by Baddeley and Hitch (1974) as depicted in Baddeley (2003b)



In 1974, Baddeley and Hitch proposed a tripartite model of WM which – albeit expanded by one component in the meantime – today appears to work as well as 30 years ago (Baddeley, 2002, 2003b; for alternative models cf. Miyake & Shaw, 1999). To cut a long story short, WM enables the temporary maintenance *and* the processing of information. To this end, different systems are employed. The classical tripartite model of WM consists of two subsidiary systems („slave systems") which are controlled by a third component, the central executive.

The slave systems subserve the maintenance of information with the phonological loop holding phonologically coded (speech-based) material and the visuo-spatial sketchpad performing a similar function for visual and spatial (probably also kinaesthetic; Baddeley, 2003a) information. Initially, the third component, the central executive, was tentatively described as a convenient „ragbag" for all functions which could not be specifically assigned to other components and as control organ for the two subsidiary systems. Meanwhile, rather concrete assumptions on the functions of this system exist and above all, the term central executive is now frequently used throughout the land of psychology and neuroscience. In fact, it is regarded as the system that provides the actual basis of complex cognitive and intellectual performance. Due to its paramount importance, the central executive is described in detail after outlining the functions of the storage systems (cf. Baddeley, 1996, 2002, 2003a,b).

6.1 The classical Tripartite model by Baddeley and Hitch

The phonological loop represents the simplest and best understood component of WM. It is a temporary storage system for any piece of information which can be encoded phonologically, i.e., by means of speech. Besides verbal information it also stores numbers as they are usually encoded as number words and not as visuo-spatial images. The introduction of this system allowed a better interpretation of several findings from psychological memory span paradigms than could be made with the previously applied classical STM model (Atkinson & Shiffrin, 1968). In these paradigms, a list of sequentially presented information units (numbers, letters, words) has to be memorised and reproduced subsequently (in the correct order). The memory traces of the information units typically fade away within a short period of time (2 to 3 seconds) unless they are refreshed by (subvocal) rehearsal – we are all familiar with this through the everyday situation of memorising a phone number from reading it in the phone book until dialling. This example illustrates the two main functions of the phonological loop which are regarded as subcomponents by Baddeley: the phonological store maintaining speech-based information and an articulatory or subvocal rehearsal system reviving the memory traces time and again. Although this model could be empirically substantiated (cf. Baddeley, 2003b), the question concerning the function of the phonological loop beyond subserving simple memory span paradigms remained at the centre of attention. Several studies (cf. Baddeley, 2003a) could demonstrate that this system is particularly important in – both first and second – language acquisition. For instance, it was found that a disruption of the phonological loop (e.g., by articulatory suppression, i.e. a single word is continuously repeated while reading lists of vocabulary) greatly impairs learning new words in a second language. In another study with Finnish children it was observed that the success in learning English is associated with the phonological memory span. There are also neuropsychological reports on patients with impaired function of the phonological loop who could hardly build associations between words of their first language and those of a foreign language, although they had no deficits in associating different words of their first language. Moreover, the capacity of the phonological loop has turned out to be a good predictor of the success of first language acquisition, especially if artificial words have to be reproduced. These and further evidences (cf. Daneman & Merikle, 1996) point at a strong relation between the WM system and language learning. It is assumed that the phonological loop facilitates language acquisition in two ways: The phonological store provides resources for the temporary representation of new phoneme sequences, and the articulatory rehearsal system facilitates storing new words in long term memory through rehearsal.

The phonological loop is specialised for speech-based information, whereas the visuo-spatial sketchpad fulfils parallel functions for visual and spatial information. This system is mainly involved in cognitive demands which require the maintenance and manipulation of non-speech-based information (e.g., in spatial orientation or spatial imagery). The capacity of this system is even correlated with performance in architecture or engineering (Baddeley, 2003b). Even though this slave system has been investigated less intensively than the phonological loop, a comparable distinction between a storage component for visuo-spatial information („visual cache") and a rehearsal system („inner scribe") is proposed. Beyond the obvious involvement of the visuo-spatial sketchpad in the aforementioned demands, recent evidence underlines its importance in language processing. Children suffering from Williams syndrome (a hereditary disease) show comparably preserved verbal but impaired visuo-spatial abilities. For instance, they were presented sentence processing tasks of different complexity levels and of different contents. It turned out that these children performed poorly (as compared to a control group) in sentences involving spatial or visual syntactic information (e.g., spatial relations such as *above, below, in*; visual relations such as *brighter vs. darker*). This finding has been interpreted as a first evidence of the sketchpad's importance for language processing, at least if certain (spatial) contents or relations are involved.

The third system in Baddeley's WM model, the central executive, can be regarded as a central control system responsible for a number of important decisions. As mentioned above, the specific functions of this system remained largely unclear in the first years. Baddeley himself initially compared the central executive to a homunculus, a little man who, for example, decides when each of the two slave systems should be used (cf. Baddeley, 2002). The term 'executive' also suggests that the system is not only informed about the processes taking place in the other systems but that it also exercises some sort of control over them (Posner & Dehaene, 1994). For complex cognitive performance or – as described above, for goal-directed manipulation of information – at least three prerequisites have to be fulfilled: (1) The goal to be attained has to be cognitively present. (2) Attention has to be focused on the relevant, to be manipulated contents, selected from all available information coming from outside (environment) and inside (memory). (3) Mental operations continuously have to be evaluated in light of their efficiency and efficacy for goal attainment and inappropriate operations have to be suppressed. These central prerequisites require the storage function of WM on the one hand, and the goal-directed usage of processing (attentional) resources on the other hand. Attention is selectively drawn to relevant information, whereas irrelevant information is inhibited; at the same time attention can be directed to at least two processes: the mental operation itself (e.g., mental calculation) and the supervision of goal achievement by evaluating the usefulness and efficiency of the performed operations. This kind of attention control is presently regarded as the core function of the central executive (e.g., Baddeley, 2003a,b; Collette & van der Linden, 2002; Engle et al., 1999; Smith & Jonides, 2003; Süß et al., 2002), although, throughout the scientific investigation of this system, several cognitive functions have been subsumed under the term central executive. In fact, most of them were supervision functions which are essential in goal-directed behaviour.

This short outline of the functions of the central executive suggests that this system is involved to different extents in different cognitive demands. In highly automated routine tasks it will be considerably less strongly involved than in demands that are novel and require controlled and goal-directed information processing. The differentiation between controlled and automatic information processing (Posner & Snyder, 1975; Shiffrin & Snyder, 1977), one of the central concepts in cognitive psychology, refers to this continuum of involvement of central executive functions. Highly automated processes (such as driving a car) can be performed with only little cognitive load; novel and/or complex cognitive demands (such as mentally solving a difficult arithmetic problem) require controlled information processing which is associated with a high cognitive load and strong involvement of the central executive (cf. Ackerman, 1986). In addition, these examples emphasise that certain activities or cognitive demands cannot be localised merely on this continuum, but that they are also subject to intraindividual changes. Performing a task which initially required controlled information processing (e.g, the first driving lesson) can become a highly automated activity with increasing practice or training (e.g., in an experienced driver). Hence, the more a task demands the controlled manipulation of information, the more it requires a person's WM resources, enabling the temporary maintenance *and* processing of information.

6.2 Working memory and cognitive performance

We all know through personal experience that not every complex cognitive task can be solved „in mind"; we sometimes have to make use of external aids (e.g., writing down intermediate results) or we simply meet our limits, for instance, in more complex items of classical intelligence tests. A central characteristic of WM is its limited capacity. This capacity is subject to both, intraindividual changes (in the course of development) and interindividual differences. Thus, it appeared reasonable to relate the individual's WM capacity to different kinds of cognitive performances to examine the extent to which the limited WM capacity determines individuals' cognitive abilities in various areas. WM is often measured by means of so-called *dual-tasks* which require the simultaneous performance of two tasks (usually drawing on the typical functions of WM, viz. storage and processing). A frequently cited example for such a dual task is the reading span task (Daneman & Carpenter, 1980). In this task, sentences are presented which have to be judged as either true or false (e.g., „All men wear beards"). Additionally, the participant has to memorise the last word of each sentence and reproduce these words in the correct order after the presentation of 3 to 7 similarly constructed sentences. In another task, the so-called counting span task (cf. Engle et al., 1999), individuals are required to count the number of elements (e.g., digits) on a screen, memorise the results and reproduce them after a number of trials. The average number of correctly reproduced information units, be it words or numbers, is usually considered as a measure of the individual's WM capacity. Besides these exemplarily described tasks, a large number of WM tests have been devised which either draw on WM as an entire system or on specific subsystems (phonological loop, visuo-spatial sketchpad, central executive).

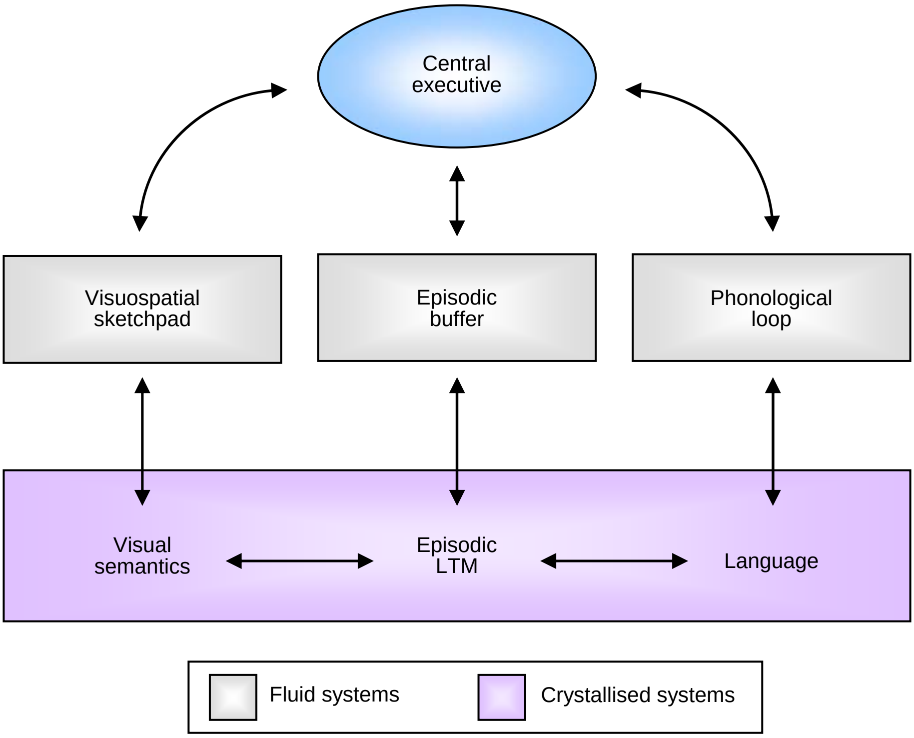
How is the herewith assessed WM capacity related to cognitive performances and abilities that are „closer to reality"? Indeed, associations with manifold variables were observed in several studies, among them reading and language comprehension, learning impairment in children, numerical thinking, learning of vocabulary, and spatial imagery (cf. Engle et al., 1999). As differences in these performances could be explained comparably well by differences in WM capacity, the question of how strongly WM capacity is associated with broad cognitive abilities, like intelligence, arose. The first study explicitly addressing this research question was conducted by Kyllonen and Christal (1990) who observed surprisingly high correlations (*r*s of .80 to .90) between measures of WM capacity and the reasoning component of intelligence (logical thinking). This even led the authors to equate (fluid) intelligence with WM. Likewise, subsequent studies (e.g., Ackerman et al., 2002; Colom et al., 2004; Conway et al., 2002) provided evidence of a substantial association with different indicators of intelligence, whereby the original assumption of WM as a key factor in complex cognitive performance has been further corroborated. Currently, WM capacity can be regarded as the best predictor of intelligence that has ever been derived from theories on human cognition (Süß et al., 2002).

Engle et al. (1999) investigated which WM functions show the strongest associations with cognitive performance or intelligence. To this end, they applied a simplified WM model merely distinguishing the storage component (STM, independent of the content) and the central executive. Accordingly, WM consists of STM, the central executive and a measuring error. In the aforementioned study they presented several cognitive tasks that either required STM only or additionally drew on the central executive, i.e. on WM. By employing factor analyses and structural equation modelling they could not only demonstrate that these two types of tasks can be differentiated empirically, but also that only the capacity of WM and not STM is associated with intelligence components. Following their simplified model, they could moreover show that the correlation between WM capacity and (in their study: fluid) intelligence can be traced back to the central executive; the pure storage function turned out as being unrelated to intelligence. The authors argued (as did Conway et al., 2002) that the strength of the relationship between the performance in a given cognitive task and intelligence primarily depends on how strongly the central executive is involved. Performance in pure memory span tasks, which can be solved by means of simple cognitive mechanisms such as articulatory rehearsal or chunking of information (see the description of the multi-component model of Baddeley below) should accordingly be unrelated to complex cognitive abilities. The performance in WM tasks, which draw on both, storage and processing components (such as „dual tasks") and which require controlled attention should, in contrast, be related (cf. Conway et al., 2003; Kail & Hall, 2001). This conclusion appears highly plausible and conforms nicely to other findings in intelligence research, for instance, to the observation that performance in elementary cognitive tasks (e.g., reaction time tasks) is only weakly related to intelligence; however, if their complexity is augmented (which implies the additional recruitment of controlled attention), the correlations also increase (cf. Mackintosh, 1998). How strongly the central executive is involved in a certain cognitive demand is not only a question of the task type but also of interindividual differences. Individuals who already have developed efficient strategies to memorise information, can do this virtually automatically, whereas others – lacking such skills – more strongly have to utilise attentional resources. A certain task might be more like a classical STM task for the first group, whereas it may represent a WM task for the latter. Hence, interindividual differences are not only reflected in different capacities but also influence the involvement of the central executive.

6.3 The multi-component model by Baddeley

The hitherto presented details have referred to the components of the classical WM model introduced in 1974 by Baddeley and Hitch. Even if the application of this model still appears to be appropriate in many cases, some empirical evidence did not conform to the postulate of two content-specific storage systems and one central executive. In particular, Baddeley (2000, 2002, 2003a,b) describes two significant deficits of his classical model: (1) There is a need for a system allowing visual and verbal codes to be combined in long-term memory encoding. (2) The classical model cannot explain how larger quantities of information which clearly exceed the capacity of either slave system (e.g. contents of narrations or tales) can be stored. This showed up particularly clearly in patients with brain lesions who, despite having grossly impaired long term memory, could immediately recall the contents of text passages containing 20 or more idea units. The outlined deficits of the tripartite model resulted in the proposal of a fourth component, namely the episodic buffer. This is assumed to be a limited capacity system that depends strongly on the central executive and allows binding together information of different contents (codes) and sources to so-called episodes. By introducing this system, a stronger association between WM and long term memory was built which goes beyond the original assumption that novel information passes through WM until it finally arrives in long term memory. In the new multi-component model, the WM systems are strongly connected with the contents stored in long-term memory, predominantly via the episodic buffer. These connections also accommodate the everyday observation that new information is not perceived and processed independently of stored knowledge. Long-term memory can even play an important role in simple memory span tasks (STM tasks). One might think of people who do not memorise a presented list of numbers in a mechanical way but apply different strategies drawing on their knowledge. For instance, they may associate single numbers with year dates, resulting in a smaller number of information units (the principle of „chunking"). Such strategies would not be possible if long-term memory were not highly interconnected with WM.

Figure 2 Multi-component model by Baddeley (2000) as depicted in Baddeley (2003b)

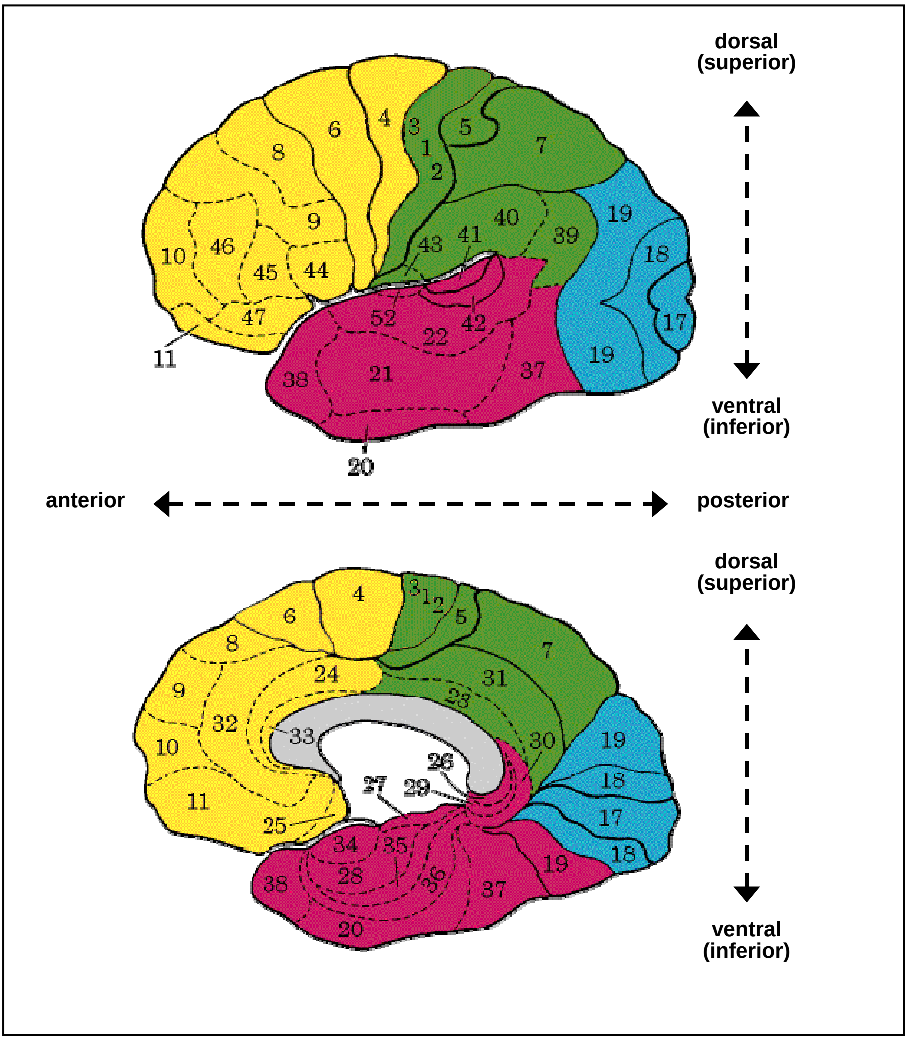


6.4 The neuronal bases of working memory

In light of the high relevance of WM several neuroscientists felt urged to localise the functions of this cognitive system in the human brain. In fact, many fundamental assumptions by the working group of Baddeley were already based on neuropsychological findings of patients with cognitive deficits caused by brain lesions. For instance, they report on patients who were hardly able to acquire new knowledge (drawing on long term memory) but whose short term memory was unimpaired. In other patients exactly the opposite was observed: impaired verbal memory span but normal functioning of long term memory and hardly any deficits in everyday performance (cf. Baddeley, 2003b). These findings substantiate the distinction between short and long term memory and, moreover, the extension of the short term memory model towards a more differentiated WM model. The question of the localisation or the neuroanatomical differentiation of the components, however, could be more thoroughly investigated by means of neuroimaging methods. Meanwhile, a large number of studies drawing on different facets of WM performance and associating different functions and systems of WM with specific brain areas have been conducted (cf. the reviews by Collette & van der Linden, 2002; Fletcher & Henson, 2001; Kane & Engle, 2002; Smith & Jonides, 2003); only for the recently introduced episodic buffer system no concrete assumptions or empirical findings seem to exist. Of particular interest was the search for the neuronal substrate (or correlate) of the central executive as it represents the core component of WM. Before referring to this central component, the empirical evidence regarding the two „slave systems" should be outlined.

At the neurophysiological level the evidence is more clear-cut for the phonological loop and its subcomponents. Most of the studies (reviewed in the aforementioned papers) point to (a) a left-hemispheric localisation, and, (b) a distinction between an anterior articulatory rehearsal system and a posterior phonological store. In detail, the phonological store has been localised in Brodmann area (BA) 40 (temporo-parietal, see Figure 3) – an area whose lesion results in short term memory impairment. The articulatory rehearsal system comprises the well-known Broca's language area (BA 44, inferior frontal) and supplementary motor area (BA 6) – both represent areas involved in the production of speech. The visuo-spatial sketchpad, in contrast, has turned out to be mainly localised in the right hemisphere which conforms to the general association of visuo-spatial performance with the right hemisphere (cf. Vogel et al., 2003). The visual cache is located in posterior areas (BA 19, occipital), whereas the visuo-spatial analogue of the articulatory rehearsal system (inner scribe) is distributed over BA 6, 47 (supplementary motor area, inferior frontal), and 40 (temporo-parietal; cf. Baddeley, 2003b).

Figure 3: Cytoarchitectonic map of cortical areas according to Brodmann (1908)[3]



This figure contains the lateral view of the left-hemispheric cortex (upper part of the figure) and of the median cut of the brain (lower part of the figure). The different lobes (frontal lobe, parietal lobe, temporal lobe, and occipital lobes) are demarcated by different greyscales.

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[3] Brodmann divided the cortex into 52 areas with regard to histological and functional criteria. For instance, the Brodmann areas (BA) 41 and 42 represent the primary auditory cortex in the temporal lobe. Brodmann's map is still widely used to describe the functional topography of the human brain.

The neuroscientific search for the central executive component of WM can look back on a longer history of investigation than the search for the slave systems, as already the first documentations of patients with brain damages and lesions have triggered attempts to draw conclusions concerning the localisation of complex cognitive functions. Of particular research interest in this context was the frontal lobe – the anterior part of the neocortex which is more highly developed in humans than in other species. In fact, the prefrontal cortex (PFC) contains more than 30 % of all cortical neurons and is highly interconnected (mainly reciprocally) with other structures of the human brain, including cortical (e.g., parietal and temporal) as well as subcortical ones (e.g., hippocampus, thalamus, amygdala). This fact also contributed to trying to localise complex functions in this young evolutionary brain structure. According to recent review articles, lesions of the frontal cortex were observed to result in several kinds of deficits of cognitive abilities, inter alia attention, motor control, spatial orientation, short-term memory, learning, creativity, or reasoning (cf. Fuster, 1988); even psychiatric disorders such as schizophrenia are associated with the frontal cortex (e.g., Antonova et al., 2004). In particular, patients with frontal lobe lesions show deficits in performances requiring some kind of cognitive control in goal-directed behaviour, which is known as „dysexecutive syndrome". The individual elements of a complex behaviour are usually left intact, but problems emerge when these elements have to be coordinated in a task-appropriate way (e.g., the coffee is stirred before the milk has been poured in). In view of these findings it does not appear surprising that areas of the frontal lobe were observed to light up whenever complex cognitive tasks, especially WM tasks, are performed. By administering tasks of different demands and various experimental designs it was possible to assign the functions of the central executive to different areas of the frontal lobe. In sum, three functionally distinguishable areas of the frontal cortex are assumed in literature: (1) the dorsolateral PFC (DLPFC), lying superior to the inferior frontal gyrus (BA 9, 46), is particularly responsible for active and selective manipulation of information in WM; (2) the ventrolateral PFC (VLPFC) lying below the inferior frontal gyrus (BA 44, 45, 47), contributes to the maintenance and updating of WM contents; and (3) the anterior frontal cortex (AFC), lying most anterior (BA 8, 10), plays an important role in the active selection and maintenance of goals and processes. These areas and functions seem to reflect the core of the central executive, even though additional functions are sometimes attributed to the aforementioned regions. Similarly to the slave systems there is some empirical evidence that verbal information primarily recruits the left hemisphere and visuo-spatial information the right hemisphere, but the respective findings are not consistent, particularly for those areas subserving the more complex functions (DLPFC and AFC; cf. Fletcher & Henson, 2001).

The attribution of central executive functions to prefrontal cortical areas also elicited large interest in neuroscientific intelligence research since WM and intelligence are strongly related. Unequivocal neurophysiological evidence was wished for in order to find an answer to the controversial question whether intelligence is a unitary construct („g", cf. Jensen, 1998) or whether there are multiple and independent intelligences (cf. Gardner, 1983) distributed over the brain. One of the first studies in this context was conducted by Risberg et al. (1977) who presented two parallel versions of a well-established non-verbal intelligence test (Raven's matrices; Raven, 1958) to 12 men. In the first test administration, the authors observed an increased blood flow in frontal and post-central areas, whereas the second administration (of the parallel version) led to flow increases solely post-centrally. They interpreted the stable post-central activation as an indicator of this region's involvement while solving the intelligence test items. The activation decreases in the frontal lobe, though, were attributed to other, unspecific factors such as reduction of anxiety or control processes. They explicitly stated that „great care has to be taken in relating increases in frontal regions to any specific type of mental task" (Risberg et al., 1977, p. 796). Findings from subsequent studies with more elaborate experimental designs, however, again emphasised the utmost importance of frontal brain areas for intellectual performance. For instance, Duncan et al. (2000) compared tasks with high and low demands for general intelligence („g") and found systematic activations of the lateral PFC, which was regarded as evidence of the localisation of „g" in this brain area. Other authors employing similar experimental designs, in contrast, report a distributed activation (over anterior and posterior regions), which challenges the equation of general intelligence and PFC (cf. Gray & Thompson, 2004).

At present, the involvement of prefrontal cortical areas in intellectual performance and abilities can be considered indisputable (cf. Gray & Thompson, 2004; Kane & Engle, 2002). Likewise undisputed is the role of these areas for several cognitive functions which are subsumed under the term 'executive' and which can be nicely integrated in current WM concepts (Baddeley, 2003b; Engle et al., 1999; Süß et al., 2002). In additional consideration of the strong relationship between WM capacity (in particular, the central executive) and fluid intelligence at the behavioural level, the conclusion appears justified that complex cognitive performance is mediated by WM functions which, in turn, are subserved by a neuronal network of different brain areas controlled by the executive function of the PFC (see also Heyder et al., 2004; for cortico-subcortical circuits in central executive functions).

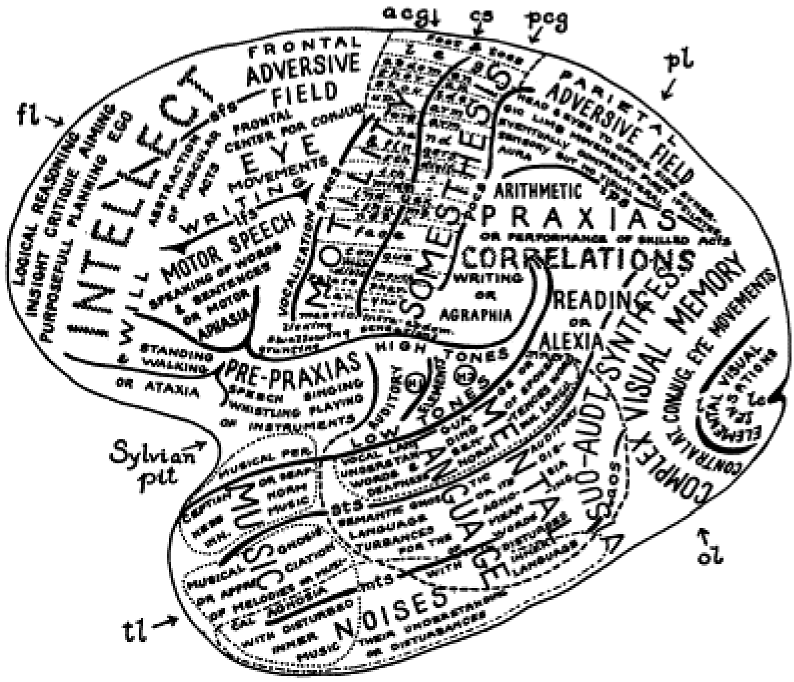
7. Pinpointing cognitive functions in the human brain

Following the short outline of current evidence regarding the localisation of different working memory components, the question should be addressed whether qualitatively distinguishable cognitive functions such as mathematical thinking also have a clear-cut neuronal correlates or, respectively, how clear-cut such correlates can be. It appears plausible that different brain areas are engaged in mathematical thinking compared to text comprehension. If a mapping of such functions were feasible, new vistas would open up for educational research, in particular for the investigation of research questions requiring methods that go beyond traditional behavioural measures. For instance, answers to the question could be found whether different types of teaching mathematics to different extents involve specific brain areas required for good mathematical performance. At an individual level, the question would arise if brain activation patterns allow conclusions about whether a student already applies „appropriate" solution strategies or whether he or she is still trying to solve the problem by suboptimal means. However, answers to such questions are only attainable if at least one central prerequisite is met: each (complex) cognitive function or process must correspond to a specific neuronal activation pattern which can be used as a marker of the applied solution strategies. Before discussing the potential of neuroscience in this context, some relevant research on the localisation of cognitive functions in the human brain is outlined.

7.1 Functional topographies

The idea that different psychological processes might have an unambiguous neuronal correlate in the human brain goes back to findings from behavioural observations of patients with brain lesions. In the second half of the 19th century, Paul Broca reported on a patient who had permanently lost his ability to speak due to a lesion in the left frontal lobe. Karl Wernicke observed considerable impairments in language comprehension in individuals with lesions in the left temporal lobe. After these initial reports the floodgates opened and a great many of studies were conducted (cf. Marshall & Fink, 2003) in which, for instance, visuo-spatial ability was ascribed to the right posterior cortex (Jackson, 1876), visual information processing to the occipital lobe (Lissauer, 1890), or memory performance to the medial temporal lobe (Alzheimer, 1908). Results from lesion studies as well as electrical stimulations of cortical regions during brain surgery (e.g., Penfield & Jasper, 1954) resulted in functional maps of the brain, as exemplarily presented below.

Figure 4: Localisation of psychological functions in the human brain according to Polyak (1957), reproduced by Savoy (2001)



When comparing this historical map to current neuroimaging findings considerable correspondence will be found. As an example, in the historical map the phenomenon „intellect" is localised in the prefrontal cortex in the historical map and the findings of a PET study by Duncan et al. (2000) similarly assign general intelligence (g) to lateral prefrontal cortices (see chapter 6.4). Likewise, language processes are ascribed to frontal and temporal regions, visual information processing to occipital regions or motor functions to central areas (motor cortex). Most of these associations between brain areas and psychological functions are still valid and can also be found in current functional topographic maps (Nichols & Newsome, 1999; Savoy, 2001). Nevertheless, it may be questionable whether all psychological processes and functions can be unequivocally pinpointed in the human brain or whether there are considerable differences between basic functions (e.g., colour perception, motor processes) and higher-order cognitive functions – irrespective of whether the functions are classified by content (verbal, numerical, figural, spatial) or by involved cognitive processes (attention, memory, reasoning etc.). In fact, the present body of evidence challenges the assumption of a „cupboard model" where every function is located in a specific „drawer". Moreover, the attribution of certain central executive functions to narrowly circumscribed areas of the prefrontal cortex shows the systematic involvement of this region in different demands rather than the fact that only this area is active during working memory performance (cf. Collette & van der Linden, 2002). In light of the strong interconnectedness of various brain areas (especially of the frontal cortex) it appears highly plausible that every complex cognitive performance requires the (coordinated) interplay of different areas. In order to further illustrate this assumption, findings from the extensive review by Cabeza and Nyberg (2000) who aggregated the results from a total of 275 PET and fMRI studies on different cognitive functions should be cited (see also Cabeza & Nyberg, 1997). They reviewed studies on attention, perception, imagery, language, working memory, priming, and semantic, episodic, and procedural memory following a functional classification, on the one hand, and a topographical classification on the other hand. Despite finding obvious correspondences in the activation patterns between different studies on the same cognitive function, the reviewed results could only be aggregated at a rather gross level. Activation patterns during attention and working memory demands were observed in prefrontal and parietal areas, language and semantic memory retrieval appeared to recruit left prefrontal and temporal areas, episodic encoding was accompanied by left prefrontal and medial temporal activations, episodic retrieval required prefrontal, medial temporal and posterior regions, etc. Particularly noteworthy are the obvious overlaps of activated areas during *different* cognitive demands. The authors describe, for instance, the dorsoparietal area BA 7, which was consistently activated in studies on attention, spatial perception, spatial imagery, working memory, and (episodic and procedural) memory. This activation was mostly interpreted within the domain of the investigation: as an attention area in attention studies, as a perceptual area in perceptual studies, or as a working memory area in working memory studies. Another example of the uncertain correspondence of cognitive functions and brain regions refers to Broca's area (BA 44). Marshall and Fink (2003) summarised the results as follows: This area not only plays a role in the production of speech but also in the syntactic processing of language, in processing musical syntax, in the perception of rhythmic motion, in imaging movement trajectories, and visuo-spatial skills. Consequently two conclusions can be drawn:

(1) The lacking neuronal correspondence of distinguishable cognitive functions might be due to the fact that the latter resides on a different abstraction level than neuronal processes. Therefore, similarities of correlated cognitive demands should be investigated to gain insight into the function of a specific brain region (Cabeza & Nyberg, 2000). A certain configuration of activated areas would then allow drawing conclusions about the cognitive function of a certain area.

(2) One and the same brain area may possibly take over different functions depending on the other activated areas within the same network (the neural context determines the cognitive function; cf. McIntosh, 2000). Thus, simple functional topographies must be replaced in favour of a deeper investigation of interactions between brain areas. Both assumptions appear plausible and are issues addressed in current research efforts.

7.2 Starting points for educational research

Even though the specific function of single brain areas during cognitive demands is still largely unknown and the functional differentiation of neurophysiological activation patterns is only schematically feasible at present, current findings do suggest potential perspectives of how neuroimaging methods can be used to identify cognitive processes. Of course, researchers cannot determine on the basis of activation patterns whether a person is thinking of a house or a face (cf. Haxby et al., 2001) or which associations emerge while reading a text – but certain information processing strategies may be distinguished. This holds particularly true for strategies which involve different mental representation forms (such as verbal vs. visuo-spatial). In an fMRI study by Reichle et al. (2000), for instance, strong correlations between strategies applied in cognitive task performance and brain activation patterns were found. They administered the Sentence-Picture-Verification task (Carpenter & Just, 1975), in which participants are presented a sentence describing a spatial relation of symbols (e.g., „It is not true that the star is above the plus"). Subsequently, a picture is presented which either conforms to the previously described configuration (a plus above a star) or not (a star above a plus). Participants are required to decide as quickly as possible whether the sentence corresponds to the picture or not, i.e. to verify or falsify the sentence. Prior to measuring brain activation, participants were trained to solve the task by employing a verbal (without visual imagery) and a visual strategy (with explicit instruction to create a mental picture). Analyses revealed that the application of the verbal as compared to the visual strategy resulted in a considerably stronger activation in the left anterior areas (Broca's area), whereas the visual strategy was accompanied by stronger parietal activation (bilaterally). Moreover, by computing the activation difference between Broca's area and left parietal cortex a correct classification of the individuals' strategies in 10 of 12 cases could be attained.

The distinction between verbal information processing, usually accompanied by left hemispheric activations (cf. the localisation of the phonological loop described in chapter 6), and visuo-spatial thinking, primarily involving parietal areas, right-hemispheric or bilateral (see also Vogel et al., 2003), is well-established and could represent a starting point for the application of neuroimaging techniques in educational research; for instance, in the investigation of different strategies during mathematical problem solving: Mathematical problems can be solved in different ways. In the simplest way (e.g., in the task: 2 x 6 = ?) the solution can be retrieved from memory, which was found to recruit language regions in the left frontal cortex (Dehaene, 1997). More complex mathematical tasks, in contrast, do not only demand a deliberate and goal-directed manipulation of information (and, thus, a stronger recruitment of central executive, prefrontal brain areas) but also the application of concrete solution strategies involving either verbal or visuo-spatial representations. Differentiating these two strategies at a neurophysiological level could allow inferences on how certain problems are solved. The additional costs of neuroscientific methods would especially be worth taking if this distinction cannot or only in-sufficiently be made at the behavioural level, for instance, if individuals perform similarly well albeit applying different strategies. In a recently published study on college students, Sohn et al. (2004) investigated the influences of different presentation formats of equivalent mathematical problems on the individuals' activation patterns. They presented algebra problems of two complexity levels, which were either presented in a verbal, story format (e.g., „Brian earns $7.00 an hour and gets $9.00 tips for his earnings. How much does he earn in 3 hours?"), or in a symbolic, equation format (e.g., „7H + 9 = E, H = 3, E = ?"). The students' performance (derived from reaction times and solution rates) did not differ depending on the presentation format, but the activation patterns did. The verbally presented problems were associated with activation increases in left prefrontal areas whereas bilateral parietal areas showed significant activation increases only in the non-verbal presentation format. „Behavioral equivalence, therefore, does not necessarily imply neural equivalence." (Sohn et al., p. 1194).

Stronger activation in one brain region as compared to another could indeed allow drawing conclusions about the employed cognitive processes or strategies, both, in comparing different groups (Sohn et al., 2004) as well as at an individual level (Reichle et al., 2000). However, it is still widely unknown whether a neurophysiological distinction of different strategies can be made similarly well in simple problems as in more difficult problems. Variably difficult tasks do not only result in the recruitment of different brain areas (e.g., stronger contributions of prefrontal areas in complex mathematical problems as compared to simple fact retrieval) but also in changes in the overall level of activation. How strongly the brain is activated during the performance of a given task is moreover a function of an individual's ability, comprising his or her general cognitive ability (general intelligence) and also domain-specific expertise. A person's cognitive and neurophysiological activation will be the lower, the more intelligent a person is, the better he or she has learned to solve a problem by applying prior knowledge. The finding that (successful) learning results in activation changes in the brain is not only well-established but also represents another starting point for the application of neuroscientific methods in psychological research. If learning processes are accompanied by typical, possibly also topographical, activation changes, these changes can be used as well as markers of the learning progress as activation patterns can be used for the identification of solution strategies.

8. Activation changes accompanying learning

A central characteristic of several learning processes has already been described in the context of Baddeley's working memory model, viz. the transition from controlled to automatic information processing. Finding a solution to a given problem at the beginning of a learning process may require intense and deliberate examination which, however, will be demanded less with increasing skills. This well-known phenomenon can be observed in different domains and represents a central concept of cognitive change. In fact, this concept seems to be especially well applicable in investigations of neurophysiological correlates of learning as it is in line with current working memory models (e.g., Baddeley, 2003b) postulating a link between controlled information processing and the central executive (Engle et al., 1999). In light of the considerable body of evidence attributing central executive processes to anterior (especially prefrontal) brain areas, it would appear reasonable to investigate learning-related changes in this (largely) content-unspecific area of the brain. The more controlled information processing a task requires, the higher is the central executive's involvement and the more strongly are its neuronal correlates engaged. Another advantage of this concept is its applicability to different time periods (see also Posner & DiGirolamo, 2000). Practising rather simple cognitive tasks usually results in a certain level of automatisation within a short time period whereas complex cognitive demands, if ever, only become automated following longer learning processes.

8.1 Neurophysiological correlates of short-term learning processes

Most neurophysiological studies on learning processes focused on rather short time intervals or learning phases, respectively. Only a few studies explicitly deal with the potential effects of long-term learning, which is due to economic factors and a lower internal validity of such experimental designs (cf. Haier, 2001). But it is exactly this kind of learning which is relevant for educational research as, for example, a second language is neither acquired within minutes nor within some days. In the following, exemplary findings on the neuronal correlates of short- and long-term learning are described with respect to three research questions: (1) How does the level of activation change through learning? (2) In which way do the topographic activation patterns change through learning? (3) What are the correlates of the activation changes?

The first question can be answered quite well based on current neurophysiological studies. As expected, learning (in terms of automatisation) often results in activation decreases in several brain areas (e.g., Andreasen et al., 1995a,b; Haier et al., 1992a; Risberg et al., 1977; Vandenberghe et al., 1995; but see also Haier, 2001 for contrary findings). This effect was tellingly demonstrated in a study by Haier et al. (1992a) who trained 8 men in the well-known computer game „Tetris" (placing strong demands on visuo-spatial information processing) over a time period of 4 to 8 weeks. The training took place at least 5 times per week and resulted in a sevenfold performance increase (from about 11 to about 80 lines). Before and after the training period PET scans were administered to measure brain activation (or glucose metabolism rate, respectively) whilst playing the game. The second scan revealed a considerably lower activation than the first one in nearly all assessed cortical areas (most prominent in parietal areas) or, in other words training led to widespread activation decreases. Even though this finding appears highly plausible with regard to increasing automatisation, it may be called into question how better performance can be achieved with less activation. One potential answer to this question could be: by increasing neural efficiency. „We believe that during the first attempts at playing the game, the subjects are trying out many different cognitive strategies for the task, thus using many different brain circuits involving varied brain areas. After much practice, it is likely that subjects have developed a set strategy for performance of the task and thus use fewer brain circuits and/or fewer neurons per circuit with the resulting less overall brain activity." (Haier et al., p. 142). In fact, there is presently a large body of evidence demonstrating that superior performance is related to lower brain activation (e.g., Grabner et al., 2004; Haier, 2003; Neubauer et al., 1995), suggesting that efficient brain activation is one basis of good performance. However, efficient brain activation does not mean that all brain regions are less active during cognitive performance but rather that the activation is distributed depending on the requirement: task-relevant brain areas should show an adequate activation whereas task-irrelevant areas should be activated only weakly or may even be deactivated (for similar findings, see Olesen et al., 2004). Thus, the key to efficient brain activation seems to lie in the topographical activation distribution which may reflect the result of successful learning.

The question for specific topographic activation changes accompanying learning, in contrast, cannot be answered as clearly (Haier, 2001). Referring to the varying involvement of central-executive processes throughout the learning process, it may be expected that the activation primarily resides in prefrontal areas at the beginning of the learning process whereas, with increasing skill level, the activation focus should shift from this rather unspecific prefrontal to task-relevant brain areas. There is actually some evidence supporting such an activation relocation which is often termed „anterior-posterior shift". In the study of Habib et al. (2000), for instance, participants were trained on a verbal discrimination task over five learning and test trials. In the first test trial, the authors observed significant correlations of the discrimination performance with the activation in left prefrontal and medial temporal areas. In the fifth and last test trial, though, no associations with prefrontal activation were observed whereas significant correlations were found with activation in the basal ganglia and in the temporal cortex – regions which are strongly related to memory processes (cf. Gabrieli, 1998). Similar activation shifts from rather task-irrelevant to task-relevant brain regions were also reported in other studies (e.g., Petersen et al., 1998; Raichle et al., 1994; Sakai et al., 1998), even though these changes do not often follow the simple pattern of an „anterior-posterior shift". But, despite the high plausibility of such findings, not all studies report clear-cut activation changes after learning – some studies observed general decreases (as in the aforementioned study by Haier et al., 1992a), others even general increases (e.g., Grafton et al., 1992). Besides methodological factors restricting the studies' generalisability (e.g., sample size, applied reference condition in subtraction analyses, analyses of „regions of interest"), the inconsistent evidence might also be due to neglected individual differences. After testing the first two participants, it should – at the latest – be evident that individual differences exist at both, the neuroanatomical and the neurophysiological level (Haier, 2001). Although these differences can certainly contribute to a deeper understanding of learning, they are regarded as undesired confounds in many neuroscientific studies. This holds particularly true if neuronal differences are associated with psychological variables (such as intelligence) which, in turn, may influence the learning processes.

Pioneering work in the investigation of psychological correlates of neurophysiological activation patterns and changes was done by the research group of the American psychiatrist Haier in the aforementioned Tetris learning study (Haier et al., 1992a). Facing activation decreases following the five-week training they examined whether this neurophysiological correlate of learning may moreover be an indicator of the learning success. Therefore, they correlated the extent of activation decrease from pre- to post-test with the performance improvement and, indeed, found substantial effects in all brain areas: Those individuals with the largest performance improvements displayed the strongest activation decreases. Hence, learning success could directly be mapped onto the activation decreases. In a second analysis of the data (Haier et al., 1992b) they additionally investigated which individuals benefited most from the training at the neurophysiological level (i.e. who had to activate their brains least during the second PET scan) by correlating the activation decreases with psychometrically assessed intelligence scores. Again, substantial correlations emerged in several brain areas (in particular in frontal areas), suggesting that the more intelligent individuals could increase their neural efficiency more strongly than their less intelligent counterparts. This finding could be replicated in a recently published study by Neubauer et al. (2004) who administered a 20-minute reasoning training and also revealed substantial correlations of activation decreases and intelligence, again most prominent in frontal brain regions.

Taken the outlined findings together, it can be stated that (a) learning processes are usually accompanied by activation decreases in certain brain areas, (b) in some cases an activation shift is observable (increase in some, decrease in other areas), and (c) neurophysiological changes may be related to individual differences (learning success, intelligence). These conclusions appear to hold at least some validity for activation changes following short-term learning or training which were investigated in the aforementioned studies. The question remains, though, whether there is empirical evidence that these findings can also be generalised to long-term, ecologically more valid learning phases, or whether they are solely expressions of automatisation of simple cognitive activities.

8.2 Long-term learning and neurophysiology

Unfortunately, only a few studies exist that allow conclusions on the neurophysiological effects of long-term learning. To our knowledge, longitudinal studies in controlled learning environments with repeated measurements are completely absent, thus, results from studies following alternative methodological approaches have to be considered. In most cases, individuals who have already acquired specific cognitive competencies over a long period of time (usually of some years) are compared with individuals without these competencies. Within the framework of expertise research, Volke et al. (2002), for instance, compared chess experts and novices during the performance of chess tasks. They found (1) that the experts primarily activated posterior brain areas in solving the chess tasks, whereas the novices engaged anterior areas, and (b) that the brain areas displayed larger activation coherence in experts than in novices. Both findings were interpreted in terms of more automatic and neurally more efficient information processing in experts due to long-term training (see also Grabner et al., 2003, for similar evidence in taxi drivers). Interpretations of this kind, however, are not entirely conclusive as only neurophysiological (or even neurostructural; cf. Maguire et al., 2000) group differences are examined and no records exist which prove that these groups did not already differ in many variables (which may impact on neuronal parameters) before learning or training. Furthermore, such studies do not deal with school-related learning but rather refer to specific expert samples; thus, the generalisability of the findings is questionable also for this reason. Hitherto, studies on effects of school learning are even scarcer than expert studies. A notable exception is the PET study by Castro-Caldas et al. (1998) who contrasted activation patterns of illiterate and literate individuals. They recruited 18 elderly women (12 illiterates and 6 literates) from Portugal who grew up in the same small town. In this village parents could not afford to send all of their children to school – it was common to keep the eldest daughter at home to help with the work while the younger ones attended school. Therefore, some women had not acquired literacy. Since all women had the same sociocultural background or even came from the same family, both groups were highly comparable with regard to manifold variables. Previous studies uncovered some cognitive tasks that can sensitively differentiate illiterate and literate individuals. In one of the tasks, participants were requested to repeat either meaningful (e.g., „banana") or nonsense words (e.g., „bonina"). Literates possess multiple cognitive pathways to perform this task successfully: they can refer to their vocabulary and memorise the words in this way (lexico-semantic strategy) and/or they memorise the word phonologically in that they imagine a word representing the given phoneme sequence. Illiterates, in contrast, are not able to make use of this phonological pathway as they cannot associate phonemes with letters, i.e. they lack a phonemic-graphemic matching. Performance differences primarily emerge if nonsense words have to be reproduced as the illiterates cannot rely on their vocabulary any longer, whereas meaningful words can be memorised similarly well by both groups. What were the results of this study? The number of correctly reproduced meaningful words was comparable in both groups (98 % vs. 92 % correct in the literates vs. illiterates). In the nonsense words, however, only 33 % were correctly reproduced by the illiterate group whereas the literates achieved 84 % correct responses. Subsequent analyses uncovered that most of the illiterates' errors were changes in the phoneme structure of the words, i.e. they repeated a word that sounded similar. So far, these results could be anticipated. What was new, however, was the finding that these differences were also reflected in brain activation patterns. While the similar performance in the meaningful words was accompanied by comparable brain activation (a network of parietal brain areas was involved in both groups), the illiterates engaged different brain areas (as compared to the literates) while reproducing the nonsense words. More precisely, they quite strongly activated a region in the right frontal lobe which did not light up in the literate counterparts. Since this region is usually not associated with language processes, the authors interpreted this finding as evidence that the appropriate functional network for phonological encoding is absent in the illiterates. Therefore, they have to engage a kind of „general-purpose support system" in the frontal lobe to solve this task.

8.3 Conclusion

Every complex cognitive performance requires goal-directed manipulation of information. This manipulation is subserved by a network of different brain areas with the prefrontal regions exerting a control function, which is reflected in central-executive processes at the cognitive level. Which functions other brain areas as part of a complex network in different cognitive functions subserve, though, has not been clarified yet. Current findings from neuroimaging studies rather demonstrate considerable overlaps in activation and thus, cognitive functions cannot be localised unequivocally in the human brain (see chapter 7). The question for the neuronal basis of human learning and the change of behaviour through experience, are of particular interest for educational research (cf. Rösler, 2005).

Learning processes as well as cognitive functions can be analysed and described at different biological levels, ranging from changes in the intracellular protein synthesis, over synaptic reorganisation, to the activity of larger neuronal networks (see also chapter 5). Here, the focus was exclusively on the latter level of analysis, since (a) current neuroimaging methods mostly depict exactly these processes of the brain at work, and (b) it may be assumed that psychological phenomena requiring an extensive interplay of neuronal networks can be best described at a level that neighbours the behavioural level with regard to its complexity (cf. Rösler, 2005 and chapter 3).

The description of correspondences between cognitive functions (or behavioural processes) and neurophysiological phenomena is certainly not exhaustive but rather aims at demonstrating where a cooperation of neuroscientific and educational research could be seminal. The cited findings should, moreover, have shown that the investigation of neuronal bases of cognitive functions in general and learning processes in particular is still in its infancy, both with respect to the available technical methods and the functional models of the human brain. The view of a functional „cupboard model" appears to be inadequate in light of present findings; thus, new concepts on the functioning of the human brain have to be devised. Research on time courses and interactions of different brain areas during cognitive performance reflects such a promising approach. Most interestingly, it was the pioneer of the well-established cytoarchitectonic parcellation of the cerebral cortex, Korbinian Brodmann, who stated nearly 100 years ago: „One cannot think of their [mental faculties] taking place in any other way than through an infinitely complex and involved interaction and cooperation of numerous elementary activities. … in each particular case (these) supposed elementary functional loci are active in differing numbers, in differing degrees and in differing combinations. … Such activities are … always the result … of the function of a large number of suborgans distributed more or less widely over the cortical surface." (Brodmann, 1909, cited in Raichle, 2003).

9. The dopamine system

Most of the synaptic signal transmission in the human central nervous system involves the release of chemical messengers, so-called neurotransmitters. The flexibility and plasticity of this type of signal transmission (excitatory and inhibitory processes, synapses of modulating sensitivity) is the basic requirement for higher-order brain functions. Unlike neurotransmitters such as norepinephrine and epinephrine, dopamine is particularly associated with memory processes as it is produced by neurons in the respective brain regions. Dopaminergic neurons predominantly occur in two areas: (1) in the substantia nigra, i.e. a part of the brainstem that owes its name to its black appearance caused by densely-packed neurons, and (2) in the ventral portion of the tegmental area which is also located in the brainstem. Different dopamine pathways project from these areas. The pathway from the substantia nigra to the dorsal striatum is primarily discussed with respect to motor functions (patients with Parkinson's disease have an insufficient dopamine concentration in the nigrostriatal system). The mesocorticolimbic dopamine system (projections from the ventral tegmental area to limbic and cortical regions, inter alia nucleus accumbens, amygdala, hippocampus, and prefrontal cortex), in contrast, is associated with motivation and memory processes (Wise, 2004).

Several animal studies (cf. Schultz, 2002; Wise, 2004) have revealed that dopaminergic neurons show specific responses to certain events. The majority of neurons are activated when a rewarding stimulus is presented (e.g., food or drugs), especially if the reward occurs (partly) unexpected. If an expected reward fails to appear, activity of the dopaminergic neurons is inhibited. These reactions have not only turned out to be critical in mediating enjoyment in the context of drug addiction but also in memory consolidation (e.g., Stark & Scheich, 1997; Stark et al., 2004). In many experiments, animals (mainly rats) learn to show a specific behaviour by means of operant conditioning. This means, that they are rewarded for showing desired reactions by receiving some sort of treat (positive reinforcement) or by an expected punishment failing to occur (negative reinforcement). The key role of dopamine in reward processing, however, has been challenged by some empirical findings (e.g., the finding that neutral or aversive stimuli activate the dopamine system as well; Ungless, 2004). This may, inter alia, be due to different approaches in investigating such reactions. Two methods are frequently used in animal experiments: measurement of electrical activity of dopaminergic neurons by means of single-cell recordings (fast, short-lived reactions) and the direct assessment of dopamine release by means of microdialysis (fast onset, but of longer duration). Animal experiments could moreover reveal that the application of dopamine antagonists (chemicals inhibiting dopamine functioning by blocking postsynaptic receptors) such as neuroleptica can reduce or even eliminate the reinforcement effect and, consequently, also the conditioning or learning effect (Wise, 2004). If, on the contrary, the dopaminergic reactions are augmented (e.g., by applying dopamine agonists) the learning success usually improves, even if the treatment is administered after learning. The latter finding has also supported the notion that the consolidation of new memory traces (or of novel information, respectively) is mediated by the dopamine system and, thus, could be improved (see also Jay, 2003). However, it should be kept in mind that these findings derive from animal studies in which „learning” equals primarily conditioning, i.e., establishing and consolidating simple stimulus-reward or reaction-reward relations. Therefore, the generalisability of such findings to human learning can be called into question.

In addition, other methods than those in animal studies have to be applied in the investigation of dopaminergic reactions accompanying psychological processes. The following three methods are usually employed in humans: (1) Investigations of patients with dopamine-related diseases (e.g., Parkinson's disease; Frank et al., 2004); (2) administration of drugs affecting the dopamine function (e.g., Mehta et al., 2004); (3) application of modern neuroimaging methods. The latter allows either the measurement of the activity of topographically circumscribed neuronal assemblies in different experimental conditions (e.g., fMRI to detect activation changes in dopaminergic brain regions; McClure et al., 2004), or the indirect assessment of dopamine release by tracers binding to dopaminergic receptors (in PET; e.g., Alpert et al., 2003; Bartenstein, 2004; Koepp et al., 1998; Laruelle, 2000).

Taken together, there is wide consensus that the dopamine system plays an important role in reward processing, in learning, and in drug addiction. Animal research has already advanced to a stage in which hypotheses on different mechanisms are empirically tested and validated (cf. the review by Wise, 2004). The investigation of biochemical processes in the brain certainly represents a reasonable and necessary extension in human research. PET scans allowing in-vivo measurement of neurotransmitter release appear to be the most promising technique in this context. However, these measurements should not be limited to the currently quite „popular” dopamine but should rather aim at elucidating the interplay of different neurochemical mechanisms. As outlined in chapter 4, there are several restrictions of fMRI and PET in their application in children; therefore, alternative technologies have to be developed to pursue such research questions in the context of educational neuroscience. Current evidence on the role of the dopamine system in those complex learning processes that educational research deals with, however, appears to be rather limited. Hence, implications for learning in school based on findings from (animal) conditioning studies should be scrutinised.

10. Direct brain-computer communication and neurofeedback: On the application of modern neurofeedback technology in educational research

Can the brain be prepared for learning in an unspecific way? Can brain activity be influenced to make specific learning processes run more efficiently? Recent technological developments seem to offer new forms of learning based on direct communication between man and machine. Neurofeedback plays an important role in the development of modern brain-computer interfaces enabling to control a computer cursor, a robot or a wheelchair by mere thought. This chapter outlines the theory of neurofeedback and of modern brain-computer interfaces (BCI) with the aim of providing some impulses for innovative research approaches. In particular, this chapter focuses on their basics, on methodical aspects, and on their potential. Finally, some conclusions on their application in educational research are drawn.

10.1 Basics of neurofeedback research

In the last three decades, neurofeedback research has impressively demonstrated that brain activity can be influenced by EEG biofeedback training. Concretely, electrical brain activity is continuously registered whereupon specific parameters are fed back in visual or acoustic form. The form of feedback (visual or acoustic signal, analogue vs. digital feedback) has turned out to be critical for learning success (Utz, 1994; see also Neuper & Pfurtscheller, 1999).

Despite many decades of research in this field, there is presently no generally accepted theory on how neurofeedback works. Many researchers regard EEG biofeedback training as a form of operant conditioning and emphasise aspects such as feedback modality, reward, and motivation. The importance of these factors has been particularly shown in studies with children (cf. Siniatchin et al., 2000). Other researchers compare biofeedback training to the acquisition of (motor) skills. In this case, cognitive processes, for instance finding an appropriate mental (control) strategy, are accentuated (Roberts et al., 1989; Neuper et al., 1999). In a broader context, the acquisition of control is also regarded as adaptive behaviour (Schwartz, 1979; Mulholland 1995; Pfurtscheller & Neuper, 2001). But, as controlling ones own brain activity involves subconscious processes, theoretical explanations of the underlying mechanisms are generally limited. Empirical-pragmatic research rather concentrates on the conditions under which this phenomenon emerges and on potential fields of application. Several studies have revealed that different electrophysiological parameters can be brought under operant (or self-) control; for instance:

- Evoked Potentials (Rosenfeld et al., 1969)
- Event-related Potentials (Birbaumer et al., 1981)
- Slow Cortical Potentials (SCP; Birbaumer, 1984)

- Frequency components of oscillatory activity (e.g., alpha, theta: Kamiya, 1968; Egner et al., 2004; SMR: Sterman et al., 2000; Vernon et al., 2003; mu rhythm: Wolpaw et al. 2002; Neuper et al., 1999)

Recent investigations have reported that even operant control (self-regulation) of regional brain activation (hemodynamic changes as reflected in the BOLD signal) is feasible (DeCharms et al., 2004; Weiskopf et al., 2003).

10.2 Clinical neurofeedback applications

The practical application of neurofeedback has predominantly been demonstrated in clinical studies. In this context, two approaches are relevant: the modulation of specific EEG frequency components (e.g., sensorimotor rhythm) and the volitional control of slow cortical potentials. Barry Sterman, the pioneer of neurofeedback, examined feedback trainings of the so-called sensorimotor rhythm (SMR). SMR delineates EEG activity in the frequency range between 12 and 16 Hz occurring over the sensorimotor cortex while an individual is in a state of active alertness but inhibits any form of movement. This activation pattern was first identified in cats and later also in humans. SMR activity is presumably generated in thalamo-cortical feedback loops and seems to express inhibitory mechanisms („thalamic gating"; Lopes da Silva, 1991). Sterman revealed that SMR activity in cats can be enhanced by operant conditioning. Most importantly, the animals trained with SMR feedback showed striking changes in behaviour, in particular a remarkable resistance to pharmacologically induced seizures (Sterman et al., 1969). Therefore, it seemed to be reasonable to train SMR activity also in humans. Besides increases (or synchronisation) of specific oscillatory frequency components, the level of cortical activation is also reflected in slow cortical potentials. A slow negativity in brain potentials corresponds to an increase of cortical excitability (higher level of depolarisation) and, thus, can be considered as an indicator for activation, attention, and information processing. Positive potential shifts, in contrast, reflect decreased excitability and a lower activation level (relaxation; Birbaumer, 1984).

Self-regulation of the aforementioned brain potentials is effective in disorders that are characterised by a regulatory dysfunction of cortical activity, for instance, in attention deficits and hyperactivity. In epileptics, either particularly SMR activity is trained, which leads to normalisation of the EEG (Sterman et al., 1996; Sterman 2000), or their excessive excitability is to be reduced by inhibiting slow cortical potentials (SCP training; Rockstroh et al., 1993; Kotchoubey et al., 2001). Empirical evidence from several decades of research prove that both types of neurofeedback training can indeed result in a reduction of seizure frequency (and duration) in epileptic patients (Monderer et al., 2002)

Another promising application of EEG feedback has been uncovered in children and adolescents with attention deficit syndrome, hyperactivity, and learning impairments (Lubar et al., 1995; Lubar & Lubar, 1999). The hyperkinetic disorder (attention deficit hyperactivity disorder, ADHD) involves inattentiveness, impulsivity, and hyperactivity. It is presumably caused by dysfunctional dopaminergic cortico-subcortical systems, which are essential for executive functions and behavioural control (Levy, 1999; Swanson et al., 2000). Findings of structural changes in the frontal lobe and in the basal ganglia support this assumption (e.g., Castellanus et al., 1996). Affected adolescents (as compared to healthy controls) display an increased theta activity (4-8 Hz), most prominent at frontal cortices, and a decreased activity in higher frequency ranges (Mann et al., 1992). Consequently, patients are trained to reduce their theta and at the same time enhance their SMR and beta activity (e.g., 16-23 Hz). This training results in decreased hyperactivity, less need for medication as well as improved concentration and school performance (Lubar et al., 1995; Linden et al., 1996).

Taken together, several studies have supported the efficacy of neurofeedback training at the neurophysiological and behavioural level. In particular, pathological electrophysiological activation patterns can be regulated or normalised, respectively, which may be due to changes in thalamo-cortical networks (Sterman, 1996). However, the methodical shortcomings of some clinical studies (e.g., small samples, inappropriate experimental design, non-standardised diagnostic measures) entail the necessity of future large and well-designed evaluation studies (cf. Monderer et al., 2002; Rossiter, 2004).

10.3 Improvement of cognitive functions by means of neurofeedback

With respect to its potential application in educational research, the question arises of what benefits of neurofeedback can be expected in healthy individuals (with normal EEG patterns). In contrast to the rather extensive clinical neurofeedback research, only a few studies have addressed effects of EEG feedback on cognitive performance. However, there is a considerable body of literature on functional links between cognitive performance and modulations in oscillatory brain activity. In this context, specific frequency components (e.g., theta, alpha or gamma components) are related to cognitive functions like attention, memory, language processing, intelligence, or creativity. For instance, by employing repetitive transcranial magnetic stimulation (rTMS), Klimesch and coworkers (2003) provided clear-cut evidence for a direct functional relation between oscillatory neuronal activity (power in upper alpha band) and cognitive performance in a mental rotation task. Participants whose parietal cortex was stimulated by means of rTMS before working on the task (mental rotation of cubes) displayed significant performance improvements. Interestingly, this beneficial effect only emerged if the stimulation frequency was in the upper alpha range, suggesting that neuronal activity in task-relevant brain areas can be modulated (perhaps even with a longer-lasting effect) by neurofeedback training.

Previous EEG feedback studies on the association between specific cognitive functions and training of distinct frequency components have provided very promising results. SMR training in healthy participants was found to significantly improve performance in attention, concentration, and (semantic) working memory tasks (Egner & Gruzelier, 2001, 2004; Vernon et al., 2003). Theta training, in contrast, appears to be associated with improved creative (e.g., musical) performance (Egner & Gruzelier, 2003).

10.4 Direct brain-computer interfaces

Volitional modulation or self-control of brain activity also provides the basis for quite spectacular applications, such as direct brain-computer communication. Self-regulation of specific EEG signals can be used, for instance, to control computer cursors (Wolpaw et al., 2002; Neuper et al., 1999), or to select letters for writing on a computer monitor (Birbaumer et al., 1999; Neuper et al., 2003). In this vein, even severely handicapped patients can communicate with their environment. An impressive example thereof was a report by Birbaumer et al. (1999) on a completely paralysed patient who was able to compose verbal messages with an EEG-based language system (Thought-Translation-Device, TTD).

The basic principle of brain-computer interfaces (BCI) lies in the conversion of the patient's mental activity into appropriate trigger signals (Vidal, 1973; Pfurtscheller & Neuper, 2001; Wolpaw et al., 2002). To this end, several EEG signals are recorded at different positions on the scalp and processed in real-time. Specific methods of biosignal processing and pattern recognition enable the generation of individual „adaptive" classifiers that allow the detection of different cognitive processes in EEG in real-time (Pfurtscheller et al., 1997; Guger et al., 2001; Obermaier et al., 2001). A central precondition therefore is that effective mental strategies are found which are accompanied by different cortical activation patterns and can be deliberately (re-)produced. The main problems in this context comprise the selection of appropriate EEG parameters and their online classification, for instance, by means of artificial neuronal networks (Pfurtscheller et al., 1997). Adaptive methods of parameter extraction have proved of value in the classification of EEG patterns (Pfurtscheller & Neuper, 2001; Schlögl et al., 2002). In this approach of classification, training not only occurs on the patient's part, but also the computer has to „learn" to identify and classify individual EEG patterns.

An EEG-based brain-computer interface could represent an additional mode of communication between human thought and the (learning) environment in the future. Previous studies on the efficacy of such communication (in terms of transferable information) have revealed that the detection of different types of cognitive processes in real-time is basically feasible (Obermaier et al., 2001). This technology opens up new vistas in observing and, furthermore, influencing dynamic information processing (e.g., while learning) in the brain.

10.5 Potential applications in educational research

Direct brain-computer interfaces introduce a new form of learning, which in the future may be offered in addition to instruction in school. Moreover, this technology may also be useful in the empirical examination of educational theories. By means of BCI technology, neurophysiological „brain states" (e.g., patterns of bioelectrical brain activity) can be detected in real-time. Thus, dynamic aspects of learning and their (neuro-) physiological correlates, respectively, become directly measurable and describable. Further research could, for instance, investigate to what extent the identification of relevant brain states (or their dynamics, respectively) in different cognitive demands (e.g., verbal vs. visuo-spatial tasks) is possible.

In addition, it appears conceivable to trigger task presentation in a learning situation depending on spontaneously emerging brain states. Real-time EEG analysis may be used to present certain tasks only in predefined brain states (e.g., defined as high theta or alpha power) and to link them to performance parameters (e.g., speed or accuracy of information processing). Experimental studies may reveal which EEG parameters are appropriate for triggering the presentation. Such an approach could (a) experimentally validate the relevance of detected brain states, and (b) contribute to improve cognitive performance online by brain-state dependent task presentation. In this context, it seems important to develop special feedback training for different tasks as well as to individually adapt the feedback to the learning person.

Combining brain-computer interfaces with multimedia learning environments would allow both, online-monitoring of electrophysiological activity and interactive control of the learning environment. In fact, the integration of brain interfaces in multimedia applications is already being investigated (e.g., Ebrahimi et al., 2003). Such a system may contribute to more comprehensive investigations of dynamic aspects in learning. At present, studies on psychophysiological changes (EEG, EOG, ECG) in virtual learning environments (e-learning) or multimedia applications are increasingly gaining importance, especially with respect to computer-aided instruction at school and university. These findings on psychophysiological (especially neurophysiological) changes during virtual learning may indeed constitute the basis for the development of neuroscientific training programmes.

11. Results of the workshop „Educational research from a neuroscientific perspective" (Berlin, November 2004)

In the preparation of this expertise a workshop was organised to discuss the potential of neuroscientific contributions in research on learning and instruction. Beforehand, all participants were asked to submit proposals for rewarding and promising research projects in which neurophysiological methods are to be applied to investigate educational research questions (see the respective questionnaire in the appendix). This brainstorming on future scientific projects resulted in a list of 16 contributions which will be outlined in the following.

Design of learning environment

The main focus in this category lies on the influence of different learning environments which includes the form of presentation of the learning material as well as various types of tutorial interaction. Regarding the design of the learning material the usefulness of multimodal and multimedial modes of presentation was discussed. In light of neurophysiological findings demonstrating that learning material is stored in different brain regions according to the presentation modality it was proposed to examine whether and in which material multimodal forms of presentation facilitate recall and improve learning outcome. In this context, computer-based learning environments allowing multimedial presentation of information have frequently been mentioned. As it is still largely unclear which factors of the learning environment actually facilitate learning and how multimodal and multicodal information is integrated, these questions should be tackled in further research. Concerning the design of tutorial interaction, mainly studies on the impact of various forms of feedback on learning progress were submitted. In addition to the effects of certain designs on cognitive performance, stress experience and emotional and motivational aspects which are closely related to neurochemical mechanisms (e.g., the dopamine system) also shall be considered. Further proposals addressed the importance of sleep and rest phases on learning success and the neuroscientific explanation of teacher-student interactions.

Efficient learning

Whether a specific learning environment leads to success is mainly subject to the learning process which, in turn, may run variably efficient depending on the individual. The topic „efficient learning" was approached from various angles: First, from a cognitive scientific perspective it was proposed to investigate whether efficient vs. less efficient learning processes can be neurophysiologically distinguished in order to elucidate the neuronal bases of successful learning. Moreover, studies on sensitive phases for efficient learning, the neuroscientific investigation of „interest" in contrast to motivation, and examinations on complex strategies for parallel information processing can be ascribed to this field. Differential perspectives taking individual differences in learning efficiency into account complement the first approach. This second perspective focuses on the importance of (and interaction between) giftedness and talent, the individual's learning history and prior knowledge for successful learning. In addition, it should be investigated which functional and structural brain parameters reflect individual differences in these components. Once efficient learning has been identified at the neurophysiological level, such findings could be applied to systematically prepare the brain for learning or to improve cognitive performance by means of neurofeedback training. The interest in the evaluation of such a neurophysiological training method in various domains was reflected in several proposals.

Besides rather general questions regarding the design of learning environments and the efficiency of learning processes, proposals concerning the following school-related subject domains were submitted: language as well as mathematics and science education.

Language

A number of research proposals dealt with various aspects of language processing, both in first as well as in second language acquisition. Regarding first language acquisition, the following research questions were postulated: The importance of emotional cues for the acquisition and maintenance of words shall be investigated in early childhood. In preschool children and dyslexic children, the validity of Orton's theory of dyslexia in different languages as well as the examination of learning deficits and the development of methods for their early diagnosis were postulated. Regarding foreign language learning the emphasis was primarily placed on psychological and neuroscientific processes of second and third language acquisition. In particular, the transition from controlled to automatic processing of verbal information and its mental representation was addressed. Beyond dynamic changes in second language acquisition another focus was laid on the evaluation of different methods of instruction with respect to their contribution to successful learning. This also includes the investigation of various age groups, starting from school children to grown-ups.

Mathematics and science education

The second prominent field of school-related research comprises proposals on learning processes and deficits in mathematics and science. Mathematical abilities are again viewed from a developmental perspective which tries to gain insight into typical and atypical development of number comprehension by means of longitudinal studies. The thereby obtained findings shall contribute to a better early diagnosis of children who show learning deficits or impairments in this field. Furthermore, a proposal concerning deterministic and stochastic reasoning also was submitted. This contribution seeks to examine the neuronal bases of different number representation formats (natural frequencies, percent, probabilities) as well as sex differences. Another proposal dealt with trajectories of learning in mathematical-scientific domains. Here, the neurophysiological basis of different operation and thinking processes which have hitherto been differentiated predominantly by means of video analyses should be investigated.

12. Conclusions and outlook: What can educational research and brain research expect from each other?

12.1 Learning as subject of scientific investigation

The term „learning" subsumes a number of processes taking place in the central nervous system and allowing individuals to better cope with demands from their environment. This holds likewise true for a bee, learning to recognise food cues, and for a scientist developing a new theory in his domain by intensive considerations. The general conditions of learning are primarily determined by the individual's species and its environment. Belonging to a certain species inter alia determines how information is perceived and which behaviour can be acquired. As bees only have vibration perception, they cannot be conditioned to sonic signals, and not even the most attractive reward will motivate a cow to walk on its forelegs. Something can only be learned if the environment the individual lives in places appropriate demands and offers respective learning opportunities. A cage-housed rat that always gets only one type of food at the same place cannot learn where particularly delicious food can be found and how to get there. A person growing up in an illiterate culture remains illiterate even though he or she might possess the best cognitive potential for learning to read and write. How and how much an individual can learn is, besides species and environmental factors, also influenced by the individual cognitive conditions which are the result of genetic variations within a species and of individual experiences. If, due to accident or disease, a dog loses its hearing, it cannot be conditioned to a bell any longer.

The interaction between learning and the brain may be characterised as following: Brain development follows the genetic programme of an individual and limits his or her potential learning experiences. At the same time, the brain constantly changes through learning and, thus, also influences what is learned in the future and how this is learned. Learning is undoubtedly a fascinating phenomenon, and several scientific disciplines approach it from different perspectives. Neuroscience aims at elucidating learning-related brain functions, for instance: which brain areas are involved in learning and what biochemical processes take place at the synapses during the learning process? Which lasting traces of learning can be found in the brain? In which anatomical and biochemical properties do individuals differ who learn varyingly fast and efficient? Several questions of this kind can hitherto solely be investigated in animals, but it can be assumed that some findings may be generalisable to humans. In fact, many types of learning are similar in humans and animals – among those are, for example, conditioning processes: previously unrelated stimuli become associated in memory and, thus, behaviour that is followed by positive consequences occurs with higher probability. Every creature being capable of receiving sensory information and of displaying behaviour is learning in this way. A pigeon will repeat the movement immediately shown before the receipt of a grain because it has established an expectation. Human behaviour is more often determined by simple associative learning than we are actually aware of. As an example, actually harmless objects may, due to their previous perception in an emotionally stressful situation, evoke unpleasant feelings or even strong fear.

Until the 1960s, stimulus-response learning constituted the main research focus in learning psychology. This line of research (sometimes ideology) has widely become known as „behaviourism". Whenever neuroscientists investigate the neurophysiology of learning in animals, they refer to research paradigms, theories and classifications devised in behaviouristic psychology of learning. Now, these classic concepts help us to better understand animal brain functions. Where and how does the central nervous system respond if something is learned by reward instead of punishment? Which brain areas are involved and what neurotransmitters are released in positive reinforcement (reward) in contrast to negative reinforcement (withdrawal of aversive stimulus, e.g., preventing an electric shock by escaping)? Evidence on the neurophysiological mechanisms of stimulus-response learning are also important in tracking human learning – as much is learned in a very uncomplicated way: If a certain action is followed by reward, it is maintained; if it is followed by punishment, it is stopped. Systematic reinforcement can support learning of complex and permanent patterns of behaviour in animals as well as in humans.

Learning by reinforcement also plays an important role at school. How can children be motivated to listen to the teacher's explanations instead of looking out of the window or running around? Which incentives must be offered to students to prevent them from becoming demotivated by continuing failures? Teachers are confronted with such questions day-to-day, and if they succeed in keeping the students at it, also (from an evolutionary perspective) rather ancient brain areas such as the limbic system are involved. If children experience success, for instance, by comprehending a difficult text passage after having repeatedly reread it, this positive learning experience is, inter alia by means of dopamine, stored in the brain and thus, it can be repeatedly activated. The limbic system of a physics student who has, after intensive efforts, finally grasped the theory of relativity may react similarly as the limbic system of a mouse which has just learned where to find especially delicious cheese. Hence, learning in humans and animals can sometimes be explained by similar mechanisms. The basic neuronal principle of learning is frequently described in terms of a principle by the Canadian psychologists Donald Hebb: „What fires together, wires together." Neurons being activated at the same time will reciprocally activate themselves in the future. Just imagine a simple learning process: A rat sits in a cage equipped with a lever and a lamp flashing up at irregular intervals. When the rat presses the lever, it sometimes gets a pellet of food. After some time, the rat will have learned that the desired reward is only provided if the lever is pressed immediately after the lamp has lit up. In consequence, the rat will no longer press the lever at random but only after the light flashed. The connections between three types of neurons are strengthened: (1) sensory neurons being responsible for the perception of the light stimulus, (2) motor neurons being involved in pressing the lever, and (3) neurons that subserve the perception and positive evaluation of the food pellets. Hence, it is assumed that the activation of single cells within this network increases the probability that other interconnected neurons also are activated (what fires together, wires together). This can be illustrated with the following imaginary example: in the sensory perception of food pellets also neurons are involved that are responsible for the perception of round shapes. If a ball is presented to the rat, these neurons start to fire. In turn, the activation will spread to strongly interconnected neurons; for instance, motor neurons producing the necessary movement to press the lever. Consequently, the rat's perception of a ball might release an impulse to move its forepaws. In a nutshell, the brain is continuously changing, which also impacts on future experiences and behaviour.

Some knowledge taught at school can be acquired by mere reinforcement of building associations, e.g., multiplication tables or vocabulary of a foreign language. If the problem „7 x 3 = ?" is correctly answered with „21" the student is rewarded; incorrect solutions are ignored. Basic vocabulary of a foreign language can also be acquired in this manner. However, if nothing else happens in the learner's brain besides simply establishing (externally-controlled) associations, largely unusable knowledge is acquired. Children having learned multiplication tables by reinforcement of correct responses can promptly provide an answer to „4 x 8 = ?", but they do not know that they only have to double the answer to solve the problem „4 x 16 = ?". If associations such as „chair-Stuhl, table-Tisch, carpet-Teppich" are stored in memory, this does not necessarily imply that these words are also used in composing German sentences. The mental competency typical for human beings is not to learn by building mere associations (i.e., not only establishing externally-controlled connections in the brain) but to actively (i.e., without external incentives) reorganise knowledge in a way to be able to use it later in coping with novel demands. In fact, this is exactly what makes human learning so special. Humans are capable of more than just being conditioned passively. We can develop new knowledge by reasoning about available information. Even if we do not have an existing association between the problem „387 + 465 = ?" and its solution, we can quickly reject the proposed answer „843" because we know that the sum of two odd numbers is always an even number. Even if we never heard the sentences „No Frenchman likes foie gras. Peter is a Frenchman." before, we can nonetheless draw the conclusion that „Peter dislikes foie gras". If someone is pointing at a tree and saying: „The leaves of this tree are not green but blicket," we immediately know that „blicket" denotes a colour. If we know that striped suits are worn in jails and a friend tells us: „My job is a life-sentence", we will not infer that he is wearing a striped suit at work but rather that he feels his freedom restricted.

Even though there is presently no comprehensive theory on the acquisition of skills such as reasoning or understanding analogies in cognitive science, it is definitely clear that these skills cannot solely be learned by systematic administration of rewards. Skinner's behaviouristic attempts to reduce mathematical problem solving or language acquisition to stimulus-response learning cannot be taken seriously. Admittedly, findings on stimulus-response learning are multi-faceted and also interesting; but the typically human way of learning could not be sufficiently explained thereby. In the 1960s, behaviourism has given way to the often-cited „cognitive revolution" whereafter psychologists started to focus on such types of learning that require a reorganisation of knowledge in the learner's brain. This is also the case in most school subjects where consciousness, language, symbol systems, insight and reasoning are essential.

In sum, current progress in clarifying the neurophysiological bases of stimulus-response learning also contributes to a deeper understanding of some types of human learning. Neurophysiological mechanisms underlying the phenomenon that positive consequences increase and negative consequences decrease the probability of certain behaviour may, in fact, be similar in humans and animals. But, from a scientific perspective, not only similarities but also differences between humans and animals are of interest. It does matter at the performance level whether someone has learned by insight (probably accompanied by an „AHA!" experience) or whether a rat in a cage establishes simple stimulus-response associations by negative reinforcement. If knowledge is acquired by insight, some mistakes will not recur, and this knowledge can be used to solve novel problems – even if they superficially differ from previous ones. If only mere stimulus-response associations were established, they diminish as soon as they are no longer activated (except for fear and food aversion conditioning). Hence, gaining a new insight can result in sustained reorganisation of knowledge and learning.

As cellular processes can hitherto only be investigated in animals, no conclusions on the cellular mechanisms of typically human learning can be drawn at present. As discussed in chapters 4 and 7 of this expertise, available neuroscientific methods provide a very rough picture of human brain functioning. However, we can also further our knowledge about human learning beyond neurophysiological explanations. This is discussed in the following section.

12.2 What makes human beings different: Institutionalised learning in the cultural context

Animals – and human beings as well – are permanently learning, but they do not attend school. In many respects, animals can move more efficiently than humans, but they do not invent specific types of sports. Animals make use of niches to find food but they do not cook. Animals can process quantitative information but they do not engage in mathematics. Animals communicate with each other with signals but hey do not use a syntax allowing them to build up a steadily increasing and rich language. Animals mark their territories but they do not pass down written pieces of work. Animals orientate themselves in the physical world but they do not acquire knowledge about laws of nature that drives technical development. Mankind undoubtedly has produced amazing achievements in its cultural history; but men have not left it to chance. The genetic endowment controlling our brain functions has not notably changed in the last 40,000 years, but several millenaries passed by before those cultural achievements have been developed that are nowadays parts of the school curriculum and taken for granted. The following list provides an overview of key cultural achievements:

for 5,000 years: Use of script
3,000 years: Use of mathematical symbol systems
2,200 years: Physical concept of density (Archimedes)
800 years: Arabic number system established in Europe
400 years: Analytical geometry (Descartes)
300 years: Laws of mechanics (Newton)
50 years: Structure of DNA

Mankind was not endowed with script from its very beginning; we have lived many millennia without it. The same holds true for mathematics. Even a very intelligent Roman would not have been able to solve the problem

„CIV : XXVI = ?"

because the Roman number system, which neither included decimals nor the number zero, was not designed for such complex divisions. Graphs of linear functions enabling to depict proportional concepts in different domains have been used for less than 300 years.

Current discussions in Germany predominantly focus on failures of the educational system. However, these discussions do not consider that it is actually astonishing how school manages to teach children knowledge and competencies that took centuries or millennia to evolve. Against this background, the fact that Germany does not accomplish this enormous achievement as well as other countries could be considered of minor relevance. Beyond questions such as how to facilitate learning in school, cognitively-oriented researchers on learning and instruction are also interested in a rather general question: how is it possible for students with a brain that has not notably changed in the last 40,000 years to attain the intellectual status of their culture within a few years? This can undoubtedly be attributed to the use of symbol systems such as language, script, mathematics, pictures and diagrammatic representations. Symbol systems can be regarded as mental tools that allow for the construction of meaning in concepts, ideas, or plans (Stern, 2001). Moreover, these thinking tools are being developed further and so they enable us to constantly approach new contents. This idea can also be found in *Leviathan* by Thomas Hobbes (1651), Part I, Chapter 4: „For example, a man that hath no use of Speech at all, (…) if he set before his eyes a triangle, and by it two right angles, (such as are the corners of a square figure,) he may by meditation compare and find, that the three angles of that triangle, are equall to those two right angles that stand by it. But if another triangle be shewn him different in shape from the former, he cannot know without new labour, whether the three angles of that also be equall to the same. But he that hath the use of words when he observes, that such equality was consequent, not to the length of the sides, nor to any other particular thing in this triangle; but onely to this, that the sides were straight, and the angles three; and that that was all, for which he named it a Triangle; will boldly conclude Universally, that such equality of angles is in all triangles whatsoever; and register his invention in these generall terms, Every triangle hath its three angles equall to two right angles. And thus the consequence found in one particular, comes to be registered and remembred, as an Universal rule; (…).”

Language allows the construction of meaning that goes beyond mere sensory experiences. We can talk about infinity although we are permanently confronted with limitations in our everyday life. We can prefix „in-” in order to invert the meaning of words. The term infinity can even be grasped by means of mathematical symbol systems. Numerical digit systems such as the decimal system do not have a largest number but always allow finding another number that is larger than the previous one. The argument that human beings could acquire their reasoning ability only on the basis of literacy is discussed by Olson (1996).

Investigating human learning means to engage in the acquisition and the usage of symbol systems as thinking tools to construct meaning. Although the development of script required millennia, most children have learned to read after some months in school. Even though the Arabic number system was developed only 1,200 years ago, most primary school children can divide and understand that zero is a number. The human brain is apparently endowed with resources that, if appropriate learning opportunities are available, allow using symbol systems which, in turn, can be applied as tools to broaden ones mind. In the last decades, several insights into universal mental resources in humans have been achieved. As a pioneer in this context, the famous linguist Noam Chomsky assumed that the ability for language acquisition is programmed into our genes (i.e., universally available). Thus, in the human brain a kind of universal grammar programme exists that facilitates the acquisition of any existing language. Since humans are prepared for language, they can acquire it without systematic instruction. At present, Chomsky’s assumption of a universal grammar has been challenged in linguistics (cf. Tomasello, 2003); nonetheless it remains undisputed that basic mechanisms controlling language acquisition are genetically embedded in humans.

In the last 20 years developmental psychology has investigated the competencies of babies. Of course, they cannot convey their knowledge in conversation, but their behaviour – for instance, their gaze or their grasping and sucking actions – suggests that they already know a lot about the physical and social world. In this context, it is referred to primary or privileged knowledge. For example, the ability of visual and acoustic discrimination contributes to the learning of literacy (Goswami, 2003). Humans are also well prepared for discriminating small quantities, and they learn counting almost as naturally as their mother tongue (Wynn, 1992).

Learning arithmetic or reading and writing is no problem for the majority of children. But soon after school entry it becomes evident that part of the children do not benefit from the offered learning opportunities. They do not learn to read and write, to do arithmetic, or may even experience difficulties in both subjects. It is unquestioned that – at least in some of these children – these learning impairments are caused by cortical dysfunctions rather than by environmental factors. For instance, it is a well-established finding that the phonological awareness is impaired in dyslexic children. They cannot segment the phonological structure of speech, which, however, is inevitable for learning phonetics. Likewise, it is known that an early phonological training prevents later problems in learning to read and write. The research group of Usha Goswami – one of the leading researchers on the acquisition of literacy worldwide – already looks at the brain during language processing. They could support the assumption that dyslexic children indeed do not spontaneously segment words phonologically. At the Göttingen Conference of the „Deutsche Gesellschaft für Psychologie“ (German Psychological Society) in September 2004, however, Usha Goswami emphasised that hitherto no practical implications can be derived from neurophysiological examinations.

Likewise, dyscalculia (a specific learning disability affecting the normal acquisition of arithmetic skills) may be caused by cortical dysfunctions. The research group of Stanislaus Dehaene has already uncovered basic brain functions underlying arithmetic. But it holds similarly true for dyscalculia that the largely successful training programmes that are currently available do not build on findings from brain research but rather on cognitive scientific and didactic assumptions.

Even if deviations from normal brain functions hamper the acquisition of cultural achievements in some individuals, learning disabilities are not restricted to this group. As a matter of fact, the learning goals described in the curricula are often met by only a few students. Even after 13 years of education with final university entrance diploma only a handful of students are able to compose well-structured texts in their mother tongue, not to mention in a foreign language. In mathematics and science, the majority of students have adapted a number of strategies allowing them to „muddle through”. But, as PISA reveals, they have not gained a deeper conceptual understanding that is required in solving novel problems.

Some of the well-meant advice from brain research on the improvement of school learning is justified with the notion that only the look into the brain can clarify controversial theoretical discussions in educational research. Contrary to this notion, however, there is wide agreement among researchers in the field of learning and instruction as to the framework of insightful learning in school, summarised as follows by Baumert et al. (2004):

- Insightful learning is an active individual process of construction by which knowledge structures are modified, enhanced, integrated into networks, organised in hierarchies, or newly generated. Insightful learning crucially relies on the active mental processing that is implied in any active analysis of the social or natural environment or in the use of symbol systems.
- Insightful learning means making sense of things by mastering new contexts that organise and structure knowledge. For this, the object has to have a minimum intellectual and/or practical appeal for the learner.
- Insightful learning depends on individual cognitive conditions, but mainly on prior domain-specific knowledge. The quality and ease of further learning is crucially determined by the extent and organisation of the available knowledge base.
- Insightful learning, while being highly systematic, is always situated and bound up with a specific context. Knowledge acquisition will typically occur

in a social context, and knowledge will carry the marks of the specific context in which it was acquired. The fact that knowledge is situated often results in its being constrained in its range of application. In order to enhance this range, a variation of the contexts in which knowledge is acquired and applied must be provided.

- Insightful learning is regulated by motivation and by metacognitive processes (e.g., planning, control, evaluation).
- Insightful learning is supported by certain cognitive mechanisms. These include the building of knowledge units with high informational content that can be remembered and retrieved as a whole (chunks), the emergence of which will be fostered by the use of multiple forms of knowledge representations. They also include the automation of action sequences and reasoning operations.

Findings from different research paradigms in cognitive science, developmental psychology and educational research are compatible with these assumptions. No serious researcher on learning and instruction would argue the converse. NONE of the aforementioned basic assumptions derives from brain research, and there is presently NO neuroscientific finding that would necessitate a revision of any of these statements or could refine them.

The enlisted conditions for insightful learning direct the development of efficient learning opportunities, and the teacher's task is to confront students with demands that require them to engage actively with the learning content. Moreover, students should also be offered the opportunity to activate and revise knowledge that is incompatible with the learning goal. How this can be realised in different subjects, for different learning goals and age groups, shall be developed together with researchers specialised in didactics and be evaluated in educational research. Learning formulas from „neurodidactics" do not necessarily contradict the outlined conditions of insightful learning, but they do not tell us anything about the decisive component of learning in school, viz. the knowledge structures. However, it is exactly this shortcoming that makes their advice dangerous. Successful teachers possess pedagogical content knowledge – there are no controversies about that in educational research. This means that teachers have to know how particular topics, problems, or issues are organised, represented, and adapted to meet the diverse interests and abilities of learners, and how they should be presented during instruction (Shulman, 1987). Stated differently, teachers doing a good job know how students learn certain contents. They understand their students' initial difficulties and know how to respond to these. Teacher education has to offer the opportunity to acquire this special type of knowledge.

However, it may have severe consequences if teachers simply follow well-meant „neurodidactic" advice because they are overcharged in designing content-oriented learning environments due to lacking pedagogical content knowledge. For instance, if „neurodidactics" suggests that learning should always involve concrete actions, primary school teachers who know little about mental processes in learning literacy will have the pupils bake, knead and make letters out of clay. These activities, though, cannot replace specific writing and reading exercises adjusted to the respective competence level. Valuable time of instruction in school would be wasted. Likewise, the „neurodidactic" advice to use as many visual representations as possible because humans are endowed with excellent visual memory may provoke confusion and blind and harmful actions. Instead, visual representations have to be employed at an appropriate time. Which type of picture facilitates learning under which conditions has been extensively investigated, and the obtained findings are already considered in the design of multimedia learning environments. To simply add more pictures would lead into a wrong direction.

If the German Federal Ministry of Education and Research (BMBF) aims at promoting research that improves learning in school, content-oriented research on instruction should be demanded. Researchers specialised in didactics and educational researchers should devise learning environments and plans for their dissemination in subjects that are considered important. The Sinus programme in mathematics is an example hereof.

In addition, it is reasonable to promote cooperation between educational research and neuroscience. Such collaboration could contribute to a deeper understanding of human brain functions typical for human beings, on the one hand, and obstacles in school learning, on the other hand.

13. Beyond immediate applicability: Potential research questions where cooperation of neuroscience and educational research is desirable

„If neuroimaging is the answer, what is the question?"
(Steve Kosslyn, 1999)

Interesting scientific discussions can be expected to result from an exchange between educational research and neuroscience. Already, some successful examples exist. In the field of cognitive development, which is closely linked to educational research, the acknowledgement of psychological as well as neuroscientific research has accelerated the progress of knowledge on multiple layers. This is explained in more detail in chapter 3 with the example of the scaling error. Within the next years a better understanding of typical human brain functions that are also of central importance for learning in school can be expected. Among these are processing of speech, numerical reasoning, consciousness or memory processes.

Also the neurosciences will profit from cooperation with educational research as for gaining a better understanding of typical human brain functions, learning in school downright inflicts itself as an object of investigation. Meanwhile, multitudinous conditions that either facilitate or complicate learning have been elucidated in empirical educational research. Such conditions can lie in the task itself, in the person or in the learning environment. Discovering which brain functions correlate with performance changes depending on these conditions can further our understanding of the human brain. However, concerning the design of such investigations, it has to be kept in mind that the precision of measurement of psychological methods like observation of behaviour, testing or interviewing is often higher than that of brain imaging methods. Thus, significant effects can only be expected with strong impact factors (independent variables). As a consequence, it seems advisable to initially conduct intra- and interindividual comparisons of brain activation during school learning under conditions that have already yielded large effect sizes in previous studies.

The interest of cognitively oriented educational scientists in neuroscientific methods especially originates from the aspiration to find indicators of potential difficulties or success in the brains of learning people that have not yet emerged in behaviour or achievement. Even though brain research at the moment cannot tell the characteristics of good instructional practice, in the future its methods might allow us to determine whether learning input reaches the student at all and how it is used for further development of competencies. In light of the methodological problems that are related to the recoding of brain activities, too much optimism, however, appears precipitant at present. Reliable conclusions on brain activation require the aggregation of data over different tasks and subjects. In other words, in order to make an assertion about the EEG patterns of one individual during a certain cognitive activity it is necessary to record the individual EEG (during this specific activity) several times. Hence, subjects repeatedly – sometimes 50 trials are necessary – have to perform problems of the same type. This may be particularly problematic as it has to be assumed that the type of brain activation changes with repeated confrontation with the same demand. But even after 50 measures and the aggregation of the thus acquired data, often no sufficiently reliable person parameter is achieved. Conclusions can usually be drawn only if the data of many individuals is aggregated and thus, statements that demand correlation analyses can rarely be made. However, methodological progress can be expected in the next few years which will enable significant results with few measures even at an individual level.

Despite the aforementioned present methodological limitations, there are research questions at the interface of neuroscience and educational research where new insights can be expected from looking into the human brain. Though conclusions concerning the extent and localisation of brain activities are rather vague at an individual level, also highly aggregated data can provide interesting hints. Comparing anterior and posterior cortical activation, for example, allows drawing conclusions whether a task predominantly requires the retrieval of already established knowledge (stronger activation of the posterior cortex) or the development of new solution strategies (stronger activation of the frontal brain area). From a comparison of activation in the left versus right hemisphere (in right-handers) inferences can be made whether verbal (stronger left-hemispheric activation) or visuo-spatial (stronger right-hemispheric activation) resources were employed to master a task. Together with performance data and behaviour observations these – on their own not very informative – indicators might well lead to a better understanding of human learning and thinking. In the following, ten research questions that arose during the preparation of the workshop (chapter 11) are discussed exemplarily, in which cooperation of neuroscience and research on learning and instruction might prove seminal.

13.1 Ten potential research questions

1. *What deviant brain functions do individuals with learning difficulties display?*

   Brain functions associated with dyslexia and dyscalculia are currently investigated by numerous researchers. Leading work groups in several countries have already been mentioned in previous chapters. Their research inter alia aims at the development of assessment methods for early diagnosis of potential impairments, but so far, neuroimaging methods only rarely allow more accurate predictions than those that can be made by means of performance tests and behavioural observations. However, in the foreseeable future, an increase of the diagnostic validity by including neurophysiological methods can be expected. New insights into the neurophysiological bases of impairments in learning also enable a deeper understanding of speaking, reading, writing, doing arithmetic and mathematical reasoning within the „normal range".

2. *Can sensitive periods for learning be identified?*

   While impairments in cognitive development and learning are intensively researched and increasingly understood, only little is known about ways to stimulate the cognitive development of children with good cognitive preconditions. Although the basic conditions for an undisturbed cognitive development can be scientifically described, hitherto we cannot say whether and in what ways specific competencies can be effectively fostered. On the basis of current research findings, for instance, no statements can be made concerning the question whether and when it may be sensible to administer visuo-spatial training in young children to facilitate later comprehension of geometry. Even if neurophysiological studies are still difficult to perform with children, educational researchers and neuroscientists should exchange experiences on issues of learning and early childhood development. As already exemplarily outlined for the scaling error, the different lines of research can benefit from each other.

3. *How are different types of knowledge represented in the brain and how do they change through learning?*

   From a cognitive scientific perspective, learning represents an adaptation of the knowledge structure to new demands. Cognitive psychology differentiates procedural and declarative knowledge, where the former is knowledge on how to perform some task and the latter is factual and conceptual knowledge stored in verbal or figural codes. At a gross level, knowledge can be regarded as an interconnected network which changes with each activation. Learning impacts on this network by establishing stable connections between single knowledge elements, which may result in automatisation and explication of knowledge. Automatisation means that single knowledge elements activate one another reciprocally and control behaviour without deliberate decisions by the learner. If automated knowledge is drawn upon to master a task, this can be done „by the way" so that cognitive resources are available for parallel activities. Automatisation results from repeated execution of the same activity. Once knowledge is automated, it is fairly resistant to change and may even impair coping with new demands.

   Explication means that knowledge is deliberately accessible and can be communicated by means of symbol systems (language, pictures, mathematics). Cognitive manipulations on knowledge can be performed with the aid of symbolic representations and thus, knowledge becomes increasingly flexible and can be applied to solve novel problems. In everyday life, such processes are known as „insight", „the penny has dropped", or „AHA experience". Cognitive scientific approaches to this probably most important type of learning are still unsatisfying, and we are miles away from understanding its neurophysiological foundations. Irrespectively of that, research on learning and instruction has identified several conditions which foster explication and insightful learning. We know quite well, for instance, how the collaboration of learners should be organised. Also the construction of exemplary solutions or the stimulation of analogical thinking by giving contrasting examples is fairly well investigated, and these findings are already incorporated in designing learning opportunities.

Comparing brain activity of individuals who learned in an insightful condition with those who did not, may contribute to a better understanding of comprehension. How automatisation and explication of knowledge is reflected in the brain can be investigated fairly well in second language learning and also in the acquisition of mathematical competencies.

4. *Are general brain functions trained by domain-specific learning?*

The observation that a person cannot memorise specific information – be it a multi-digit number, a new word or a definition – can be explained in various ways by referring to different scientific concepts. In educational research this would be attributed to a lack of prior knowledge to which new information can be linked. From a functional perspective, which is also adopted by brain research, it would be referred to as impairments in concentration or memory of this individual. Plainly stated, educational research would look for the deficits in the software, whereas neuroscience would concentrate on the hardware.

Results from educational research suggest that the construction of a knowledge base is the only way to improve cognitive competencies. From empirical research on learning and instruction it must clearly be advised against the intention to foster cognitive competencies in school, for example by means of brain jogging or training on cognitive methods, quasi out of touch with the content. Based on cognitive psychological theories on acquisition and application of knowledge, however, no statements on neurophysiological activation processes can be made. Whether the brain can be prepared „unspecifically" for learning, e.g., by neurofeedback (see chapter 10), cannot be explained at the level of knowledge psychology. The long-term goal of cognitive and educational science must certainly be the formulation of theories on acquisition, representation and application of knowledge in a way that they directly tie in with neuroscientific theories. This requires interdisciplinary exchange.

5. *How does memory consolidation take place in favourable and less favourable conditions?*

Although school as well as the extracurricular environment continuously offer learning opportunities the selected learning goals, however, can frequently not be achieved or only with delay. The process of forgetting often occurs so fast that there is no lasting learning effect. Stated differently, the consolidation of acquired knowledge is often suboptimal. One potential reason for this may be knowledge interference. New incoming information prevents the consolidation of recently acquired information. Hence, the learning process may have been optimised by a resting period at due time. The importance of sleep as a consolidation processes begins to become evident in neuroscientific research which is also of great interest for designing self-organised learning. Neuroscientific studies frequently administer artificial learning material such as meaningless syllables, but it is worth investigating whether school-relevant material such as English vocabularies could be presented instead. Experimentally controlled variations in school learning virtually call for the investigation of consolidation processes.

6. *What error processing mechanisms exist and how do they influence the learning process?*

   A learning process always begins with an error: A task cannot be mastered or can only be coped with inadequately; thus, errors originate. Processing error feedback is an essential part of learning, and from learning research it is known that there are large individual differences. There is great need for research on errors in school learning. At present, it is only rudimentarily clarified under what conditions it may be beneficial for the learning process of students to permit making errors, and where errors should be prevented because they would negatively impact on further learning. The reflection of productive and less productive error processing strategies in the learners' brains is of great interest for research on learning and instruction.

7. *Can individual differences in the efficiency of brain functions be compensated at the level of cognitive information processing?*

   Expertise research, research on cognitive development in childhood, and research on performance development in school have revealed that a well-structured and elaborate knowledge base is a necessary and sufficient condition for cognitive achievement. When prior knowledge is included as a predictor, individual differences in intelligence lose importance in the explanation of performance differences. Of course, these findings in no way dispute the existence of individual differences in intelligence. It is unchallenged that performance differences reflected in intelligence tests derive from the efficiency of brain functions which, in turn, are partly of genetic origin. But, even though no influences of intelligence differences emerge at the performance level in individuals with sufficient prior knowledge, more and less intelligent persons could differ in cortical information processing. Looking into the brains of variably intelligent individuals whilst solving problems from domains in which they possess rich knowledge can provide interesting findings on the neural bases of individual intelligence differences.

8. *Can differences in learning trajectories be traced back to differences in cortical information processing?*

   Successful learning is reflected in performance increases; a task which could not be mastered before can now be mastered. The required time for successful learning can vary strongly. A single learning trial could be enough to reach the target, but it is also possible that only persistent engagement in the subject accompanied by many setbacks eventually leads to success. Educational research distinguishes learning and performance because it is assumed that during the learning process fundamental changes in the knowledge structure occur, even before the performance criterion is attained. Even if, for instance, an abrupt performance increase is observed in the wake of an

„AHA" experience, learning took place beforehand. However, the differentiation between performance and learning is a purely theoretical one, as long as performance is the only indicator of learning. It may work sometimes, with considerable effort, to identify precursors of a successful learning process, but this requires a very intensive and time-demanding examination of the respective content domain. It would be of exceptional benefit for educational research if indicators of successful learning were found before the performance criterion is attained.

9. *Can different cortical activation patterns depending on the problem format be found?*

   Several studies from fields such as logic, mathematics and science education have shown that the difficulty of in form similar problems strongly varies depending on the context and the situation. This, for instance, is the case with arithmetic word problems. As a possible explanation it is assumed that, in contexts in which numbers are regarded as counting tools, privileged numerical concepts can be drawn upon. Problems with natural frequencies are also notably easier to solve than probability problems. Intraindividual differences in brain activation patterns depending on the problem format could, in many respects, shed light on the functioning of the human brain. As very large discrepancies in solving problems of different formats are observable at the performance level, such differences should also be reflected at the level of brain activation.

10. *How do brain functions change in dependence on learning environments?*

    There are several different options regarding the design and presentation of learning material, e.g., with respect to the question for an integration of pictures and text. In light of an optimal individual use of working memory, particularly the design of computer-aided learning environments is discussed in educational research. In particular starting from Baddeley's working memory model (see chapter 6), it is being investigated how visually and auditorily presented information may complement each other. Looking into the individual brains in a learning environment designed according to cognitive scientific principles, may elucidate whether the theoretical assumptions considered in its construction have merit. Computer-aided learning environments can be designed in a way that several neuroimaging methods can be applied.

13.2 Final review and recommendations for research support

Although it cannot be expected in the near-term that school learning can be optimised with the help of brain research, it can be assumed that its methods will contribute to a deeper understanding of certain aspects of school related learning sometime in the future. In turn, findings and paradigms from educational research can contribute to insights into brain functions typical for human beings. Foundations for interdisciplinary discussions should be laid to allow the development of interesting and feasible research questions. At present, it appears to be a reasonable claim to include as many interested scientists from different disciplines in the discussion as possible. Findings and paradigms from different lines of research should be presented in interdisciplinary workshops, and, based on this, promising research questions can be specified and evaluated with respect to their feasibility.

Precisely, this may look as follows: At least one educational researcher and one neuroscientist apply at the BMBF for funding to organise a workshop, to which national and international researchers are invited. At this workshop concrete research designs should be planned and collaborations should be established. The workshop will be announced in due time on the homepage so that other researchers can also request for participation.

Following such a workshop, research grants for concrete studies can be applied for. These studies should be designed in a way that a publication in an international journal with a peer-review system can be submitted at the end of the project. The acceptance of follow-up applications primarily depends on the quality of the journal publication.

All disciplines involved in the BMBF research programme „Thought Processes" should be invited to devise research questions and approaches that overcome current limitations. Hence, the research questions outlined in chapter 13.1 not only constitute a coherent research programme; they also initiate a dynamic research process in which all parties involved need to turn to new developments within their respective domains, to discuss and to expand them further.

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Appendix

A1: Questionnaire „Educational research from a neuroscientific perspective“

In preparation for this workshop all participants were asked to submit proposals for valuable and promising research projects which employ neuroscientific methods to gain deeper insight into educational research questions.

Questionnaire

Please respond to the questions in the file which you will soon receive per e-mail.

Name:

Question 1: I can participate in the workshop on November 19th-20th (please mark with a cross)

Yes ☐ No ☐

Question 2: What does your desired research project look like?

Imagine you could spend a great amount of research money on any innovative project (with a maximum duration of 5 years) which has to keep to the following rules:

1. The participants are presented school-relevant tasks related to mathematics, science, verbal or written mother-tongue, or foreign languages. (The domain of music and arts shall presently remain unattended to as it will be focused on in a subsequent project.)
2. Cognitive-scientific concepts must be drawn on to explain competencies in the aforementioned fields (e.g., working memory, automatisation, conceptualisation, implicit/explicit knowledge, inert knowledge, transfer, intelligence, attention). These cognitive scientific concepts may also be correlated with other psychological constructs (e.g., emotion and motivation).
3. Besides obtaining variables by means of psychological methods (interview, observation of behaviour, performance tests), neurophysiological methods (e.g., EEG, PET, fMRI) must also be applied. Moreover, the relationship between psychological and neurophysiological variables must be specified.

The choice of experimental design is completely up to you. For instance, you may vary specific aspects of your tasks in experimental studies or you may expose participants to different learning conditions in experimental training studies. In quasi-experimental studies you may investigate psychological and neurophysiological variables depending on the individual’s learning history (e.g., quality of instruction) and/or personality traits (e.g., intelligence). In longitudinal studies you may examine questions of interindividual variability and stability, and in microgenetic studies you can investigate developmental trajectories. You may even merge different designs as long as you have a plausible research question which requires such a combination. In planning you may suppose that you have all required resources (co-workers, assistants, equipment).

You are welcome to plan projects conjointly with the colleagues on the list. If you would like to call in further colleagues who are not on the list, I would ask you to consult me beforehand as my travel fund is limited.

Regarding the selection of participants you should not limit your sample to students and teachers. As long as it is referred to competencies acquired in school, everything is allowed. You may conduct studies on precursor abilities in toddlers and babies as well as on impacts of learning history in school on adults. You do not even have to limit your research on human beings if you can account that precursor abilities of higher-order cognitive competencies can be investigated especially well in animals.

Please describe (in another colour) your desired project as briefly as possible, following the headlines listed below. Finally, I request you to state at which points you can draw on your own research experience and where you would appreciate collaboration with other experts.

- Research question
- School-related content and type of cognitive demand
- Involved psychological concepts
- Participants
- Desired neurophysiological method
- Design
- Expected results

Enjoy planning without financial or temporal limitations but with strong content orientation!

Question 3: Are there any published or unpublished papers in which part of your desired research project has already been realised? Please include them in the attachment or place a link.

A2: Participants of the workshop

The following researchers participated in the workshop „Educational research from a neuroscientific perspective" from November 19^{th} to 20^{th}, 2004 in Berlin.

Name, First Name Title	**Department**	**Institute / University**
Ansari, Daniel Prof. Dr.	Department of Education	Dartmouth College
Bösel, Rainer M. Prof. Dr.	Department of Psychology	Freie Universität Berlin
Buchaas-Birkholz, Dorothee Dr.		Federal Ministry of Education and Research
Buchholz, Christiane		Federal Ministry of Education and Research
Dorlöchter, Marlies PD Dr.	Project Management Organisation of BMBF in DLR (PT-DLR) – Health research	German Aerospace Centre
Euler, Manfred Prof. Dr.	Department of Physics Didactic	Leibniz Institute for Science Education (IPN)
Falkenstein, Michael PD Dr.	Cognitive Neurophysiology	Institute for Occupational Physiology at the University of Dortmund
Felbrich, Anja	Department of General Education and Instructional Research	Humboldt-University of Berlin
Fickermann, Detlef		Federal Ministry of Education and Research
Frith , Uta Prof. Dr.	Institute of Cognitive Neuroscience and Department of Psychology	University College London
Grabner, Roland H. Mag.	Department of Psychology	University of Graz
Hardy, Ilonca Dr.	Center for Educational Research	Max Planck Institute for Human Development
Herz, Andreas Prof. Dr.	Institute for Theoretical Biology	Humboldt-University of Berlin
Hüther, Gerald Prof. Dr.	Department of Psychiatry and Psychotherapy	Georg-August-University of Göttingen
Indefrey, Peter Dr.	Acquisition/Dynamics of Multilingualism	Max Planck Institute for Psycholinguistics
Jacobs, Arthur M. Prof. Dr.	Department of Cognitive Psychology	Freie Universität Berlin
Klann-Delius, Gisela Prof. Dr.	Department of Philosophy and Humanities	Freie Universität Berlin
Körndle, Hermann Prof. Dr.	Department of Psychology IV	Dresden University of Technology
Li, Shu-Chen Dr.	Center for Lifespan Psychology	Max Planck Institute for Human Development
Lindenberger, Ulman Prof. Dr.	Center for Lifespan Psychology	Max Planck Institute for Human Development

Name, First Name Title	**Department**	**Institute / University**
Martignon, Laura F. Prof. Dr.	Department of Mathematics and Informatics	University of Education Ludwigsburg
Narciss, Susanne Dr.	Department of Psychology IV	Dresden University of Technology
Neubauer, Aljoscha C. Prof. Dr.	Department of Psychology	University of Graz
Neuper, Christa Dr.	Department of Psychology	University of Graz
Ohl, Frank Dr.	Department of Auditory Plasticity and Speech	Leibniz-Institute for Neurobiology
Palm, Günther Prof. Dr.	Department of Neural Information Processing	University of Ulm
Plötzner, Rolf Prof. Dr.	Department of Media Didactic	University of Education Freiburg
Rösler, Frank Prof. Dr.	Department of Psychology Section of Cognitive Psychophysiology	Philipps-University-Marburg
Saalbach, Henrik	Center for Educational Research	Max Planck Institute for Human Development
Saniter, Andreas Dr.	Department of Physics Didactic	University of Bremen
Scheich, Henning Prof. Dr.	Department of Auditory Plasticity and Speech	Leibniz-Institute for Neurobiology
Schumacher, Ralph PD Dr.	Department of Philosophy	Humboldt-University of Berlin
Stern, Elsbeth Prof. Dr.	Center for Educational Research	Max Planck Institute for Human Development
von Aufschnaiter, Claudia Prof. Dr.	Department of Science Didactic	University of Hannover
von Aufschnaiter, Stefan Prof. Dr.	Department of Science Didactic	University of Bremen
Guests		
Schneider, Michael	Center for Educational Research	Max Planck Institute for Human Development
Rötger, Antonia	Center for Educational Research	Max Planck Institute for Human Development
Cierniak, Gabriele		University of Koblenz-Landau

The following researchers could not participate in the workshop but submitted research proposals: Niels Birbaumer, Prof. Dr., University of Tübingen; Onur Güntürkün, Prof. Dr., University of Bochum; Andrea Rodenbeck, PD. Dr., University Göttingen; Wolf Singer, Prof. Dr., Max Planck Institute for Brain Research

A3: Programme of the workshop

Friday, November 19th, 2004	
11.00 – 12.00 am	Elsbeth Stern: • Address of welcome and introduction of the participants • Brief introductory lecture: „Is talking of brain-suitable learning reasonable?” Lecture Ralph Schumacher: „What are the relations between explanations from neuroscience, psychology and pedagogy? Considerations on the problem of theory reduction.”
12.00 am – 1.00 pm	Lecture Uta Frith: „How the brain learns“ *Discussion topic:* What are educational researchers looking for in the brain and what can they find?
1.00 – 2.00 pm	Lunch in Hotel Henriette
2.00 – 3.15 pm	**Motivation and emotion at a neuronal level and their impact on learning in school** Lecture Henning Scheich: „Dopamine mechanisms and success-oriented learning“ *Discussion topics:* Consequences on the design of learning opportunities, with special focus on feedback. Do any neurophysiologically determinable emotional/motivational states exist which facilitate or inhibit learning? *Statements are requested from:* Michael Falkenstein, Gerald Hüther, Hermann Körndle, Günther Palm, Frank Rösler
3.15 – 4.00 pm	**At what point does the brain say „no“? Aspects of short and long-term plasticity** Short lecture by Elsbeth Stern and Henrik Saalbach: Brain Development: Chances and limitations for learning *Statements are requested from:* Daniel Ansari, Uta Frith, Gerald Hüther, Ulman Lindenberger, Aljoscha Neubauer
4.00 – 4.30 pm	Coffee break
4.30 – 7.00 pm	**Knowledge acquisition and application in school-relevant fields (first language, foreign languages, mathematics, science)** *Discussion topic:* Will education researches find what they are looking for in the brain? Short lecture Elsbeth Stern *Statements are requested from:* Rainer Bösel, Michael Falkenstein, Shu-Chen Li, Ulman Lindenberger, Frank Ohl, Günther Palm, Frank Rösler Short lecture Elsbeth Stern: „Findings from educational research on the acquisition of intelligent knowledge in central school subjects”

	Continuation: The development and interaction of different forms of knowledge (implicit, explicit, procedural, conceptual, declarative) are discussed as well as causes and handling of mistakes. Short lecture Roland Grabner: Overview of the submitted research proposals on learning in languages, science and mathematics Supplementary statements from a didactic perspective are requested from: Ilonca Hardy, Peter Indefrey (foreign languages); Anja Felbrich, Laura Martignon, (mathematics); Stefan von Aufschnaiter, Manfred Euler (physics) *Supplementary statements about research on learning impairments are requested from:* Uta Frith, Arthur Jacobs (dyslexia); Daniel Ansari (dyscalculia)
8.00 pm onwards	Dinner
Saturday, November 20th, 2004	
9.00 – 9.45 am	Continuation: Acquisition and application of knowledge in school-relevant subjects
9.45 – 11.15 am	**Can the brain be unspecifically prepared for learning?** Lecture Christa Neuper: „The applicability of modern neurofeedback technology in educational research" *Discussion topic:* Application in school learning Short lecture Roland Grabner: Overview of the submitted research proposals on efficient learning and design of learning environments *Statements are requested from:* Daniel Ansari, Rainer Bösel, Michael Falkenstein, Ulman Lindenberger, Aljoscha Neubauer, Frank Rösler
11.15 – 11.30 am	Coffee break
11.30 am – 1.00 pm	**Brain research and multimedia learning** Lecture Rolf Plötzner: „Trends and questions of research on multimedia learning" *Discussion topics:* 1. Multimedia learning in central school subjects *Statements are requested from:* Peter Indefrey (foreign languages); Laura Martignon (mathematics); Claudia von Aufschnaiter, Andreas Saniter (physics) 2. Are multimedia environments especially suitable for neurophysiological research? *Statements are requested from:* Uta Frith, Gerald Hüther, Arthur Jacobs, Susanne Narciss, Frank Rösler
1.30 – 2.30 pm	Lunch in Hotel Henriette
2.30 – 3.30	Final discussion

A4: Workshop materials

The following questions were presented to participants in order to encourage discussions:

Questions:

I. Regarding which aspects do results of brain research require a „rethinking" in educational research?
   1. Where do findings from brain research suggest that learning can be facilitated in a way which has hitherto not been considered in educational research?
   2. Does brain research already provide any hints that school learning can NOT be supported in a way educational research (not school practice) has assumed?

II. Are neuroscientific methods at all suitable for empirically testing theories from research on learning and instruction?
   1. Can we gain insights by means of neuroscientific methods that go beyond what we can assess with observation of behaviour, interviewing or performance testing? What are brain researchers looking for in the brain?
   2. What are brain researchers finding in the brain?
      a. Which neurophysiological methods are appropriate?
      b. What kind of stimulus material can be employed in neurophysiological studies?
   3. Which neurophysiological characteristics can be regarded as correlates of psychological processes (cognitive, emotional, motivational)?
      a. Which neurophysiological characteristics are – to our present knowledge – not related to psychological processes?
      b. For which psychological constructs involved in learning have we not been able to find neurophysiological correlates yet?

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Ever since modern imaging techniques have permitted us to gain insight into the neuro-physiological processes of information processing in the human brain, scientists as well as lay persons give in to the fascination of images of the thinking and learning brain. But the findings of neuro-physiological research in learning and instruction so far hardly allow for unequivocal interpretations. Conclusions to be drawn, if any, are on a very general level and, unfortunately, too often foster the belief that the results of brain research could provide an easy opening for, e.g., improvements in academic learning.

Beyond these immediate practical uses of the findings of neuro-physiological research, however, the time indeed has come to approach the question of how the methods of brain research may help us to come to a better understanding of the processes of teaching and learning.

Therefore, the authors of this report have compiled the relevant studies and paradigms of neuro-physiological research, using them as a basis for developing promisiong research perspectives.