# A cognitive neuroscience perspective on learning and memory in aging

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**Abstract.** Learning is intrinsically related to forming long lasting memories. The last decades have seen an explosion in research related to how memories are formed, how they are processed and what their underlying neural substrates are. One of the most noticeable changes associated with aging is a decline in learning and memory abilities. Although there is now a wealth of publications in this area of research, it is nevertheless surprising how much is still unknown about the processes of high level learning in the elderly from a neuroscience perspective. This paper summarizes research from predominantly cognitive neuroscience that focuses on the relation between neural substrates and learning and memory in the *healthy elderly* (roughly as of 50 years of age). In this context, particular emphasis will be given to research on foreign language learning.

Lernen ist unabdingbar mit der Bildung bleibender Erinnerungen verbunden. Die letzten Jahrzehnte haben einen explosionsartigen Anstieg von Publikationen in der Lern- und Gedächtnisforschung erfahren, vor allem hinsichtlich der Bildung, Verarbeitung und Speicherung von Gedächtnisinhalten sowie den zugrundeliegenden neuronalen Substraten. Zu den auffälligsten Veränderungen im Alter gehört ein Leistungsabfall hinsichtlich bestimmter Aspekte des Lernens und des Erinnerungsvermögens. Umso erstaunlicher ist es daher, dass trotz der Fülle der Arbeiten im Bereich der Lern- und Gedächtnisforschung kaum neurowissenschaftliche Untersuchungen über komplexe Formen des Lernens bei gesunden älteren Menschen existieren. Der vorliegende Beitrag gibt einen Überblick über Forschungsergebnisse der kognitiven Neurowissenschaften mit besonderem Fokus auf die Beziehung zwischen neuronalen Substraten und Lernen und Gedächtnis bei *gesunden älteren* Menschen. Dabei wird der Forschung zum Fremdsprachenerwerb besondere Aufmerksamkeit gewidmet.

**Schlagwörter:** brain, neural substrates, learning, memory, L1, L2, aging, cognitive fitness, Gehirn, neuronale Substrate, Lernen, Gedächtnis, L1, L2, Altern, kognitive Fitness.

## 1. Introduction

From the day we are born – and even before – our brain is ready to learn. Experiences are captured and stored and memories are created. Learning is thus intrinsically related to forming long lasting memories. Although most of us do not remember things that happened in early childhood, it is nevertheless astonishing how many new memories we can form and store, how many early and recent memories we can consciously recall, and how memories become so automatized that we do not even realize they exist unless we fail to activate them. One of the most noticeable cognitive changes in aging is a decline in learning and memory abilities, and it is not always easy to draw a line between what is still normal age-related decline and what is pathological. With the increasing number of old people in the population and the increase in life expectancy, society is more and more challenged and confronted with the health consequences these changes entail such as the growing number of people who develop dementia. This situation has led to a vast effort to elucidate the processes underlying aging and especially the

neurophysiological bases. The large number of literature that has accumulated on the topic makes it necessary to clearly focus this paper. *The objective of this paper is to summarize research from predominantly cognitive neuroscience that focuses on the relation between neural substrates and learning and memory in the healthy elderly.* What are the cerebral mechanisms underlying cognitive changes in aging? To what degree can we influence these cognitive changes and cerebral mechanisms, and does our current knowledge provide guidance for action? Although the term "elderly" has been defined as a chronological age of 65 years old or older, much of the research on the elderly includes people as of 50 years of age. In the context of this paper I will thus include research that refers to this age group. I will first present a summary of the main findings which is subsequently followed by a more detailed description of the concepts, theories and illustrative experimental work on which these findings are based. I will conclude with suggestions for future directions.

## 2. What neuroscience tells us about learning and memory in aging: a summary

For learning to occur we must be able to store and retrieve information. This information is organized in various memory systems. The most common taxonomy distinguishes long-term memory from working memory. Long-term memory, in turn, has been subdivided into memory for facts and events (declarative memory) and memory for skills (procedural memory). It is important to note that the memory systems are not separate entities but are viewed as interactive systems that work in a complementary and competitive fashion. Most cognitive systems -- including language -- rely on declarative and procedural memory. The mental lexicon has been associated with declarative memory and the mental grammar with procedural memory. Neuroscience supports this distinction as different neural substrates and circuits have been identified for the various memory systems. At a molecular level, learning has been related to changes in the strength of synaptic connections (synaptic plasticity) and to the formation of new neurons (neurogenesis) in specific brain regions. And at a biochemical level, specific neurotransmitters (e.g., dopamine, serotonin), proteins (e.g., BDNF) and hormones (e.g., estrogens) have been shown to exert modulating effects on the operations of memory systems.

Aging affects the brain in various ways and at different levels. At a macroscopic level we can observe shrinkage of the brain (i.e. brain atrophy). At a microscopic level this has been associated with a decrease in the density of white matter pathways, a decrease in neuron size and density and changes at the biochemical level. These changes occur in different brain regions and to different degrees. Most affected are regions in the prefrontal cortex, a brain region that is heavily connected to other brain areas and involved in planning, organization, decision making and integration processes. The prefrontal cortex also plays a role in aspects of memory such as retrieval processes and functions of working memory.

In addition to these neurophysiological changes, age-related cognitive changes have also been observed. These changes are not uniform but show mostly disproportional effects. Most affected are processing speed, working memory functions, certain aspects of long-term memory and executive control processes. Other aspects of memory as well as verbal and emotion processes are less affected until very late in life. Importantly, there is no one-to-one correspondence between changes at the neurophysiological and cognitive level. Further, substantial differences in the individual cognitive performance of the elderly have been described despite similar observed "pathological" changes in the brain. To account for this phenomenon, various suggestions have been advanced. One suggestion is that some elderly individuals have more cognitive reserve than others and are thus in a better position to cope with brain pathology. Another hypothesis proposes that in response to challenge the brain develops or recruits an initial set of neural circuits – so-called scaffolds – that are widely dispersed in the brain. With perfection, the network is optimized and turns into more efficient and perfect neural circuitry. While cognitive reserve has been applied specifically to the aging brain, it is assumed that scaffolding occurs throughout a lifespan and gains importance in aging.

Both the cognitive reserve and the scaffolding hypothesis rely on the brain's ability for reorganization. There is now ample evidence for such structural, functional and cognitive plasticity not only in children and young adults but throughout a lifespan and until late in life. Neuroscience has provided evidence for practice-related changes in the human brain. This evidence is mostly based on studies using various neuroimaging techniques (for a brief introduction to these techniques see, for example, Rodden & Stemmer 2008). These techniques have allowed

researchers to identify patterns of brain activation from which activation maps are created. (Note that activation refers here to structural as well as functional changes in the brain.) It is assumed that these maps reflect brain regions that are involved in specific tasks and cognitive functions. If the brain is affected by, for example, trauma, disease or some other challenge (such as novel learning), the patterns of activation may change. These changes in the patterns of activation have been discussed in terms of reorganization and redistribution. Most of the neuroimaging evidence comes from studies with young healthy adults or elderly people whose brain has been affected by disease (e.g., dementia, stroke, traumatic brain injury). Unfortunately, there are only a few studies that investigate the cerebral substrates that underlie the processes of learning across a lifespan, and especially across different age ranges in the elderly. Nevertheless, and importantly, scientific evidence shows the capability of the elderly brain for plasticity until late in life.

Although neuroimaging studies have provided a wealth of information concerning cerebral structures and networks that are implicated in cognitive task performance, there is a profound lack of studies investigating the *processes of learning in relation to cerebral mechanisms in the elderly*. This situation is exacerbated when looking at the literature concerning foreign language learning. While numerous neuroimaging studies have investigated young adults, there is currently no published study the author is aware of that investigates the process of foreign language learning in relation to cerebral mechanisms in the elderly. In young adults neuroimaging studies have focused on evidence or counter-evidence for the critical period hypothesis or for the involvement of the left or right hemisphere in second or foreign language (L2) acquisition. Neuroimaging has also been used to elucidate to what degree speaker characteristics are related to L2 acquisition or whether specific language phenomena are processed differently in the native language (L1).

Generally, when comparing *groups* of L2 or bilingual speakers with L1 speakers using hemodynamic imaging methods (functional magnetic resonance imaging, fMRI, or positron emission tomography, PET), no difference between L1 and L2 processing in terms of brain activation has been found. The few studies that reported group differences observed an association between the strength (but not the location) of brain activation and speaker characteristics such as L2 onset, L2 proficiency and L2 exposure. Note, however, that these are results from group data and not individual learners. We can thus not exclude (in fact, it is rather likely) that there are differences at an individual level. Neuroimaging methods based on psychophysiological techniques (e.g., EEG and event-related potentials, ERPs) have shown discrepant results in young adult learners concerning the attainment of L1-like processing of specific language phenomena. There are currently no studies exploring the neural underpinnings involved in the process of L2 learning in the elderly. There is also a lack of studies focusing on the effects of L2 practice and L2 teaching and learning techniques on cerebral mechanisms, and this applies to young adults as well as to older learners.

More research findings are available that concern the maintenance and enhancement of general cognitive abilities in the elderly. This research has associated education, social engagement and continuous mental and physical activity with beneficial effects on cognitive functions, changed brain structures and delayed onset or resilience for dementia in aging. Acute and chronic stress have been identified as negative modifiers for learning and memory, which, in turn, have been associated with specific changes in brain structures in the young as well as the old.
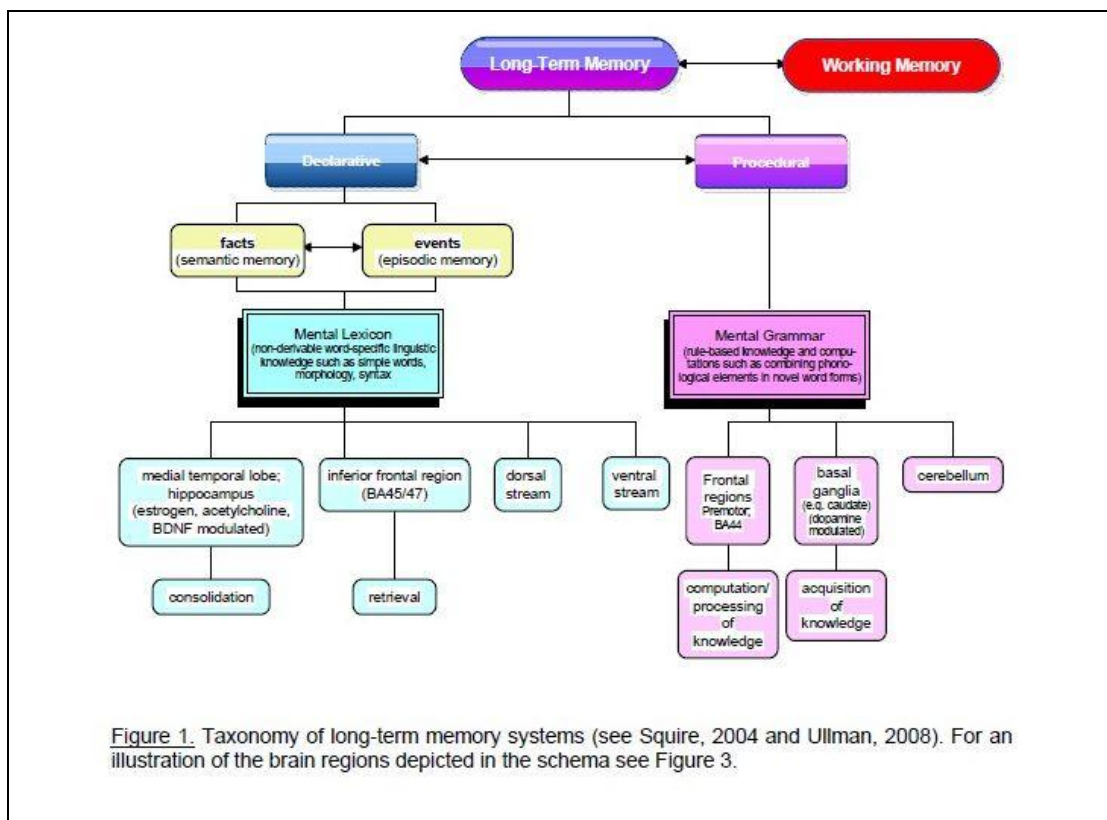
After having set the general framework, in what follows I will return to the claims made previously and provide more details on the concepts, theories and experimental research.

## 3. Learning means forming lasting memories

Although there is still controversy about the number of different memory systems, most researchers agree that there are biologically and functionally dissociable memory systems, and this is supported by neuroscience evidence. Another area of controversy relates to the development of the memory systems. While there is currently little evidence from neuroscience for the view that the multiple memory systems of adults mature at different rates during infancy, there is some evidence that this may be the case for procedural but not declarative memory. There are, however, also researchers who question these views altogether (Rovee-Collier & Cuevas 2009 and the collection of articles in Oakes & Bauer 2007).

**3.1 The classification of memory systems**

There are different classification systems of memory depending on whether the focus is on the time dimension or the processing and storage dimension. For example, when taking a time perspective the focus can be on the duration of time the information is stored (long-term versus short-term memory) or on the temporal direction (prospective versus retrospective memory). A very common distinction is long-term versus short-term memory, or working memory (Figure 1). Working memory can be viewed as an extension of the classical concept of short term memory and refers to storage and manipulation of information for a brief period of time (Figure 2) (e.g., when calculating 12 x 14 or keeping a phone number in mind until it is dialed). (For a summary on memory systems see Baddeley 2003a, b; Eichenbaum & Cohen 2001; Eichenbaum 2004, 2006; Squire 2004, 2007). Within the long-term memory system declarative memory is distinguished from non-declarative or procedural memory. Declarative (or explicit) memory refers to memories for facts (objects, people, places) and events and requires predominantly conscious recall. Memory for facts, that is information remembered independently of context (e.g., there are 16 German provinces), has also been referred to as semantic memory whereas memory for events, that is information specifically tied to personal experiences and context (e.g., my first theatre performance), has also been called episodic memory. While declarative memory is associated with learning facts and events, procedural (non-declarative or implicit) memory is involved in learning perceptual and motor skills (e.g., learning to walk or juggle) and usually does not rely on conscious recall. It is important to note that the memory systems are not strictly separate and may interact in a cooperative or competitive fashion. To some degree the memory systems may also be redundant – if one system is impaired the other system may partially compensate for the impaired system. In the context of the language system, Ullman (2008) has shown that disorders that affect language can also be characterized by disorders of the two long-term memory systems. It has been suggested that declarative and procedural memory systems play similar functional roles across language and non-language domains. Ullman (2004, 2008) has claimed that lexical memory depends largely on the declarative memory system, whereas aspects of grammar depend on the procedural memory system. Although some of the neuroimaging literature supports this view, critical voices have also been raised (e.g., MacWhinney 2005).



Figure 1. Taxonomy of long-term memory systems (see Squire, 2004 and Ullman, 2008). For an illustration of the brain regions depicted in the schema see Figure 3.

For learning to be successful information must be encoded, transferred and stored in these various memory systems. In addition, information must also be retrievable from these systems. Failure at any of these stages can thus lead to unsuccessful learning.



Figure 2. The frontal lobe systems involved in working memory (see Baddeley 2003a,b; Squire 2004).
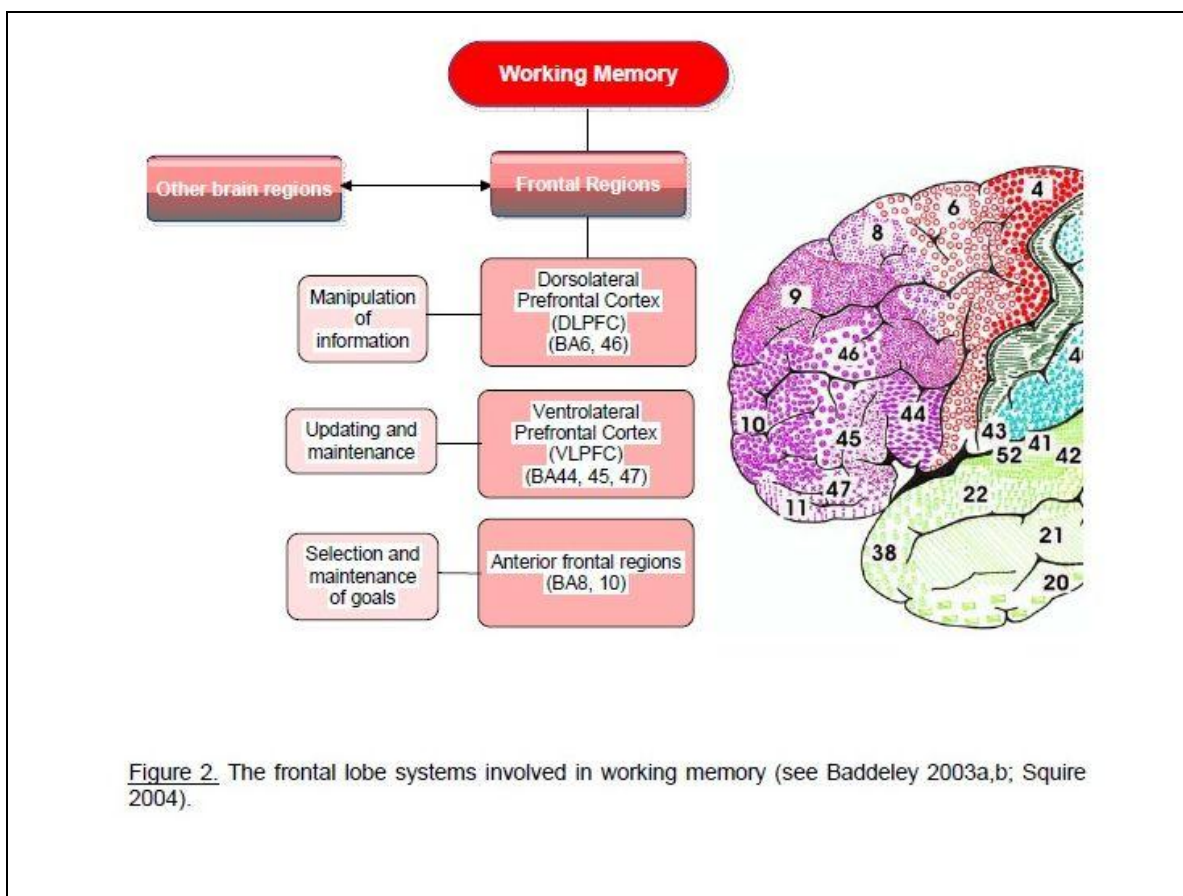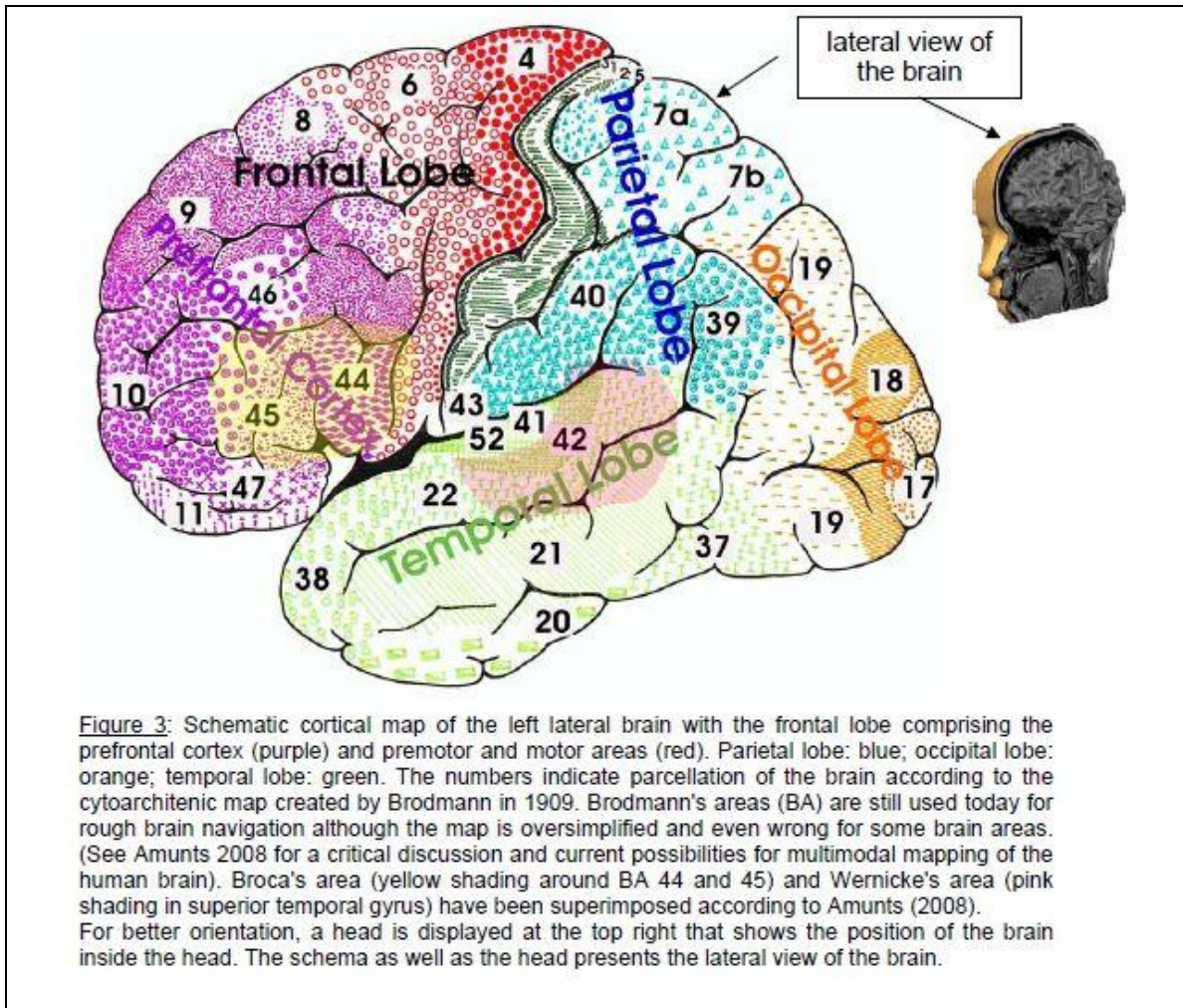
## 3.2 Neural substrates involved in memory systems

Strong support for the view that different memory systems indeed exist comes from studies showing the involvement of different neural substrates in different memory systems (Figure 1 and 2). Declarative memory has been associated with neural substrates housed deep in the medial temporal lobe (hippocampus, dentate gyrus and subicular complex, entorhinal, periorhinal and parahippocampal cortices) (see Figure 3 for an overview of the brain and Figure 5 for hippocampal structures). The hippocampal formation is an important relay station where information from different sensory systems meets, where information is sorted and associated with emotions and memories, and where information is connected to and permanently stored in other brain regions. It is here that traces of memories are laid down and new synapses and connections between neurons are formed. If the hippocampal formation is impaired or lesioned (like in Alzheimer's disease or the famous patient H.M. whose hippocampus was surgically removed) no new memories can be formed and learning is impaired or even impossible.

Procedural memory depends on neural substrates in the basal ganglia, the cerebellum, the neocortex (specifically frontal regions including premotor areas and Brodman's area 44) and the ventral stream (Figures 3, 4 and 5). If these neural substrates are impaired or lesioned (like the basal ganglia in Parkinson's disease) motor problems can, for example, ensue. Although it is assumed that the cerebral substrates involved in the various components of working memory are widely distributed and also involve the parietal cortex, the frontal cortex is particularly

important as it is involved in functions related to executive control. Different areas of the frontal lobes have been associated with various working memory functions. For example, while it seems that the "upper" (dorsal) parts of the prefrontal cortex (i.e., DLPFC; BA 6, 46) are involved in the active and selective manipulation of information in working memory, the "lower" (ventral) parts (VLPFC; BA 44,45.47) seem to support updating and maintenance of working memory contents (Figure 2). The anterior parts of the frontal cortex (BA 8, 10) have been related to the active selection and maintenance of goals and processes (Baddeley 2003a, b). Although we have emphasized here specific brain regions in relation to memory systems, it should not be forgotten that it is the connection of and interaction between these brain regions that make up memories.



Figure 3: Schematic cortical map of the left lateral brain with the frontal lobe comprising the prefrontal cortex (purple) and premotor and motor areas (red). Parietal lobe: blue; occipital lobe: orange; temporal lobe: green. The numbers indicate parcellation of the brain according to the cytoarchitenic map created by Brodmann in 1909. Brodmann's areas (BA) are still used today for rough brain navigation although the map is oversimplified and even wrong for some brain areas. (See Amunts 2008 for a critical discussion and current possibilities for multimodal mapping of the human brain). Broca's area (yellow shading around BA 44 and 45) and Wernicke's area (pink shading in superior temporal gyrus) have been superimposed according to Amunts (2008). For better orientation, a head is displayed at the top right that shows the position of the brain inside the head. The schema as well as the head presents the lateral view of the brain.

The reader is encouraged to view an anatomical section of the lateral brain in more detail and interactively at: http://teaching.thehumanbrain.info/projekte/atlanten/sagittal/.

### 3.3 The molecular level of learning and memory

So far we have related learning and memory to brain regions at an anatomical, macroscopic level. But what exactly happens at a microscopic level in the brain when we learn? Since the seminal work of Eric Kandel and his colleagues (e.g., Kandel 2001; Kandel & O'Dell 1992) it is generally acknowledged that learning is the result of changes in the strength of connections between interconnected cells. Information travels from one nerve cell (neuron) to another through projections (axons and dendrites). The terminal of these projections form specialized

junctions – so-called synapses – through which neurons signal to each other. Change in the strength of the synaptic connections characterizes synaptic plasticity. The strengthening (or "potentiation") of the connection between neurons that lasts for minutes, hours, days, months or longer is called long-term potentiation (LTP) and the weakening of the connections is called long-term depression (LTD). LTP and LTD are considered basic biological models for learning, information storage and forgetting. (For a summary of the molecular mechanisms of memory storage see Kandel 2001).
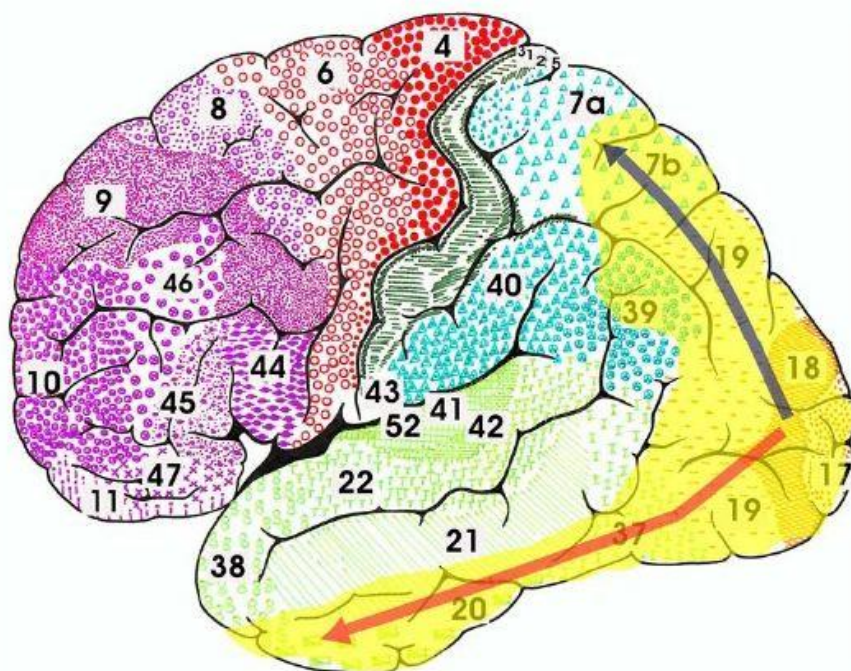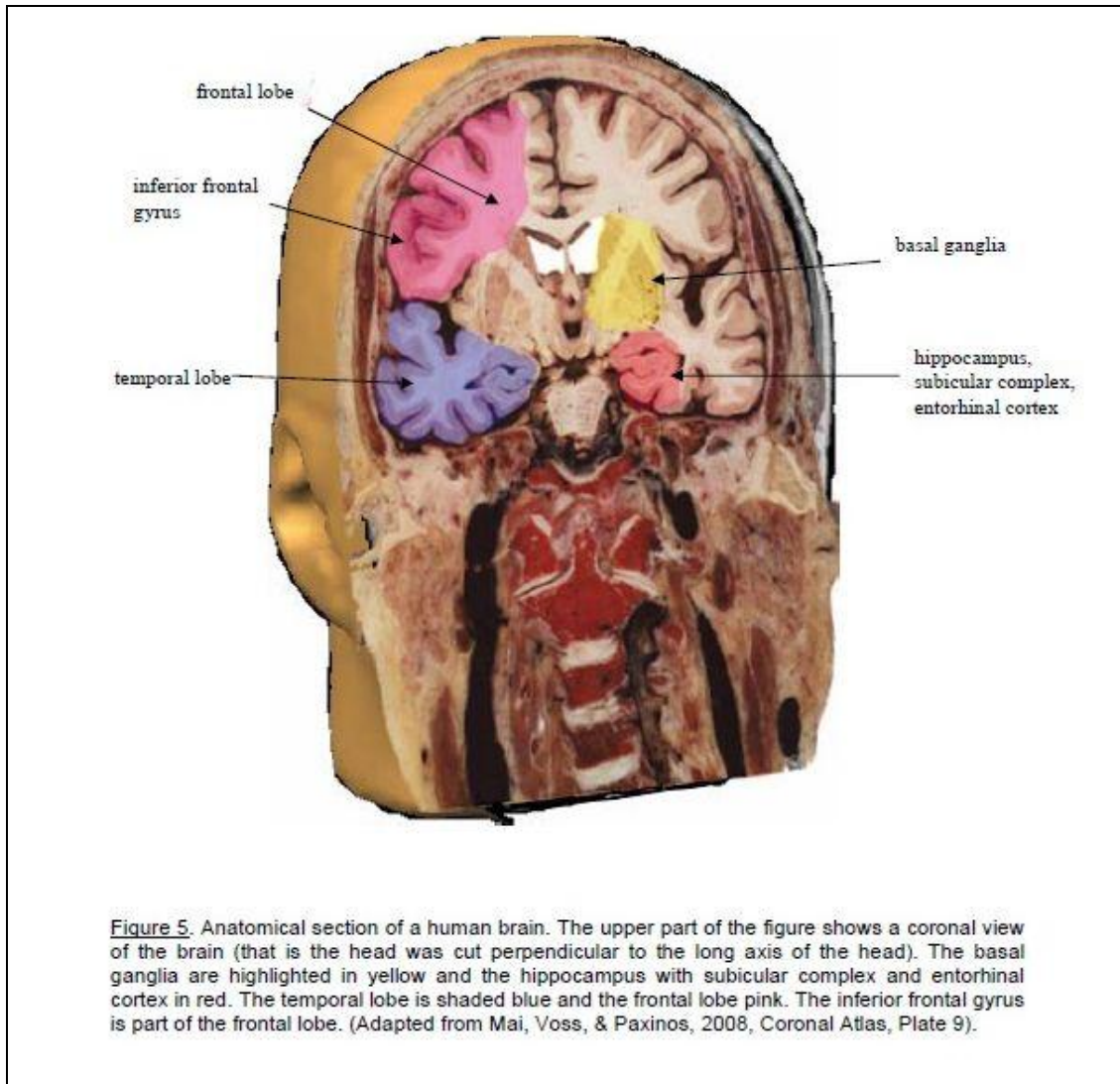


Figure 4. The original idea that the visual cortex can be decomposed into two pathways goes back to Mishkin and Ungerleider (1982). Both pathways originate in the visual cortex before they separate into a dorsal (occipito-parietal) and ventral (occipito-temporal) stream (yellow shading). The dorsal pathway is concerned with spatial properties of vision ("where") and the ventral pathway with the identification of visual objects ("what"). An alternative view describes the dorsal pathway as vision for action ("how") and the ventral pathway as vision for perception (for a summary see Farivar 2009).

## 4. Brain plasticity

In the previous sections I have argued that for learning to be successful information must be encoded, stored, manipulated in and retrieved from memory. Different memory systems are associated with different interacting neural substrates and these substrates are modulated by specific neurotransmitters (e.g., dopamine, acetylcholine), hormones (e.g., estrogens) or proteins (e.g., BDNF). During aging there are physiological changes that affect different brain regions and pathways in different ways. The question thus arises what these changes are and whether they affect learning and memory processes.

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Figure 5. Anatomical section of a human brain. The upper part of the figure shows a coronal view of the brain (that is the head was cut perpendicular to the long axis of the head). The basal ganglia are highlighted in yellow and the hippocampus with subicular complex and entorhinal cortex in red. The temporal lobe is shaded blue and the frontal lobe pink. The inferior frontal gyrus is part of the frontal lobe. (Adapted from Mai, Voss, & Paxinos, 2008, Coronal Atlas, Plate 9).

The reader is encouraged to view similar brain structures interactively and in more detail at: http://teaching.thehumanbrain.info/projekte/atlanten/frontal/true/la/.

### 4.1 Neurophysiological and cognitive changes in the aging brain

Generally, studies of postmortem brains and neuroimaging suggest that there is selective and differential shrinking of the human brain during most of the adult lifespan. White matter pathways become less dense and the size or density of neurons decreases. (For a summary of patterns and cognitive correlates of brain aging see Raz & Rodrigue 2006). Most affected by aging are regions of the cerebral surface that are important for complex processing and the generation of behavior. The prefrontal cortex is a brain region involved in planning, organization, decision making, and working memory, and it is particularly this brain region where age-related changes in and vulnerability of grey matter have been reported (Allen, Bruss, Brown & Damasio 2005; Kennedy et al. 2009; Sowell, Thompson & Toga 2004; Terribilli et al. 2009). These changes are accompanied by changes in neurotransmitter systems such as a decline in D2-dopamine and serotonin receptors. Dopaminergic receptors play an important role in attention regulation and response modulation. Other brain regions seem less affected such as temporal, limbic and anterior cingulate areas, the pons and the visual and sensory cortices. Nevertheless, although

the volume of these latter structures is mostly preserved in aging, there is evidence that visual and sensory cortices are less activated and show less neural specificity in aging (for a summary see Park & Reuter-Lorenz 2009).

Similar to the structural changes observed at the cerebral level, there are also age-related cognitive changes at the behavioral level. Although the latter might show global effects, certain cognitive functions are affected disproportionately (Salthouse & Nesselroade 2002). While processing speed, working memory, encoding of information into episodic memory and performing executive control processes tend to decline across the adult lifespan, autobiographical, semantic and procedural memory processes as well as verbal and emotional processing seem to be relatively stable until very late in life. (For a summary see Hedden & Gabrieli 2004; Park & Reuter-Lorenz 2009). It is, however, important to note that there are substantial individual differences in the rate of cognitive changes. It is also important to emphasize that attempts to relate cognitive changes with structural changes have not yielded straightforward relations. Further, brain activation in individuals may differ although their cognitive performance is similar. For example, early studies comparing prefrontal activity in young and older adults while performing verbal working memory (Reuter-Lorenz et al. 2000) and long-term memory tasks (Cabeza et al. 1997) showed different activation patterns. While young adults activated focal regions in the prefrontal cortex, older adults activated left *and* right focal areas. Since then greater bilateral activation and overactivation of frontal areas have been confirmed in numerous studies. These and similar findings have been taken as indicators of functional reorganization in an adaptive brain.

## 4.2 The scaffolding theory

Structural, functional and cognitive reorganization of the brain has been referred to as plasticity (for a summary of the concepts of plasticity see for example Buonomano & Merzenich 1998; Burke & Barnes 2006; Butz, Worgotter & van Ooyen 2009; Greenwood 2007; Jones et al. 2006). Plasticity occurs throughout a lifespan and, as mentioned previously, shows high individual variation. Studies of the cognitive performance of elderly people have consistently shown that despite observed brain pathology some elderly individuals present similar cognitive abilities compared to their brain healthy peers. Numerous suggestions have been advanced to explain these observations such as the use of compensatory mechanisms (e.g., Grady 1998), dedifferentiation, that is the loss of specialization in form or function (e.g., Lindenberger & Baltes 1997), a shift in processing strategies (e.g., Li, Lindenberger, Freund & Baltes 2001), functional plasticity (e.g., Greenwood 2007), differences in cognitive reserve (e.g., Stern 2002, 2009), or scaffolding mechanisms (e.g., Park & Reuter-Lorenz 2009; Petersen, van Mier, Fiez & Raichle 1998). Of these suggestions an attractive model is the scaffolding theory of cognitive aging as it provides a comprehensive account, testable hypotheses and integrates -- to a certain degree -- the previously mentioned hypotheses or mechanisms. In what follows I will present in more detail the scaffolding theory which is based on reflections by Petersen et al. (1998) and has been expanded and modified by Park & Reuter-Lorenz (2009).

Scaffolding is viewed as the brain's normal response to challenge. It occurs across a lifespan and involves the use and development of complementary, alternative neural circuits to achieve a particular cognitive goal. For example, when we acquire a novel skill we recruit and develop an initial set of neural circuits – so-called scaffolds -- that are broadly dispersed in the brain. As our learning advances and performance becomes more skilful, the network is optimized and turns into a more specific, efficient and perfect neural circuitry that connects functionally related brain regions. Even after we have perfected the acquired skills those brain regions that were active at the early scaffolding stages may remain minimally active. It has thus been suggested that this secondary circuitry is some sort of a backup mechanism that can be recruited in challenging situations. Challenge can be externally motivated such as the confrontation with novel or unanticipated situations or increased levels of task demand. Challenge can also be motivated intrinsically such as metabolic or structural changes to the neural substrates as happens in aging. In youth, when we encounter novel situations and new learning more frequently, scaffolding processes may be more efficient than in older age. In aging, when familiar tasks and cognitive operations become more challenging, scaffolding processes may be called upon to perform these tasks and operations. It is suggested that the primary locus for scaffolding processes is the prefrontal cortex, a brain region that is most affected in aging. As aging proceeds and neurobiological decline occurs, we will rely less on primary circuitry and engage more and more scaffolding. However, when neural pathology advances our scaffolding capacity will exceed the capacity for

plasticity and reorganization, and at some stage will lead to cognitive loss as happens in the late stages of dementia.

Although the scaffolding theory is intuitively appealing, there is currently no *direct* evidence for its support. Note that it is not entirely clear how exactly the primary circuits develop and what it means when scaffolds "turn into" more efficient circuitry. Concerning the question of whether there is a way to promote scaffolding mechanisms the authors advance several testable hypotheses. One relates to learning through practice or training. The authors believe that compensatory scaffolding can be created and dissipated by training. In this context it is also hypothesized that once older adults rely on overactivation for task performance, the target for training should be to decrease activation in secondary scaffolding areas and improve the efficiency of primary networks. If, however, older adults show significant underactivation of a network, then the focus of training should be to establish new scaffolds. Further, the authors hypothesize that it is possible although particularly effortful to create novel scaffolds to improve task performance through training. The hypothesis is motivated by evidence from the rehabilitation literature that suggests that new neural circuitry can be developed through extensive training.

## 5. The impact of practice and learning on the brain

Although the scaffolding theory seems to provide a theoretical framework for learning in aging, much is still speculative and direct experimental evidence is lacking. Indirect evidence for some of the hypotheses comes from numerous experiments that have shown that external challenge can change cortical structures and cerebral function. Changes during development as well as in response to experience can occur at several levels of the central nervous system such as changes at the molecular and synaptic level, changes in cortical maps and changes of large-scale neural networks (Buonomano & Merzenich 1998). At the physiological level, practice can lead to increased neural efficiency or to reorganization of cerebral structures. According to Kelly & Garavan (2005) practice-related reorganization of the functional anatomy of task performance can take the form of true reorganization or a redistribution of functional activations. True reorganization is characterized by a change in the location of activation. Task activation maps at the beginning of practice are different from task activation maps at the end of practice. Reduced activity in a particular brain region would reflect decreased engagement of a particular cognitive process while increased activation would reflect the development of new representations or processes and/or the engagement of an alternative system. Task activation maps that are distributed across the brain at the beginning of practice would thus suggest the involvement of scaffolding circuitry.

In the case of redistribution, the task activation map contains the same areas at the end as at the beginning of practice. The difference to reorganization is that the levels of activation *within* those areas have changed. This pattern of redistribution of activation within the same regions is associated with the attainment of automatic or asymptotic performance. This means that less attentional or control processes (typically represented in prefrontal, posterior parietal and cingulate circuitry) are necessary and storage is relatively efficient. Projecting this view to the scaffolding theory it seems that scaffolding is not necessary in redistribution, and that the change of levels of activation reflects optimization of the primary circuitry. At the current stage of knowledge, however, this remains speculation.

In an effort to support their reorganization-redistribution hypothesis, Kelly & Garavan (2005) reviewed 26 studies that investigated practice/learning effects with the neuroimaging technique. Of these 26 studies there were only four that focused on verbal learning tasks (two verbal memory tasks, one word generation task and one artificial grammar learning task) while the others related to motor, visuo-motor or perception tasks. Based on the review the authors not only supported their reorganization-redistribution hypothesis but also concluded that sensory/motor tasks and perceptual skills are associated with different functional and structural cerebral organizations compared to higher-level cognitive tasks: Practice-related changes in brain activation in response to sensory/motor tasks seem to predominantly lead to increased connectivity within primary cortex whereas cognitive tasks result in changes in connectivity between a more broadly distributed network of functional areas. A general word of caution is warranted here. Note that most studies included young or middle-aged healthy individuals and neuroimaging practice studies focusing on the healthy elderly are rare. We thus do not know whether these findings also apply to the elderly brain.

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There are other factors that influence (solely or in interaction) practice-related changes in brain activation. These are changes in performance, the time spent on the task, the subject's awareness of the task or stimulus, or processes unrelated to the task such as individual characteristics of the participants or the environment. In the context of this paper it is important to emphasize that age is a particularly critical factor. The difficulty to control all these variables and tease apart their influence on the observed activation patterns may be one reason for divergent findings.

## 5.1 Experimental work related to learning and training induced changes in the human brain

As mentioned previously, there are numerous practice-effect studies. Most of these studies involve young participants and there are only a few studies that compare practice-effects of old and young people, or of the elderly in different age ranges. One study investigated procedural learning in 44 elderly persons (50 to 67 years old) and 25 elderly control persons (55 to 67 years old) who were taught to juggle 3 balls (Boyke, Driemeyer, Gaser, Büchel & May 2008). Juggling is a complex visuo-motor skill that requires accurate bimanual arm movements, grasping and visual tracking. Only 10 persons (out of 44) of the target group and 15 (out of 25) individuals of the control group learned to juggle for 60s (target outcome performance). This was in contrast to young people (mean age 22 years) who were able to reach the performance objective in a previous study performed by the same research group (Draganski et al. 2004). It is likely that declining motor and coordination skills in aging affected the performance outcome and it remains unclear whether the elderly could have reached the performance goal through enhanced training schemes. Boyke et al. (2008) compared the volumetric measures of the grey matter of 25 individuals who had the best results in endurance juggling with the data sets of 25 controls. MRI scanning was performed before training (T1), at three months of training (T2) and three months after training (T3) had stopped. Comparing the brain volume measures at T1 and T2 the authors reported a significant increase in grey matter in the hippocampus (functionally viewed as a gateway to long-term memory) and the nucleus accumbens (functionally involved in reward systems) in the elderly as well as the young training group but not in the non-training elderly control group. Both the elderly and the young thus showed an increase in brain volume in the same areas. This volume increase was interpreted as reflecting the generation of new neurons (neurogenesis) and additional plastic mechanisms. It is noteworthy that in the elderly group no correlation was found between changes in grey matter and performance level. It is thus possible that the volume increase was due to effort and not learning per se. Unfortunately, there are no imaging data on those participants who did not reach the required performance levels as it may have been interesting to know whether the measured volume increase also occurred in those who did not fully perform. Further, no measurements were taken at different times during practice and thus no conclusions can be drawn as to whether the increase in brain volume in the hippocampus and nucleus accumbens was continuous or showed variations. It is further noteworthy that the volume increase was not maintained and disappeared three months after training had stopped. Generally, however, it was shown that training led to changes in the brain of the elderly which was similar to the changes that were observed in the young.

The studies described above reported volume changes in grey matter. Grey matter refers to cell bodies and unmyelinated fibres in the brain. White matter refers to the fibre connections between cells and has previously not been investigated in the context of aging and learning due to technical limitations. A relatively new imaging technique, diffusion tensor imaging (DTI), makes it possible to measure white matter microstructure in the human brain. This new technique is particularly important as it allows making the connections "visible" that exist between brain regions. Scholz, Klein, Behrens & Johansen-Berg (2009) studied 48 healthy adults that were split into a training and non-training control group using the DTI technique. The training group was trained in juggling for 6 weeks. The brain of all participants was scanned before training (T1), after training (T2) and 4 weeks after training had stopped. The authors reported an increase in white matter microstructure underlying a region in the parietal lobe (right intraparietal sulcus) in the training group. It is thus not only grey matter but also white matter connecting brain regions that changes through practice. The reported increase remained elevated after a 4-week period without juggling. Similar to the previous study, there was no strong relation between performance level and structural changes. As this study did not include elderly participants, it is currently unknown whether similar changes in white matter would also occur in the elderly.

Another study compared declarative learning of 38 German medical students (mean age 24 years) while preparing for a major medical exam with 12 non-medical students as a control group (Draganski et al. 2006). Brain scans

were acquired with the MRI technique 3 months before the exam (T1), the first or second day after the exam (T2) and in 23 students 3 months later (T3). The control participants were college students of physical therapy who were not studying for any exams. They were scanned two times at similar time intervals as the target group. Compared to the previously mentioned juggling studies that focused on procedural learning, this study focused on declarative learning. Generally, the study group showed a volume increase in more widely distributed brain regions which would be in concordance with Kelly & Garavan's (2005) hypotheses (see previous section). Similar to the procedural learning study by Boyke et al. (2008), Draganski and colleagues (2006) also reported an increase in hippocampal structures in the practice group. In addition, a significant structural increase in grey matter was reported in the posterior and inferior parietal cortex in the medical students but not the control group. The parietal cortex has been associated with information transfer into long-term memory, with storage of visual short-term memory, memory retrieval and involvement of the dorsal and ventral visual streams (i.e. the where, how and what pathways – see Figure 4) in learning and memory (for a discussion see Draganski et al. 2006). In addition to an initial increase in grey matter during the learning period, the posterior hippocampus showed an even more pronounced increase three months after the exam suggesting that some sort of learning continued beyond the acute learning phase. It is, however, not clear whether this increase was due to the acute learning phase or whether other learning contributed to the increase. As in the juggling study, no significant correlation was found between performance level on the medical exam and changes in grey matter. Interpretation of the findings of the study are somewhat hampered considering the low number of control subjects, the higher stress level in the target group (it is known that hippocampal structures are influenced by stress) and little or no control over learning strategies, time spent studying and personality variables. Again, it is currently unknown whether similar effects would have occurred in the elderly although previous evidence of plasticity also in the elderly brain makes some sort of changes likely.

The practice-related studies reviewed so far concerned non-language studies. The purpose was to demonstrate plasticity of the brain with practice. We will now turn to L2 studies and aging.

## 6. Second or foreign language learning and aging

Although there are numerous studies investigating the neural substrates underlying the representation and/or processing of L2 in young adults, controversies still abound (for a discussion see, for example, the collection of articles in Schumann, Indefrey & Gullberg 2006). A particular challenge is the large number of variables that need to be controlled to make studies comparable and the interpretation of findings less ambiguous such as age, gender, personality characteristics, age of acquisition, level of proficiency at various language levels, attainment, exposure and use of language, phenomena investigated and tasks used in the studies. This challenge paired with the limitations posed by neuroimaging techniques contributes to the difficulties to reach some consensus.

Despite the inherent problems of L2 studies, Indefrey (2006) compared 30 language experiments from 24 L2 or bilingual studies that used a neuroimaging technique based on the measurement of hemodynamic changes (such as fMRI or PET). The experiments included variants of word generation, picture-naming, semantic decision, and sentence or story comprehension. No difference in hemodynamic activation between L1 and L2 processing was reported for the majority of studies (based on group and not individual analyses). Those studies that reported a reliably stronger activation during L2 processing showed that this concerned specific subgroups of bilingual speakers and predominantly regions that were typically activated also in L1 processing (such as anterior cingulate, left posterior inferior frontal gyrus). Speaker characteristics that seemed to influence activation patterns were late L2 onset, low L2 proficiency, and low L2 exposure. All three factors seemed to be involved in word-level production whereas L2 proficiency played a role in word-level semantic processing in comprehension. L2 onset seemed most important for activation differences related to syntactic processing in sentence comprehension.

Using the event-related potential (ERP) technique, two studies investigated whether L2 learners processed specific language phenomena differently from native speakers. One study trained 28 young adult participants (mean age 24.1 years, range not given) in "Brocanto", an artificial language", and compared their performance to 31 participants (mean age 23.3 years) who had only been trained on vocabulary (Friederici, Steinhauer & Pfeifer 2002). After training, high proficiency participants showed typical native-speaker like ERP patterns of syntactic

processing thus suggesting that learning of an artificial language in young adulthood may reach native-speaker like processing levels – at least in terms of syntax and for an artificial language. Another study, however, did not confirm these findings. Müller, Hahne, Fujii & Friederici (2005) trained 24 young German adults (age range 20-26 years) on a mini version of Japanese and compared them to 19 Japanese native speakers (age range 19-35 years). Before and after training ERP measures were recorded in response to specific language phenomena (word, case, and classifier violations). Only responses that were correct by at least 75% entered analysis. The learner group differed in two out of three ERP measures from the ERPs of the Japanese native speakers leading the authors to conclude that different neural processes underlie the syntactic and thematic processing of L2 learners. The interpretation of the findings seems to warrant some caution considering the difference in age, gender and proficiency level in the two groups and the relatively high rate of errors made by the L2 learners.

Despite the wealth of studies investigating the cerebral structures in bilingual or L2 individuals, there is a lack of L2 studies investigating the effects of L2 practice, L2 teaching and learning techniques or different forms of learning on cerebral substrates. There is one learning study (although in L1 and not L2) that explored semantic strategy training and its effect on brain activation in 15 healthy individuals (26 to 52 years) (Miotto et al. 2006). The authors presented word lists (unrelated words, related-nonstructured words, related-structured words) that the participants had to recall while being scanned in an MRI. After the first scanning session and on the same day the subjects underwent 30 minutes of semantic organizational strategy training followed again by a scanning session. The authors reported improved performance and significant activation in various regions of the frontal cortex [bilateral dorsolateral prefrontal (DLPF), inferior prefrontal (IPF) and orbitfrontal (OFC)] for unrelated words and related-nonstructured words after cognitive strategy training. Note, however, that the interpretation of the results is hampered considering that there was no control group involved, the number of participants relatively small and the age range rather large.

Another area that is largely unexplored are studies of the neural underpinnings of the *process* of learning a second or foreign language in adulthood as well as studies comparing young and elderly learners. Similarly, there are no studies comparing successful and unsuccessful L2 learners in terms of the underlying neural substrates although such an endeavor might prove beneficial as exemplified by an L1 study (Wong, Perrachione & Parrish 2007). The authors investigated the neural correlates of learning to use the pitch patterns in words by English-speaking adults and compared successful with unsuccessful learners. While successful learners showed distinct areas of activation (increased activation in the left posterior superior temporal area), less successful learners showed increased activation in a diffuse brain network (the right superior temporal region and right inferior frontal gyrus). These regions have been associated with nonlinguistic pitch processing. In addition, prefrontal and medial frontal areas were also activated indicating increased working memory and attentional efforts. The activation pattern of the unsuccessful learners could be indicative of reliance on scaffolding while the successful learners may have honed in on primary circuitry (see section 4.2). It is interesting to note that even before training a difference in brain activation was already found in the low versus high attainment group which included higher activation of the superior temporal region in the more successful learners.

## 7. Other factors influencing cognitive vitality in aging

It was mentioned previously that some cognitive processes are more affected than others in aging such as processing speed, executive control processes and specific aspects of memory. As a result, older individuals may have difficulties with simultaneous cognitive operations and with tasks that require holding and integrating multiple items in memory. Psychological research has provided compelling evidence that training can improve cognitive and motor functions in the elderly such as motor and coordination skills, attention, memory storage and retrieval and reasoning processes (for a summary see Fillit et al. 2002). Neuroscience research has elucidated the neural circuitry that is involved in these cognitive functions. At the current stage of knowledge, however, there is no *neuroscience* evidence that would allow us to advance recommendations concerning the best learning or training technique to optimally take advantage of brain plasticity. There is, however, growing evidence of potentially modifiable factors associated with cognitive vitality in the elderly such as education and social, mental and physical activity (for a summary see e.g., Fillit et al. 2002). Low education has been positively correlated with cognitive decline in late life and risk of dementia (e.g., Callahan et al. 1996; Cobb, Wolf, Au, White & D'Agostino

1995; Farmer, Kittner, Rae, Bartko & Regier 1995; Snowdon et al. 1996; but see Evans et al. 1993). Some researchers have, however, cautioned that a selection bias in the studies may have distorted the findings (Fillit et al. 2002). Lifelong bilingualism has also been suggested as a protective factor. Bilingual patients exhibited a delay of 4.1 years in the onset of symptoms of dementia compared to monolingual speakers (Bialystok, Craik & Freedman 2007). Maintenance of social engagement and avoidance of social isolation has also been suggested as a protective factor against cognitive decline and dementia (e.g., Bassuk, Glass & Berkman 1999; Berkman 2000; Fabrigoule et al. 1995; Helmer et al. 1999). Furthermore, cognitively stimulating activities and sustained cognitive engagement across the lifespan have been linked to higher levels of cognitive functioning and delayed onset or more resilience for dementia (e.g., Bennett et al. 2003; Bosma et al. 2003; Wilson et al. 2003). Not only mental but also physical exercise has been associated with beneficial effects on cognitive function in elderly people and a decrease in the risk for dementia (e.g., Colcombe & Kramer 2003; Colcombe et al. 2003; Colcombe et al. 2006; Colcombe, Kramer, McAuley, Erickson & Scalf 2004; Kramer, Bherer, Colcombe, Dong & Greenough 2004; Larson et al. 2006; Podewils et al. 2005; Stroth, Hille, Spitzer & Reinhardt 2009). However, not all research supports these associations (e.g., Verghese et al. 2003). Discrepancies in studies might be due to differences in the types of exercise and measurements, the general health of the participants and the method of investigation. A negative modifier for learning and memory is acute and chronic stress. Numerous studies have shown that stress negatively impacts learning and memory and this has been associated with changes in neural substrates in the young as well as the elderly (for a summary see, for example, Lupien, Maheu, Tu, Fiocco & Schramek 2007; Lupien, McEwen, Gunnar & Heim 2009). Finally, there is some truth to the well-intentioned advice to put the book beneath the pillow before going to sleep. Research has accumulated that shows that healthy sleep is a critical mediator of memory consolidation (for a summary see e.g., Rasch & Born 2007; Stickgold & Walker 2007).

## 8. Conclusion

The literature on learning and teaching (including strategies and techniques) and the relation to cerebral substrates in the healthy elderly is still sparse. What is known is that we are capable of learning throughout a lifespan and that this is associated with structural and functional changes in the brain. What is unknown is whether this plasticity is similar or changes across different age ranges in the elderly. Although there is ample evidence of lifelong plasticity, little is known about how the healthy elderly can best exploit this plasticity. What are the best practice and learning techniques, and what is the best teaching approach? Would a combination with other lifestyle factors prove beneficial for learning (e.g., learning in a social context; combining mental and physical activity etc.)? What does it mean that, at times, structural changes in the brain continue to show after learning and practice has stopped whereas, at other times, the changes have regressed? Are these changes really due to learning or training per se or do they reflect other or additional mechanisms? Why is there so little correlation between performance level and changes in structural or functional brain activation? What distinguishes successful from unsuccessful elderly learners in terms of performance and underlying neural substrates?

In sum, there are still many open questions that await further research. Neuroscience research has provided evidence that learning and practice changes the brain structurally and functionally also in the elderly. At the current stage of knowledge, however, neuroscience does not provide any recipes how to best exploit this knowledge and it would be unethical to advance recommendations for best (L2) teaching and learning methods or techniques based solely on neuroscience grounds. However, findings from neuroscience research provide an excellent basis to advance testable hypotheses that -- in a concerted effort across disciplines – have good chances to provide answers to some of the questions asked previously.

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