Dissertation zur Erlangung des Doktorgrades
eines Doktors der Philosophie der Philosophischen Fakultät
der Universität des Saarlandes

VISUAL AND AUDITORY VOCABULARY ACQUISITION IN LEARNING CHINESE AS A SECOND LANGUAGE:

THE IMPACT OF MODALITY-SPECIFIC WORKING MEMORY TRAINING

vorgelegt von

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aus
Saarbrücken
2012

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Dissertation eingereicht am: 31.05.2011
1. Gutachter: Prof. Dr. Axel Mecklinger, Universität des Saarlandes
2. Gutachter: Prof. Dr. Hubert Zimmer, Universität des Saarlandes
Tag der Disputation: 30.11.2011

Das Schönste, was wir erleben können, ist das Geheimnisvolle. Es ist das Grundgefühl, das an der Wiege von wahrer Kunst und Wissenschaft steht. Wer es nicht kennt und sich nicht wundern, nicht mehr staunen kann, der ist sozusagen tot und sein Auge erloschen.

Albert Einstein

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INTRODUCTION

I INTRODUCTION

Communicating with people around the globe is becoming more and more important in an increasingly globalized world. Thereby bilingualism – the ability to speak different languages - is a condition precedent. With China`s opening to the western world, with its population of about one fifth of the world, its economic growth and increasing influence in global politics, speaking, reading and comprehending the Chinese language is vitally important. One of the most crucial aspects of second language learning is vocabulary acquisition (Green, Crinion, & Price, 2007). As words are the basic building blocks of language, the amount of vocabulary knowledge restricts the learner`s production of written and spoken language as well as the comprehension of spoken and written language produced by others (Baddeley, Gathercole, & Papagno, 1998). Nevertheless, little is known about how vocabulary acquisition in Chinese as a second language can be improved. Since the Chinese language system decidedly differs in the writing system`s design principles and the characteristics of visual and phonological appearance of the words compared to alphabetic languages (Perfetti, Nelson, Liu, Fiez, & Tan, 2010), it provokes the question which processes underlie visual and auditory word learning in Chinese and whether those processes can be trained to result in improved performance in Chinese vocabulary acquisition. In this regard brain imaging methods reveal precious insights in relevant neural networks of second language vocabulary acquisition as they might disclose specific affordances of processing words in a new language system that should provide an indication of underlying processes.

In the following, I will first introduce the functional architecture of single word recognition, as it is the basis of vocabulary acquisition in any language. I will then describe the characteristics of logographic Chinese in contrast to alphabetic languages and how these differences are reflected in neural networks for reading and speech comprehension. Next, I will outline the issue of learning Chinese as a second language in view of models and assumptions about underlying processes. After that, I will consider the role of working memory for vocabulary acquisition and specify the different impact visual and auditory working memory systems might have for learning written and spoken Chinese words. I will then provide evidence that working memory training is an advantageous approach to investigate the question whether visual and auditory working memory processes underlie Chinese vocabulary acquisition by testing transfer effects from visual and auditory working memory training on Chinese word learning (Language Training Study). In this vein, an essential question is, if working memory can be trained for visual and auditory materials separately. As this question is still open-ended, it should be addressed (exemplified for the visual modality) in the Working Memory Training Study. Further on, I will give a description of overlapping processing components of visual and auditory word learning and working memory as well as overlapping brain regions as it is considered as a precondition for transfer effects and derive the functional hypotheses for the Language Training Study. After having outlined this theoretical background, I will continue with the empirical part and first delineate common methods and results of both training studies as the questions for both studies were integrated in a single nested training study. After a discussion of the working memory training results, methods and results of the Working Memory Training Study and the Language Training Study will be presented and discussed in detail. Finally, I will give an integrative account of the results obtained, discuss the findings and their implications with respect to the models for word learning and working memory, take limitations into considerations and provide an outlook and further directions.

1 THE FUNCTIONAL ARCHITECTURE OF SINGLE WORD RECOGNITION

When focusing on vocabulary acquisition during second language learning, one needs to consider the constituents of single words and how words are recognized. A generic architecture for word recognition was proposed in the 'triangle' model of Seidenberg & McClelland (Seidenberg & McClelland, 1989) (see Figure I-1).

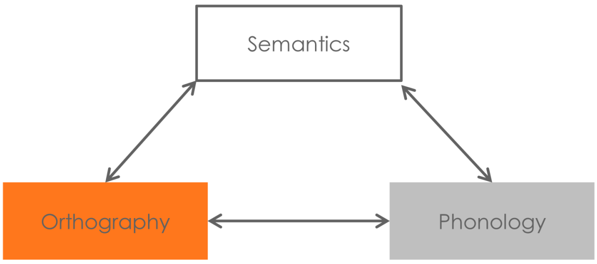

Figure I-1: The 'Triangle' Model of word recognition
(Adopted from Seidenberg & McClelland, 1989)

Orthographic, phonological and semantic codes reciprocally determine the interpretation of incoming visual or auditory lexical input (Plaut, 1997). The interaction of the codes is mediated by 'hidden' units, which are not shown in the figure. Although the Triangle model is useful in providing a generic architecture of single word processing and characterizing how orthographic, phonological and semantic codes determine learning to read new words (Harm & Seidenberg, 1999), it remains relatively limited and simplified.

Thus, in an attempt to extend this model, Grainger, Diependaele, Spinelli, Ferrand, and Farioli (2003) introduced the Bimodal Interactive Activation Model of word recognition (BIAM)

(Grainger & Holcomb, 2010) shown in Figure I-2 and added minimally distinguishing sub-lexical and lexical levels of processing within each of the orthographic and phonological pathways. The modality-specific hierarchical pathways start from visual or auditory word inputs and proceed via visual or auditory feature analysis and orthographic or phonological sub-lexical representation units to orthographic or phonological whole word representation. This hierarchical processing permits connections and transformations between orthography and phonology at different levels in the pathways (Grainger & Holcomb, 2010).

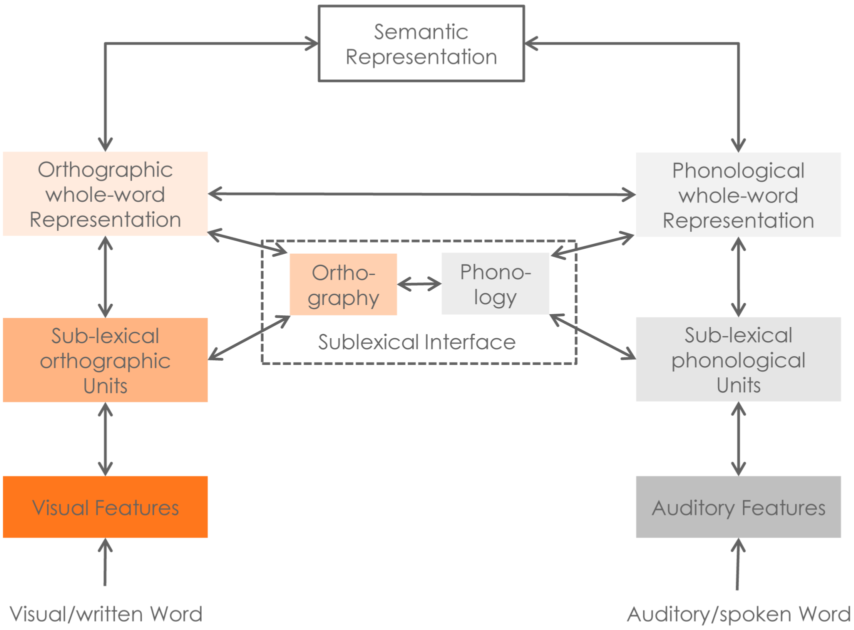

Figure I-2: The Bimodal Interactive Model of word recognition

(Adopted from Grainger & Holcomb, 2010)

When learning words in a second language knowledge about these types of information based on input from the visual and auditory modalities has to be acquired as well as their appropriate transformations.

2 CHARACTERISTICS OF LOGOGRAPHIC CHINESE IN CONTRAST TO ALPHABETIC LANGUAGES

To pave the way for showing the affordances for learning words in Chinese as a new language system it is inevitable to review how types of information relevant for single word processing and their transformations differ between alphabetic languages and logographic Chinese. As the Chinese language system decidedly differs in the writing system`s design principles and the characteristics of visual and phonological appearance of the words, the system is highly contrastive compared to alphabetic languages such as German and English (Perfetti et al., 2010).

2.1 DIFFERENCES AND SIMILARITIES BETWEEN THE LANGUAGE SYSTEMS

Accordingly, in the following differences and similarities in the orthographic and phonological structure and their mapping principles between the language systems will be outlined.

2.1.1 ORTHOGRAPHY AND WORD READING

Chinese is often referred to as a logographic and morpho-syllabic language system (DeFrancis, 1989; Perfetti & Zhang, 1995). The basic unit of the Chinese script is the character that comprises a number of strokes packed into a square configuration. Certain strokes are combined to form specific stroke patterns, radicals, as the basic components of Chinese characters. Unlike in alphabetic scripts, in which visually simple letters are organized in a linear fashion, stroke patterns in Chinese characters follow a left-right horizontal, top-bottom vertical or inside-outside orientation, which is non-linear. In complex characters radicals can be combined vertically or horizontally to form a single-character word. As radicals often bear their meanings suggested by visual shapes and have their own pronunciation, they can provide cues for the meaning and pronunciation of the whole character. However, the cue reliability is low and thus limits their usefulness in retrieving the character`s identification and pronunciation (Tsang & Chen, 2009). Instead, the processing of the whole character is necessary for recognition. In contrast to alphabetic languages, whole-character processing involves enhanced visual analysis of the complicated stroke patterns comprising high spatial frequency information and their spatial relations within the character encoded by low spatial frequency information (Perfetti et al., 2010).

As Chinese is a morpho-syllabic system, Chinese characters map onto phonology at the (mono-) syllable level, with no parts in the character corresponding to meaningless phonological segments such as phonemes. Chinese writing does not allow a true segmental analysis, i.e. grapheme-to-phoneme conversion existing in all alphabetic languages is impossible in Chinese. With this design principle in logographs, phonological codes of Chinese characters are accessible only by recourse to the direct retrieval of phonological information stored in the mental lexicon. In the alphabetic system, the word-level units can activate the word-level phonology via the use of grapheme-phoneme correspondence rules before a complete specification of all letter units has taken place. Accordingly, this style of processing follows a cascade (Berent & Perfetti, 1995; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001;

Seidenberg & McClelland, 1998). In contrast, in Chinese the word-level phonology is not activated prior to a full orthographic specification of the character and captures an asynchrony between orthographic and phonological processing. So, it is called threshold style of processing, or addressed phonology (Perfetti, Liu, & Tan, 2005; Perfetti & Liu, 2006; Perfetti et al., 2010; Tan, Hoosain, & Peng, 1995; Tan, Hoosain, & Siok, 1996).

2.1.2 PHONOLOGY AND SPEECH PERCEPTION

With respect to auditory phonology, the syllable is the basic speech unit of Mandarin Chinese, which is the major Chinese dialect. Each syllable is divided into two parts: the onset and the rime. The onset of a Mandarin Chinese syllable is always a single consonant, whereas the rime segment consists of vowels in most of the syllables (Ho & Bryant, 1997a). In contrast to alphabetic languages in which consonants are phonemically relevant and complex consonant clusters are common, Mandarin Chinese has a much simpler syllable structure and a smaller number of syllables (Zatorre & Gandour, 2008). Moreover, alphabetic languages are atonal, whereas Chinese is a tonal language. Pitch patterns are phonemically relevant in the way that variations in pitch patterns signal differences in meaning at the syllable level. There are four tones in Mandarin Chinese with a supra-segmental nature of the tone being attached to the rime (Ho & Bryant, 1997a; Hsieh, Gadour, Wong, & Hutchins, 2001).

2.2 DIFFERENCES AND SIMILARITIES IN NEURAL NETWORKS

A comparative look at underlying reading and speech networks reveals that differences and similarities between the language systems to some degree extend to neural systems in native speakers.

2.2.1 NEURAL NETWORKS FOR READING

Generally, a consensus became apparent on the alphabetic reading network. Various meta-analyses (e.g. Tan, Laird, Li, & Fox, 2005a; Bolger, Perfetti, & Schneider, 2005; Fiez & Petersen, 1998; Jobard, Crivello & Tzourio-Mazoyer, 2003; Mechelli, Gorno-Tempini, & Price, 2003; Price, 2010) support a neural network which – on a coarse-grain level – includes basically three parts: (1) left occipital-temporal areas including the left fusiform gyrus for visual-orthographic processes (2) left temporal-parietal (posterior portions of the superior temporal gyrus, angular and supramarginal gyrus) for grapheme-phoneme conversion (assembled phonology) and (3) the left inferior frontal gyrus (superior temporal sulcus, inferior frontal sulcus/insula) for phonological processing (see Figure I-3, upper panel). However, on a more fine-grained level, even within alphabetic writing systems differences in how deep or rather shallow grapheme-phoneme mappings are implemented in the script result in variations of the functional reading network (Paulesu et al., 2000).

First functional imaging studies of Chinese reading report both cross-language similarities as well as differences (Tan et al., 2001, 2003). Results showed a bilateral activation in occipital and fusiform regions for Chinese in contrast to left lateralization in alphabetic languages. Additional activation was found in the left middle frontal gyrus for Chinese only. Two meta-analyses directly contrasting reading networks of Chinese and alphabetic languages especially focusing on English seem to confirm these differences (Tan et al., 2005a; Bolger et al., 2005) (see Figure I-3, lower panel).

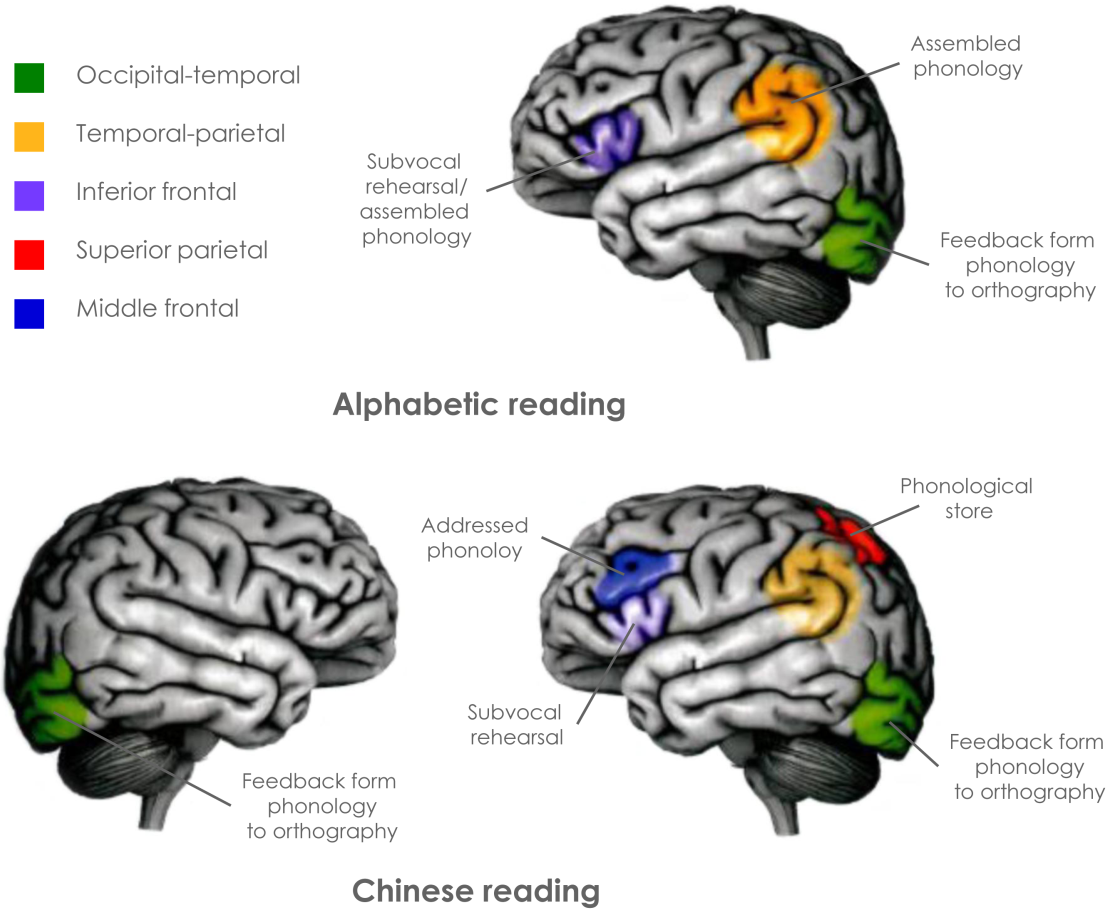

Figure I-3: Reading networks for alphabetic languages and Chinese

(Adopted from Perfetti et al., 2010, and Tan et al., 2005)

Both meta-analyses reported striking cross-language differences in that only in reading Chinese characters activations in the left middle frontal gyrus and the right fusiform gyrus was present, whereas only in reading English words the left temporo-parietal-region was active. Tan et al. (2005a) limited their analysis to those studies using explicit phonological tasks on the characters and found additional activation in a dorsal left inferior parietal region for Chinese only. Moreover, they showed that both language systems elicit common activations in the left fusiform gyrus and the left inferior frontal gyrus. Bolger et al. (2005) likewise found overlapping activations in the occipito-temporal region including the left mid-fusiform gyrus and the left inferior frontal gyrus as well as in the mid/anterior portion of the left posterior superior temporal gyrus.

Bilateral activation in the occipital-temporal cortex especially the fusiform gyri in Chinese compared to a left lateralization in alphabetic languages was explained with the specialization for spatial frequencies of the hemispheres. High spatial frequency information, which is contained in letter features as well as strokes, is assumed to be processes in the left hemisphere, whereas the analysis of coarser low spatial frequency information, that is additionally inherent in the relational pattern of larger radicals within a character, recruits the right hemisphere (Perfetti et al., 2010; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005). Additional activation in the frontal regions especially the left middle frontal gyrus seems to be distinctive for Chinese, but its functional role is still under debate. Nevertheless, there is accelerating evidence for it`s role in retaining the visual-orthographic form of the character in working memory until the phonology and meaning can be accessed in a threshold-like process (Liu, Dunlap, Fiez, & Perfetti, 2007a; Perfetti et al., 2010). Whereas left temporo-parietal regions have been attributed to assembled phonology in alphabetic languages, the dorsal left inferior parietal area has been linked to phonological (working) memory (Ravizza, Delgado, Chein, Becker, & Fiez, 2004; Smith & Jonides, 1999). Thus, this region is assumed to retrieve the syllable-level (addressed) phonology during Chinese character reading (Tan et al., 2005a). To sum up, the data on neural systems for reading suggests that although alphabetic languages and Chinese recruit overlapping brain regions the orthographic form of the script and how phonology is mapped in the writing system influences neuroanatomical circuits significantly.

2.2.2 NEURAL NETWORKS FOR SPEECH PERCEPTION AND COMPREHENSION

Several reviews and meta-analyses outlined the neural basis of speech perception and comprehension, which are mainly based on investigations in alphabetic native speakers. Although some disagreement exists on various details, there is considerable convergence about the network for alphabetic languages (Binder et al., 2000; Hickok & Poeppel, 2000, 2004, 2007; Scott & Johnsrude, 2003; Boatman, 2004; Indefrey & Levelt, 2004; Poeppel, Idsardi, van Wessenhove, 2009; Price, 2010) (see Figure I-4).

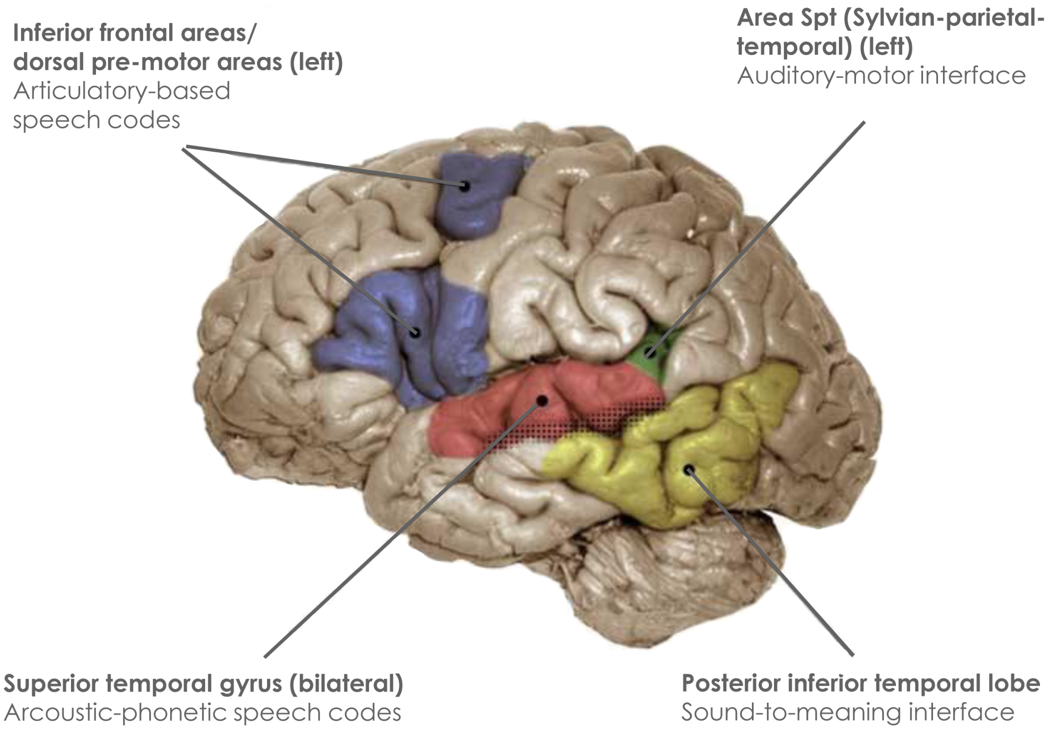

Figure I-4: The speech network for alphabetic languages

(Adopted from Hickock & Poeppel, 2004)

Processing of speech at the initial analysis i.e. the acoustic-to-phonetic mapping is robustly bilateral and mediated by core and surrounding auditory areas of the superior temporal gyrus. Subsequent computation i.e. aspects of processing that permit lexical access and further speech-based computation, is mainly left lateralized and encompass over many peri-sylvian areas, anterior and posterior aspects of the superior temporal sulcus, inferior frontal regions, temporo-parietal areas and inferior and middle temporal gyri. Starting form the superior temporal gyrus two processing streams emerge. The ventral pathway is assumed to be responsible for speech recognition as well as mapping sounds to meaning (Hickok & Poeppel, 2004, 2007; Poeppel et al., 2009) and projects ventro-laterally to more posterior parts of the superior temporal gyrus and sulcus as well as the middle temporal gyrus. The dorsal pathway is suggested to be critical for mapping sounds to articulation with dorso-lateral projections toward the parietal lobe to frontal areas (Hickok & Poeppel, 2004, 2007; Poeppel et al., 2009). Especially the sylvian parieto-temporal area is assumed to transform from auditory representations of speech to motor representations whereas frontal regions such as aspects of Broca`s area are assumed to process articulatory-based speech information.

To the best of my knowledge there are no studies directly contrasting auditory speech processing in Chinese versus alphabetic languages and only few studies of native Chinese word processing have examined the auditory modality (Liu et al., 2009; Xiao et al., 2005). Liu et al. (2009) found activation in the bilateral inferior frontal gyrus, and the superior/middle temporal gyrus in both a semantic and phonological judgment task using spoken Chinese words. Xiao et al. (2005) report highly similar activation clusters for processing of spoken Chinese pseudo-words and real words with additional activation in the calcarine and lingual gyrus, left insula, and left supra-marginal gyrus.

These data suggests that - although Chinese syllables differ from alphabetic syllables in several features - underlying auditory language regions highly overlap with the common network for speech processing. Hence, it is likely that similar processes as in alphabetic languages underlie Chinese speech comprehension.

3 LEARNING CHINESE VOCABULARY AS A SECOND LANGUAGE

The features of the Chinese language system introduced above are highly relevant when native alphabetic language speakers learn Chinese vocabulary in the visual and auditory modality. As the Chinese language differs from alphabetic languages in various aspects as outlined above, the issue arises how alphabetic native speakers acquire vocabulary in Chinese and which neural circuitry underlies written and spoken Chinese words in alphabetic native speakers.

3.1 THE COMPLEMENTARY SYSTEM ACCOUT OF WORD LEARNING

To address cognitive and neural processes by which novel words are learned in native and second languages Davis and Gaskell (2009) have proposed a Complementary System Account of word learning (see also Lindsay & Gaskell, 2010), which is based on the computational Distributed Cohort Model of spoken word recognition (Gaskell & Maslen-Wilson, 1997) and the Complementary Learning System account of learning and memory (McClelland, McNaughton, & O'Reilly, 1995; O'Reilly & Norman, 2002) (see Figure I-5).

It is hypothesized that sparse representations of new words are rapidly acquired by the hippocampus and medial temporal lobe systems, whereas overlapping distributed representations of the words are more slowly learned by the neocortex to retain stable memories for long periods. In the case of spoken word acquisition, the second stage is performed by the neocortical system involved in speech perception. The input to the system corresponds to complex spectro-temporal feature representations encoded in primary auditory brain areas on the superior temporal plane (Chi, Ru, & Shamma, 2005). Those speech segments have to be mapped onto sequences and lexical representations. The Distributed Cohort Model requires short-term storage such that information of the speech input can be accumulated over time and sequences of phonemes can be discriminated. It is assumed that this transient memory for previously heard auditory input is subserved by the anterior regions of the superior temporal gyrus (Davis & Johnsrude, 2007). Lexical identification is then separated into the phonological form and the meaning of a spoken word. The posterior-going auditory stream in the superior temporal gyrus and inferior parietal lobule map heard speech sounds onto phonological representations whereas the pathway involved in accessing meaning from speech is mainly located in the inferior temporal gyrus (Hickok & Poeppel, 2004, 2007; Price, 2010; Scott & Johnsrude, 2003).

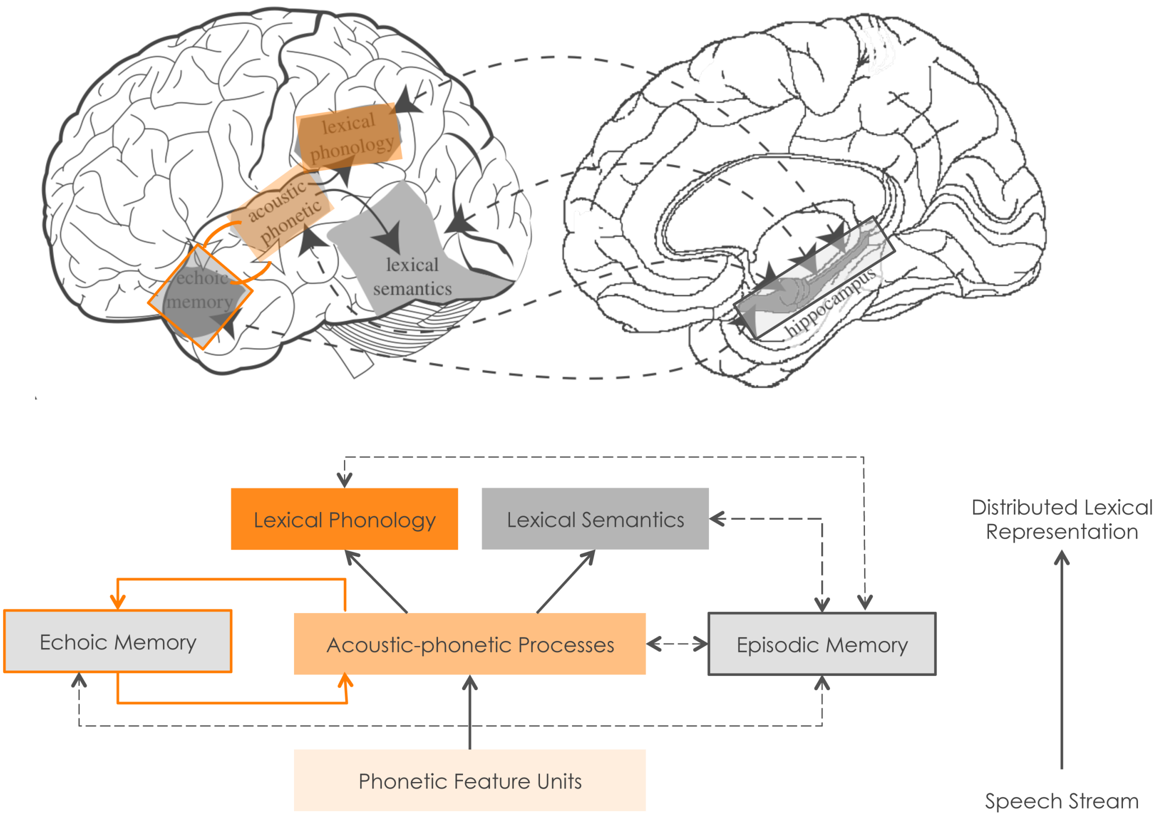

Figure I-5: Neural and functional organization of systems involved in the representation and learning of spoken words

(Adopted from Davis & Gaskell, 2009)

Although the Complementary System Account of Word Learning is only specified for novel spoken word acquisition in the auditory modality, the model is thought to cover the broad phenomenon of word learning. Hence, it proposes analogous modality-specific processing pathways in acquiring new written words.

In the case for learning Chinese as a second language, one would assume that short-term storage of auditory speech segments would equally hold true in Chinese, but that short-term storage of visual written segments that cannot be converted into phonemes in Chinese characters might require additional visual maintenance.

3.2 THE PROCESSING FRAMEWORK FOR CHINESE AS A SECOND LANGUAGE

Liu, Wang, and Perfetti (2007b) proposed a processing framework specified for learning Chinese characters as a second language, which is a modification of the Lexical Constituency Model by Perfetti et al. (Perfetti et al., 2005; Perfetti & Liu, 2006). In line with the aforementioned considerations the authors underscore visual analysis in Chinese character recognition. The model assumes similar structure and processing assumptions for second language learners compared to the original model developed for skilled native readers. As in the original model, character recognition starts with the visual input. Stroke and position information activate a group of orthographic units. Importantly, it is suggested that the decomposition of characters into radicals is essential. Thus, the model must comprise orthographic units also at the radical level prior to units at the character level contrary to alphabetic languages. The presented character receives most activation from activated radicals as well as stroke patterns and consequently reaches the threshold before other orthographic units. This ‘winner unit’ in turn activates corresponding phonological and semantic units. Semantic units are internally connected to semantically related characters; a number of semantically related characters thus receive activation and start activating their respective phonology. Onset, rime and tone units for the presented character are most strongly activated from orthographic and semantic levels, so they reach the threshold first. The threshold assumption of the orthographic units together with initial unfamiliarity of Chinese characters and their complex non-linear visual-spatial organization are likely to give rise to an important role of the visual-orthographic analysis in learning Chinese characters.

This assumption is supported by a priming study in Chinese second language learners (Liu, et al., 2007b). After the first term in a Chinese class participants showed facilitation for naming speed when characters were preceded by an orthographically similar prime, but not when the target was preceded by a phonological or semantically related prime. However, this facilitation disappeared at the end of the second term. Comparably, in an event-related potential (ERP) study Chinese second language readers revealed larger N200/P200 amplitudes at frontal and occipital electrodes for Chinese materials compared to English after the first term but not after the second, indicating that more visual processing and more effort to access lexical orthographic information were needed for processing written Chinese due to the high demand on visual analysis during lexical retrieval at the early stage of learning (Liu, Perfetti & Wang, 2006). In line with these studies, the behavioral finding that Chinese second language learners can quickly acquire the composition structure of Chinese characters (Wang, Perfetti, & Liu, 2003) suggests that visual perceptual learning is essential in early non-alphabetic learning by alphabetic readers.

3.3 NEURAL NETWORKS UNDERLYING LEARNING CHINESE AS A SECOND LANGUAGE

When learning to read Chinese as a second writing system and to comprehend Chinese speech as a second language, it is to be asked how the brain deals with these new challenges. As second language learners lack a native knowledge of the spoken language, they have to accroach spoken language while learning to read and write at the same time. Moreover, if the to-be-learned writing system is different from the native one, additional challenges might be provided (Perfetti & Dunlap, 2008). Perfetti et al. (2007, 2010) proposed that as far as possible the procedures for reading the new writing system assimilate into the procedures of the existing network. Thus, the attempt to process a new language system as if it was the native one is thought to be the default option. For Chinese native speakers learning the alphabetic writing system, system assimilation seems to hold true, because the requirements of the new system do not exceed what can be assimilated by the old as written alphabetic words do not need to be read using grapheme-phoneme-conversion but can also be read in a ‘Chinese-like’ holistic way (for respective brain imaging data see Tan et al., 2003). However, for learning a new writing system which differs dramatically from the learner`s native language total assimilation is not possible, e.g. when German native speakers learn the Chinese writing system. In such a case, Perfetti et al. (Perfetti et al., 2007, 2010; Perfetti & Dunlap, 2008) hypothesize system accommodation, i.e. learning the new writing system forces an accommodation to new procedures and corresponding neural resources. Based on these considerations, in the following a review is given on the neural circuitry of word reading and speech perception when learning Chinese.

3.3.1 NEURAL SYSTMES FOR WORD READING IN SECOND LANGUAGE LEARNERS

Brain imaging methods have been used to examine the neural activations of alphabetic native speakers when processing logographic Chinese characters. Nelson, Liu, Fiez, & Perfetti (2009) demonstrated that native English speakers who were learning Chinese for one year showed an activation pattern, which mimics the activation pattern for Chinese character reading observed for native Chinese. Instead of the left-lateralized regions supporting reading in

English, Chinese second language learners especially activated the bilateral fusiform gyri as well as the left middle frontal gyrus. Thus, for English learners of Chinese the system accommodation hypothesis (Perfetti et al., 2007, 2010) holds true: Orthographic character processing is dependent on the Chinese writing system, since the reading network need to adopt areas that are specific for the unique demands of written Chinese characters. A similar pattern of accommodation for Chinese second language learners was found in a laboratory training study (Liu et al., 2007a) after native English speakers learned a set of 60 Chinese characters during a 3-day learning period. Printed characters were learned either together with its meaning only (English translation), its phonology only (spoken Chinese syllable) or its meaning and phonology (English translation and spoken Chinese syllable). All three groups showed the accommodation pattern i.e. the recruitment of bilateral fusiform gyri and bilateral middle frontal gyri.

These data on learning Chinese orthography further suggest that alphabetic native speakers will fail to read Chinese characters unless they apply visual procedures that process global character forms, including the hierarchical organization of high spatial frequency stroke patterns arranged in a lower spatial relational pattern within a character. Since the simpler linear alphabetic visual procedures are not sufficient for reading Chinese characters, specific neural resources for the visual analysis need to be recruited.

3.3.2 NEURAL SYSTEMS FOR SPEECH PERCEPTION AND COMPREHENSION IN SECOND LANGUAGE LEARNERS

In contrast to numerious studies examining learning Chinese characters, only one training study focused on learning spoken Mandarin Chinese words in second language learners. Wang, Sereno, Jongman, & Hirsch (2003) investigated the cortical effects of training adult native English first-year students of Mandarin Chinese to identify Chinese pitch patterns i.e. lexical tones. Classic speech-related areas including Broca`s area, Wernicke`s area, auditory cortex, and supplementary motor regions were active before and after lexical tone training. Though, after training activation on a tone identification task expanded in the left superior temporal gyrus and activation increased in the right inferior frontal gyrus. These findings were suggested to reflect enrichment plasticity in which existing neural networks for speech processing are expanded or recruited to fulfill novel language functions.

Therefore, these data indicate that learning sound to word mappings in Chinese recruits similar brain regions as in alphabetic languages. More specifically it highlights the role of the dorsal auditory stream (Hickok & Poeppel, 2004, 2007) in the process of successful integration of foreign sounds to the phonology of new words. As the sensory-motor loop of the dorsal pathway is assumed to provide the neural basis for verbal working memory especially to use articulatory-based rehearsal processes during the maintenance of auditory representations (Baddeley, 1992; Hickok & Poeppel, 2004), auditory-phonological working memory is a likely candidate as an underlying mechanism of learning spoken words in alphabetic languages as well as in Chinese.

4 COGNITIVE PROCESSES SUPPORTING VOCABULARY ACQUISITION: THE CASE OF WORKING MEMORY

Further evidence, that working memory might underlie vocabulary acquisition comes from the notion that second language vocabulary acquisition in alphabetic languages is assumed to be based on phonological working memory. Before outlining a model in which this link is proposed, reviewing the relevant literature for alphabetic language and what is known for the Chinese language, I will give a rough overview about relevant working memory models.

4.1 WORKING MEMORY MODELS

Generally, researchers agree upon that working memory has strong implications for different levels of language processing such as vocabulary acquisition in alphabetic first and second languages and sentence comprehension (e.g. Chein, Ravizza, & Fiez, 2003; Ardila, 2003; Baddeley et al., 1998; Baddeley, 2003a; Ellis & Sinclair, 1996; Cowan, 1996; Lewis, Vasishth, & van Dyke, 2006). However, despite the host of working memory models most of them make little contact with models of language processing or implement links to language related processes.

In the following, I will first review the most prominent working memory model – Baddeley`s Multiple-Component Model (e.g. Baddeley & Hitch, 1974) - followed by the working memory model by Cowan (1999) – the Embedded-Processes Model - and a recent framework of a Domain-Specific Working Memory Network proposed by Zimmer (2008).

4.1.1 BADDELEY`S MULTIPLE-COMPONENT MODEL

The most influential and widely adopted model of working memory is Baddeley`s Multiple-Component Model (Baddeley & Hitch, 1974; Baddeley, 1986, 1995, 2002, 2003b) (see Figure I-6). According to this model, working memory refers to the ability to maintain and manipulate information for a short period of time (Baddeley, 2002).

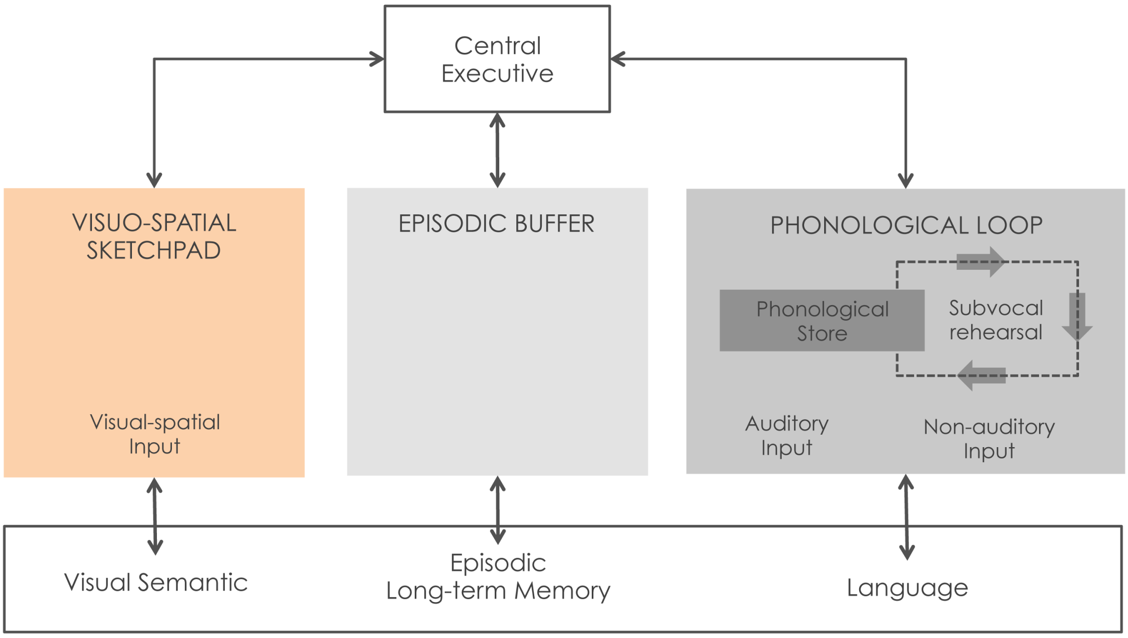

Figure I-6: Baddeley`s Multiple-Component Model

(Adopted from Baddeley, 2002, 2003b)

The original model by Baddeley and Hitch (1974) as well as the current model by Baddeley (2002, 2003b) proposes that there are separate systems for maintaining distinct types of information. The model comprises a central executive, an attentional controller, aided by two subsidiary slave systems, the visuo-spatial sketchpad and the phonological loop. The visuo-spatial sketchpad works with visual and spatial information, while the phonological loop is specialized for the retention and manipulation of auditory verbal material. The phonological loop is further divided into a passive phonological store that maintains auditory-verbal information through phonological representation and an active rehearsal process that refreshes these representations by subvocalization or ‘inner speech’. The subvocalization process is also used for transforming visually presented verbal information into auditory-verbal representations by means of grapheme-phoneme conversion. It is assumed that the primary function of the phonological loop is to mediate language learning particularly with regard to learning sound patterns of new words (Gathercole & Baddeley, 1993). Besides, the model comprises a forth component, the episodic buffer (Baddeley, 2000), which is assumed to be a limited capacity store that binds information to form integrated episodes.

A host of functional neuroimaging studies have directly addressed neural correlates of the components proposed in the model which led to a general agreement on the specific mapping between components of the model and particular brain regions (e.g. Henson, 2001, Smith &

Jonides, 1997, 1998, 1999; Chein et al., 2003). The phonological store is attributed to the left supramarginal gyrus (BA 40), whereas the speech-based rehearsal processes are performed by Broca`s area (BA 44/45). Operations of the central executive are assumed to be fulfilled by the dorsolateral prefrontal cortex (BA 9/46).

4.1.2 COWAN`S EMBEDDED-PROCESSES MODEL

An alternative working memory model, the Embedded-Processes Model, was proposed by Cowan (1993, 1995, 1999) (see Figure I-7).

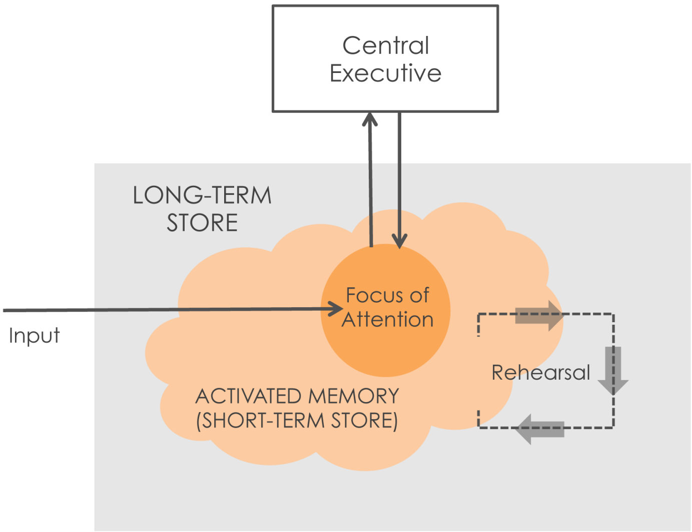

Figure I-7: Cowan`s Embedded-Processes Model
(Adopted from Cowan, 1999)

Instead of separate working memory mechanisms as proposed by Baddeley, Cowan assumes that any sort of memory process – over long or short periods of time – should accounted for by a common set of learning and memory principles. Thus, he proposed only one memory store that is equated with long-term memory. It is assumed that representations are hold as sets of associated features or feature combinations. Information can be brought to working memory in two ways: on the on hand a subset of information stored in long-term memory can be raised to a heightened state of activation for short periods of time. On the other hand, a subset of this information can be brought in the 'focus of attention' such that it is made even more salient. The focus of attention is assumed to be capacity-limited and compasses only a small amount of information at a time. This suggests that working holds information in a readily accessible state based on its activation from long-term memory. Akin to Baddeley`s assumptions, a central executive is likewise incorporated in the Embedded-Processes Model which provides a domain general processing capacity. Its main function is to reactivate decaying activity by searching through a set of memory items and ‘scanning’ them through the focus of attention (Cowan, 1992, 1999).

Cowan speculated on the mapping between the basic structural elements of his model and its underlying brain regions (Cowan, 1995). He assumes that representations in long-term memory are distributed throughout the neocortex. When incoming stimuli need to be held in working memory, the activated features determine the respective brain region in which this information will be processes and maintained. Whereas sensory features are suggested to be processed in the same regions that are also involved for perceiving the stimulus, i.e. sensory cortices, higher-order features (e.g. semantic) should activate association cortices. The functions of the central executive are likely to be performed by frontal areas especially the dorsolateral prefrontal cortex (Cowen, 1995), which is similarly assumed in Baddeley`s model. Critically, the Embedded-Processes Model assumes different contributions of the inferior parietal cortex and Broca`s area to working memory as compared to the Multiple-Component Model. The inferior parietal cortex might serve as an attentional ‘spotlight’ by focusing and shifting attention across activated memory representations rather than being involved in phonological storage. Broca`s area is thought to process and represent phonological information in general. This phonological information might be used both in attentional scanning and in speech-based rehearsal or non-mnemonic language processing.

4.1.3 ZIMMER`S DOMAIN-SPECIFIC WORKING MEMORY FRAMEWORK

Somewhat similar to the Multiple-Component Model, Zimmer (2008) suggested that content-specific modules corresponding to the sensory input process specific types of information, e.g. visual and auditory. Critically, those modules are not assumed to form separate buffers but are rather viewed as distributed representations of domain-specific information that is also used in perception and long-term memory - similarly to Cowan`s suggestions. Sensory information such as visual or auditory is processed by content-specific modules which are organized hierarchically from specific feature analysis to so-called object files that bind different features of the same object. Whereas visual and auditory modules are modality-specific, the representation of environmental space is assumed to be amodal (see Figure I-8).

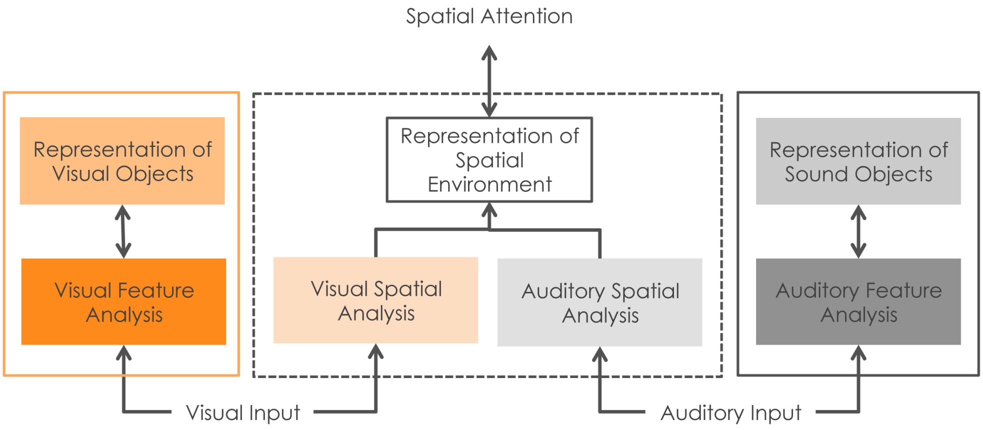

Figure I-8: Zimmer`s Domain-Specific Working Memory Framework

Domain-specific sensory and amodal spatial components of working memory (adopted from Zimmer, 2008)

Based on the ideas proposed by Ranganath (Ranganath, 2006; Ranganath & Blumenfeld, 2005; Ranganath & D'Esposito, 2005), Zimmer extends his framework by combining the aforementioned components to neural correlates (see Figure I-9).

The basic assumption is that working memory should not be viewed as a separate system dedicated to memory, but is rather characterized as processes operating on sensory information in a network widely distributed over the brain. Similarly to Cowan`s model, it was suggested that the neural basis of working memory partially overlaps with regions involved in long-term memory and perception as same structures represent active information in content-specific cell assemblies.

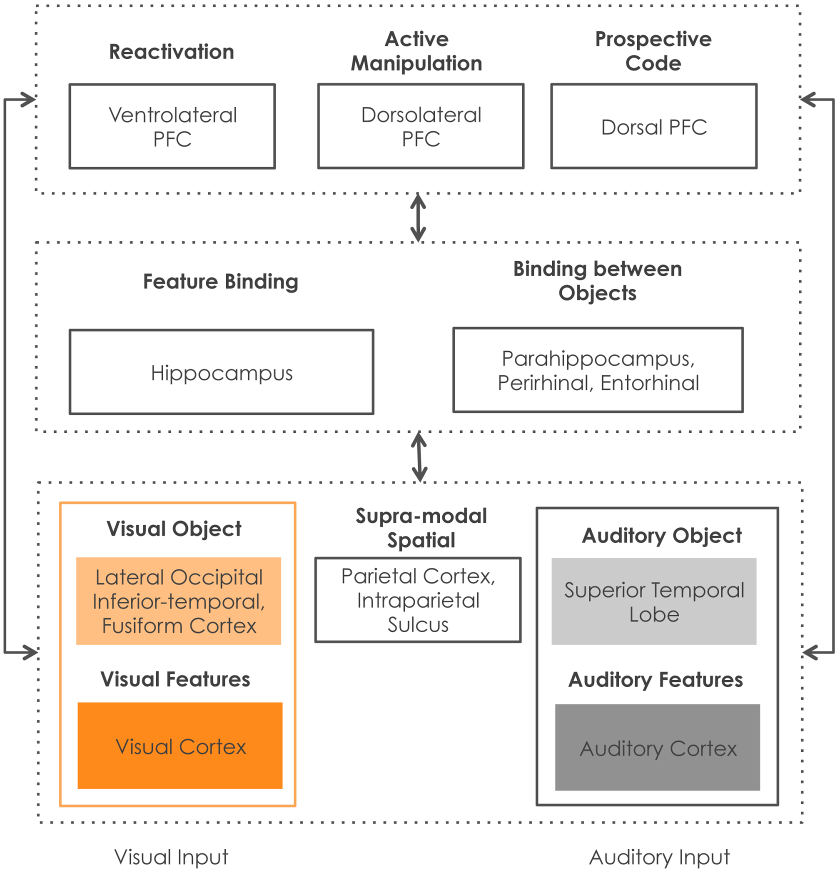

Figure I-9: Major components of working memory and their neural structures

(Adopted from Zimmer, 2008)

At the lowest level, sensory features are maintained in the respective sensory cortices. Climbing up the hierarchy, visual objects are represented in posterior visual cortices such as occipital and inferior-temporal cortex and auditory features in auditory cortices located in the superior temporal lobe. Spatial representations are assumed to be amodal and processed in the parietal cortex. For the representation of new objects, binding features within one object, and binding different objects medio-temporal areas such as hippocampal and perirhinal cortices are required. The PFC - on top of the hierarchy – facilitates the maintenance and manipulation of representations. More specifically, the ventrolateral PFC activates and reactivates representations in more posterior regions, whereas the dorsolateral PFC transforms and manipulates active information. Superior frontal regions are linked to a prospective code basically relevant for spatial information.

4.2 THE RELATIONSHIP BETWEEN WORKING MEMORY AND VOCABULARY ACQUISITION IN ALPHABETIC LANGUAGES

The aforementioned working memory models should be kept in mind when considering the link between working memory and word learning, particularly because Baddeley explicitly links one component of his working memory model to vocabulary acquisition in alphabetic languages.

Derived from the Multiple-Component Model, Baddeley et al. (Baddeley, Gathercole, & Papagno, 1998) introduced the Model of New Word Learning (see Figure I-10). It was proposed, that especially phonological working memory is needed to learn novel words in first as well as second languages. The apparent implication is that language learners have to rely on the phonological loop system that provides necessary short-term storage of novel unfamiliar sound patterns while more stable long-term phonological representations can be formed and stored as a stable lexical unit in the mental lexicon (Baddeley et al., 1998; Baddeley, 2003a) (see right panel of Figure I-10).

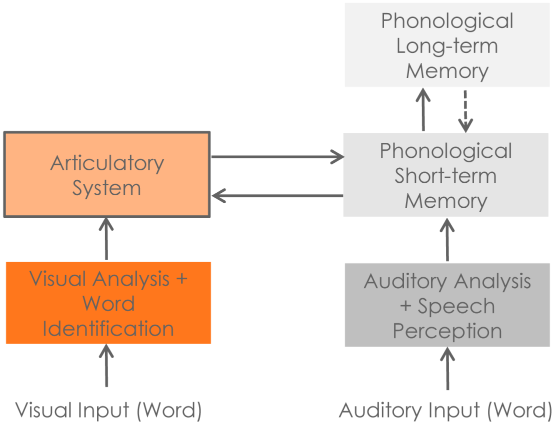

Figure I-10: The Model of New Word Learning

Components involved in short-term storage and long-term phonological learning of new words (adopted from Baddeley, et al., 1998)

If the input of the word is visual as in reading, the sequence of letters is transformed automatically into a phonological code using grapheme-phoneme correspondence rules. This information is entered into the phonological store by means of sub-vocal articulation; hence the retention depends crucially on acoustic and phonological characteristics (Baddeley, 2003a; Baddeley & Logie, 1999) (see left panel of Figure I-10). Accordingly, the relationship outlined above holds equally true for auditorily as well as visually presented words in alphabetic languages (Papagno, Valentine, & Baddeley, 1991).

Based on this model, the relationship between phonological working memory and vocabulary acquisition in first and second languages has been demonstrated in various lines of research: First, many studies focused on correlating phonological working memory with natural word learning during first language learning among young children. Phonological working memory usually measured by non-word repetition tasks consistently predicted subsequent vocabulary size (Gathercole & Baddeley, 1989; Gathercole, Willis, & Baddeley, 1991; Gathercole, Willis, Emslie, & Baddeley, 1992; Gathercole & Adams, 1993; see Baddeley et al., 1998, for a review). Second, experimental studies directly disrupted the phonological working memory component and investigated the effects on vocabulary acquisition in adults. Papagno, Valentine, and Baddeley (1991) demonstrated that when native Italian speakers learned Italian and Russian words in a paired-associate learning task, articulatory suppression (induced by repeating a non-sense syllable) worsened the learning of unfamiliar Russian words. Third, other studies looked at individual differences in phonological working memory and correlations with experimental word learning. Gathercole and Baddeley (1990) could show that children with low nonword repetition scores were faster in learning novel unfamiliar toy names compared to those children with low repetition scores. Moreover, Papagno & Vallar (1995) reported that bilingual Italian speakers perform higher than their monolingual counterparts in a non-word repetition task, an auditory digit span task, and a paired-associated learning task with unfamiliar Russian words, whereas no differences were found in general intelligence, visuo-spatial working memory and learning familiar (Italian) words. Furthermore, longitudinal studies on second language learning provided more direct evidence that the later success in acquiring foreign vocabulary is predicted by non-word repetition ability (Service, 1992; Service & Kohonen, 1995; Cheung, 1996). For example the study by Cheung (1996) revealed that nonword repetition span uniquely predicted the number of English second-language vocabulary-learning trials in native Cantonese speakers. Taken together, these studies strongly point to an overall involvement of phonological working memory in learning new words in alphabetic languages.

Although Cowan and Zimmer do not explicitly treat of the relationship between working memory and new word learning in their models (Cowan, 1999; Zimmer, 2008), at least Cowan conjectures about it. He agrees with Baddeley`s assumption that phonological working memory as measured by nonword repetition is necessary for vocabulary acquisition although he refutes the idea that the phonological loop should be speech-specific (Cowan, 1996). Further, he speculates that serial order information presumably only for items presented in the auditory modality could underlie vocabulary acquisition and other aspects of language learning such as sentence comprehension.

4.3 THE RELATIONSHIP BETWEEN WORKING MEMORY AND VOCABULARY ACQUISITION IN CHINESE

In comparison to the host of studies demonstrating the close relationship between phonological working memory and word learning in alphabetic languages, not much is known about the relation between working memory and vocabulary acquisition in the case of logographic Chinese. Critically, a simple adoption that phonological working memory might underlie written and spoken vocabulary acquisition in Chinese seems unlikely due to decidedly different design principles of the Chinese language system.

When learning Chinese vocabulary as a second language, one would assume that for learning new characters short-term retention of visual written segments is more strongly required as it is needed for learning alphabetic words. As those segments are visually more complex and cannot be converted into phonemes via grapheme-phoneme-conversion, additional visual-orthographic analysis and visual short-term storage are likely to play a crucial role. For learning new spoken words in Chinese the requirements to store auditory speech segments over short periods of time which is likewise necessary for learning spoken words in alphabetic languages would equally hold true in Chinese.

Despite the lack of studies investigating visual working memory as a predictor for language learning, a couple of studies examined determinants of reading ability in Chinese focusing primarily on visual processing skills and phonological awareness in a developmental approach. Huang and Hanley (1994) reported that visual skills such as visual form discrimination and visual paired-associate learning predicted reading in native Chinese but not in native English children. Subsequent investigations found that visual processing skills such as the ability to visually memorize abstract figures over a short period of time (Siok & Fletcher, 2001), detecting and memorizing stroke patterns (Ho & Bryant, 1997b) predicted reading Chinese characters only at early stages of learning to read, whereas at higher grades predominantly phonological skills correlated to reading abilities. In agreement with those findings, other correlational and longitudinal studies (McBride-Chang & Ho, 2005; Tong & McBride-Chang, 2010) found visual skills and orthographic knowledge, in addition to phonological skills, to contribute specifically to Chinese character recognition. The strongest evidence for the assumption that visual-orthographic processes are mandatory for Chinese character reading comes from a study by Tan, Spinks, Eden, Perfetti, and Siok (2005b). In a correlational study with beginning and intermediate Chinese readers the authors aimed to investigate which variables best predict Chinese skilled reading. Besides two tests on phonological awareness (oddity test to assess sensibility to fine-grained sounds and syllable deletion to test sensitivity to coarse sounds) and processing speed as measured by a rapid automized training task, participants were asked to copy written Chinese characters, pseudocharacters and simple 2-dimensional objects. The ability to read as indexed by the amount of Chinese characters (taken from standard Chinese textbooks) that could be read correctly within 2 minutes was best predicted by character and pseudocharacter writing, drawing simple objects, and rapid naming. Although phonological awareness also predicted Chinese reading it accounted for far less variance in a multiple regression analysis. Thus, the results were taken to show that the unique contribution of phonological awareness to reading that is known for alphabetic reading is minor for Chinese. Instead, writing (and drawing) seem to better predict reading as Children learn to deconstruct visually complex characters in their sub-components of patterns of strokes. This decomposition is assumed to take place on the visual-orthographic level and thereby facilitates learning the character`s internal visual-spatial structure. Furthermore, Tan et al. (2005b) assume that a second mechanism, motor programming, as indexed by the strong relation between object drawing and Chinese reading additionally improves learning to read.

Taken together, these findings, though heterogeneous, provide some evidence that visual orthographic processing skills often measured by working memory-like tasks are crucial especially in early stages of learning to read Chinese due to the demanding visual complexity of the characters system, but besides that phonological skills are still predictive.

The question whether short-term storage of novel sound patterns is required for learning spoken Chinese words was indirectly addressed in two studies. Wong and Perrachione (2007) examined learning of non-native auditory supra-segmental pitch patterns for lexical word identification in native English speakers. English pseudo-syllables superimposed with three pitch patterns served as Chinese-like syllables with lexical tones. Non-lexical pitch processing and previous musical experience best predicted the acquisition of these syllables. Moreover, the proficiency of Chinese language skills measured by high school grades in English-Chinese bilinguals was positively correlated with phonological working memory measured by means of an auditory phonological *n*-back task (Chee, Soon, Lee, & Pallier, 2004). Therefore, auditory phonological skills as well as auditory-phonological working memory are expected to predict learning success of spoken Chinese words akin to alphabetic languages.

4.4 HYPOTHESES ON THE RELATIONSHIP BETWEEN WOKRING MEMORY AND VOCABULARY ACQUISITION IN CHINESE

Following these lines of arguments, I assume that the language system`s design principles impose constraints in the role modality-specific working memory processes, namely visual versus auditory, play for the acquisition of visual and auditory words in a second language. I argue that working memory skills in general predict vocabulary acquisition in a second language – also in Chinese. More specifically, I assume that for orthographic learning of Chinese characters the relative contribution of visual working memory additionally to auditory-phonological components is crucial – contrary to alphabetic languages. Whereas for phonological learning of spoken Chinese words particularly auditory-phonological working memory processes should be necessary – similarly to alphabetic languages.

5 WORKING MEMORY TRAINING AND ITS TRANSFER

The majority of findings on the relation between working memory and language acquisition for alphabetic languages as well as for Chinese conducted so far were basically cross-sectional studies investigation correlations between working memory performance and language proficiency, cross-sectional studies comparing working memory performance between groups that differ in language proficiency (e.g. bilinguals vs. monolinguals, high vs. low proficient second language speakers), or longitudinal studies testing the predictability of subsequent vocabulary performance. Although these studies made strong and important contributions to the understanding of the link between working memory and new word learning in both alphabetic and Chinese languages, they bear nevertheless several shortcomings. To begin with, correlational studies cannot account for any causal relationship between two variables. They can also not exclude further unknown variables by which the correlation could additionally be driven. Furthermore, groups differing in a particular skill (e.g. second language proficiency) might also differ in several other variables such that a comparison can never undoubtedly be attributed to differences in that particular skill. Despite the fact that longitudinal studies can test whether a specific variable affects subsequent performance on a particular task, other factors such as maturation and specific environmental circumstances can be confounded. Collectively, these considerations suggest that a more direct way of investigating the link between working memory and vocabulary acquisition is generally preferable.

A unique tool to investigate the impact of different working memory processes on Chinese second language learning is their specific training. The transfer of modality-specific working memory training to performance measures of visual and auditory vocabulary learning can be applied to address this concern, since the transfer of training can be used as an approach to directly trace performance increases in vocabulary learning back to improvements in a specific processes or component of working memory (Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010).

In classic training studies, a pretest-training-posttest design is applied (e.g. Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Karbach & Kray, 2009; Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; for reviews see Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Klingberg, 2010; Buschkuehl & Jaeggi, 2010). The pretest serves as a baseline for the performance on transfer tasks prior to cognitive training. Cognitive training ideally takes place under controlled conditions in a laboratory setting to prevent from any other influences. Critically, a control group is inevitable which either does not participate in the training (passive control group) or trains a cognitive task that does not tap into the process of interest but is comparable in any other characteristics of the training paradigm (active control group). In the posttest following the training it can be tested whether the training led to improvements in the trained and transfer tasks in comparison to the control group. As the trained and control groups might coincidentally differ in cognitive abilities it is advisable to match the groups according to general cognitive abilities such as fluid intelligence, processing speed, working memory and performance in the respective transfer tasks at pretest. The experimental nature of the transfer approach takes the advantage of allowing to directly test the influence of specific trainings on the transfer tasks while other possible influences are controlled for.

Moreover, most of the studies targeting on the link between working memory and word learning so far are behavioral studies. Thus, there is not much known about underlying neural contributions. The method of working memory training and its transfer can be readily combined with brain imaging methods such as fMRI to examine how the brain changes its way of functioning in the course of training. Thereby, working memory training induced activation changes can provide important insights into the nature of cognitive processes. Most interestingly, this approach provides an extraordinary opportunity to target cognitive and neural plasticity, the potential to modify cognitive and neural processing potentials.

Importantly, especially the training of working memory functions has recently attracted a great deal of attention, since various studies showed evidence that working memory training does not reduce to retest effects, and indeed can transfer to various untrained tasks (for a review see Klingberg, 2010). On this account, working memory training and its transfer is a promising method for the issue under investigation here.

In the following I will first outline the Theoretical Framework of Cognitive Plasticity by Lövdén et al. (2010), as it provides a framework for understanding the mechanisms of cognitive training as well as the conditions under which cognitive training is effective. By this, it further provides a benchmark for interpreting and evaluation existent studies of cognitive training including working memory training as well as for designing new training paradigms. Then, I will pass on to the issue of neural activation changes associated with cognitive training, since one major goal of this thesis is to shed light on the functioning of underlying brain networks. In this vein, a useful classification of neural activation changes after training proposed by Kelly and Garavan (2005) will be introduced. Based on these considerations I will next focus on the conditions for working memory training and its transfer to untrained tasks and derive the major issues under investigation in this thesis.

5.1 A THEORETICAL FRAMEWORK OF COGNITIVE PLASTICITY

The Theoretical Framework of Cognitive Plasticity proposed by Lövdén et al. (2010) defines plasticity as the compensatory reactive change of the cognitive system in response to a primary change, e.g. brain damage or cognitive training. Manifestations of plastic alternations of brain functioning and behavior are suggested to be the secondary change. A starting point for plasticity is the ‘flexibility’ of the system, i.e. the brain`s capacity to optimize performance within the limits of the current state of functional supply. Thus, it was assumed that cognitive and brain functioning is inherently adaptive and variable in nature while at the same time restricted to an individual range of performance. Plastic changes occur, if this range of cognitive performance is changed, increased or decreased. These changes are assumed being accompanied by alternations in brain functioning and structure. The initiative cause of plastic alternation (primary changes) is principally two-fold: changes of the system`s functional supply, due to brain injury, or increasing environmental demands on functional capacity, due to cognitive training (as depicted in Figure I-11).

The key proposition is that plastic changes are only initiated if primary changes result in a mismatch between the system`s functional capacity and environmental demands. Plasticity is therefore the reaction to a supply-demand mismatch (secondary change) and not to changes in demand or supply per se (primary change). The current state of flexibility determines the degree and nature of the mismatch, which in turn determines the magnitude of plastic change. More specifically, if the system can easily respond to environmental demands, no mismatch will occur. Comparably, if environmental demands are beyond the current range of flexibility, mismatch can also not occur. Therefore, demands must be on the upper (or lower) bound of functional supply to drive cognitive plasticity. Negative mismatch is characterized by higher demands of the task than available capacity in comparison to positive mismatch in which available capacity is higher than current demands (see Figure I-11).

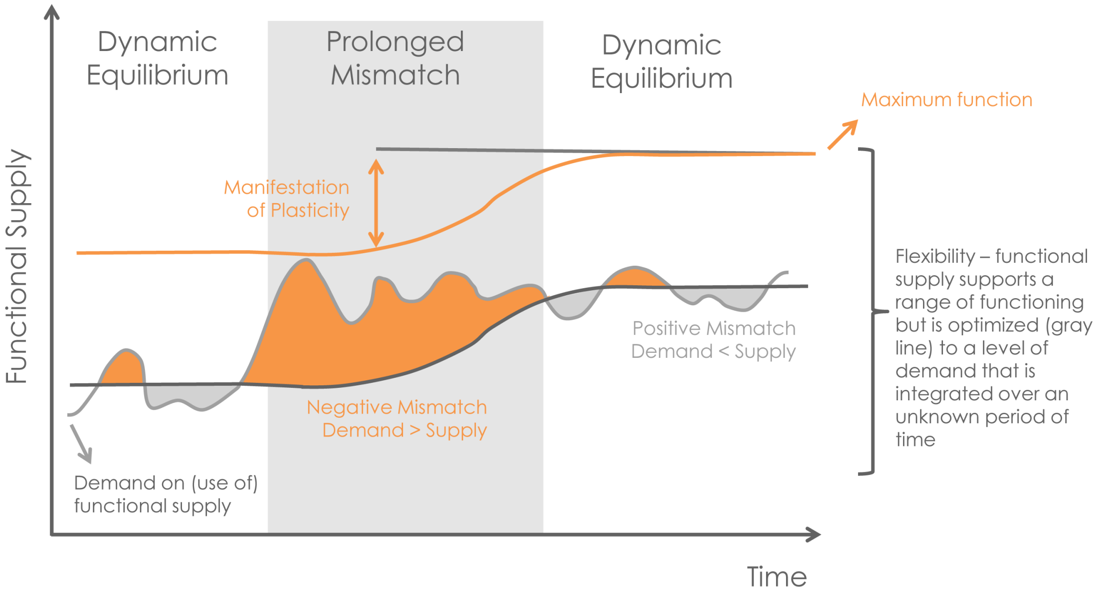

Figure I-11: Mismatch between functional supply and environmental demands caused by cognitive training

(Adopted from Lövdén et al., 2010)

For designing training paradigms this implicates that negative mismatch has to be maintained throughout the training. So, task difficulty need to be adaptive i.e. task difficulty has to change flexibly according to the participant`s current performance level. As the system normally levels off at a state of equilibrium, mismatch has to be substantially prolonged such that the system`s inherent sluggishness can be overcome.

In light of the assumptions made by the model adaptivity should be a crucial factor for the effectiveness of working memory training. The studies by Klingberg et al. (2005) and Holmes, Gathercole, and Dunning (2009) support this assumption to be evidenced by specific training effects for adaptive training, i.e. training in which the load of the task is individually adapted to the performance of each subject, compared to non-adaptive training. Moreover, as the cognitive system has to be pushed away from the sluggish state of equilibrium, substantial amount of time in which the mismatch has to be sustained is inevitable. In line with this view, Klingberg (2010) concludes in a recent review paper that a total amount of at least eight hours of working memory training or a training period of three weeks is required to achieve substantial training effects.

For the issue under investigation in the present thesis the requirements of permanent negative supply-demand mismatch throughout the training and a sufficient amount of training is of particular importance, because it garantees that the processes of interest i.e. visual and auditory working memory are actually trained. Hence, substantial training effects i.e. improvements within the trained tasks is a conditions precedent for further investigation the effect the trainings have on pre- and posttest tasks.

5.2 NEURAL ACTIVATION CHANGES ASSOCIATED WITH COGNITIVE TRAINING

Having outlined a framework for the conditions of cognitive plasticity and training, it further needs to be addressed how cognitive plasticity results in neural plasticity i.e. changes in neural activation associated with cognitive training. In an effort to provide a taxonomy for training related changes in neural activation patterns, Kelly and Garavan (2005) suggested a framework in which the distinction between two kinds of neural activation changes was made: redistribution and reorganization. Redistribution is constituted by a combination of increases and decreases in task-specific brain regions that are associated with performance attainments and decreased demands on attentional control processes as a function of practice. In particular, prefrontal cortex, anterior cingulate, and posterior parietal cortex are considered to fulfill this ‘scaffolding’ function, which gets redundant after extensive practice. These ‘scaffolding’ areas overlap with the common fronto-parietal working memory network. Redistribution can also be manifested in increased activation, which is assumed to mirror increased reliance on task- or process-specific regions. Conversely, reorganization is observed as a change in the localization of activations reflecting a ‘real‘ change in the cognitive processes performed before and after training.

The distinction Kelly and Garavan made is essential insofar as it differentiates between working memory and control processes in contrast to specific task-relevant processes which can both be improved by training but are reflected in different patterns of neural activation changes. Therefore, the brain regions itself as well as the kind of neural activation changes give hints to the nature of underlying processes that are improved by the respective training.

For the purpose of testing transfer effects from working memory training on learning Chinese vocabulary, it would be of particular importance which processes of word learning are exactly modified due to working memory training. Thus, specific regions of the language networks that are modified together with the kind of activation changes allows us to draw conclusions on the way visual and auditory working memory training modifies specific cognitive processes during word learning in Chinese.

5.3 CONDITIONS FOR TRANSFER

Most of the working memory training studies aim at using working memory training as a treatment to generally improve higher cognitive abilities and thus target at providing an applicable and effective intervention, which should result in enhanced performance in non-trained tasks, i.e. transfer effects (e.g. Chein & Morrison, 2010; Dahlin et al., 2008; Hempel et al., 2004; Holmes et al., 2009; Jaeggi et al. , 2008; Jolles, Grol, Van Buchem, Rombouts, & Crone, 2010; Klingberg et al., 2005; Mahncke et al., 2006).

In this vein, the question came up under which conditions transfer to other cognitive abilities emerge. Following the basic logic of transfer proposed by Thorndike (Thorndike & Woodworth, 1901; Thorndike, 1906), that “spread of practice occurs only where identical elements are concerned in the influencing and influenced function” (Thorndike & Woodworth, 1901; p. 250), effects on a particular task can only be observed, if it shares some commonality with the trained task. This idea was taken up by Jonides (2004) and applied in two recent behavioral working memory training studies (Jaeggi et al., 2008; Persson & Reuter-Lorenz, 2008). Jaeggi et al. (2008) examined transfer of working memory training to fluid intelligence in a sample of young adults. By applying the aforementioned logic of transfer, it was hypothesized that as working memory and intelligence share a common capacity constraint, namely the common demand for attention and binding processes, training of a working memory task that taps into these processes should increase the performance in a reasoning task. Indeed, training of a demanding dual *n*-back working memory task over 8 to 19 sessions led to significant improvements in a figural reasoning task of fluid intelligence compared to a no-contact control group. The study by Persson and Reuter-Lorenz (2008) applied a different approach to selecting training and transfer tasks on the basis of their common reliance on a specific brain region. As the left inferior frontal gyrus (IFG) is known to be recruited both in working memory tasks that involved interference resolution and semantic and episodic memory that include a high interference component, it was hypothesized that if neural overlap implicates functional overlap, transfer between these different memory domains should occur, whereas it should not, if no interference resolution is involved in the transfer tasks. Based on these considerations, training eight 50-minute sessions of the high-interference versions of three different working memory tasks were compared to those of the corresponding non-interference versions in the control group. Only the high-interference training led to increased efficiency in proactive interference resolution in the trained and also in those non-trained tasks that involved interference resolution. These data provide even stronger support for the commonality logic, as transfer was only found for those tasks that actually shared the trained process of interest.

Dahlin et al. (2008) were the first to apply the commonality logic of transfer to cognitive neuroscience and thus proposed (similarly to Persson & Reuter-Lorenz, 2008) that transfer effects only occur, if the criterion task and the transfer task engage similar processing components, which should be reflected in overlapping brain regions. The training of a letter updating working memory task over five weeks led to transfer on an *n*-back task, sharing the updating component, but not to an unresembling stroop task. The pattern of brain regions involved in these tasks before and after training revealed that activation overlap between the trained letter updating task and the *n*-back task was broad, whereas it was small between the letter updating task and the stroop task. Thus, this evidence was taken to provide unique support that transfer only emerges if (a) the trained and the transfer task share processing components and (b) overlapping brain regions are engaged in the trained and transfer tasks.

5.4 AIMS OF THE LANGUAGE TRAINING STUDY

In following this approach, this thesis aims at investigating whether working memory training can generally improve second language vocabulary acquisition in Chinese. In addition, it is questioned whether the transfer is modality-specific for the visual and auditory modality. As previous studies compared specific trainings to disentangle components of working memory (Sayala, Sala, & Courtney 2006; Persson & Reuter-Lorenz, 2008), intra-modal and across-modal transfer effects on second language word acquisition in Chinese are similarly investigated by employing two different kinds of working memory trainings which only differ in the sensory modality of stimuli, i.e. visual versus auditory. Thus, the key purpose was to explore how visual and auditory working memory training affects learning Chinese visual and auditory words conjointly as well as specifically and how these trainings differ in their modulation of activation changes in underlying brain networks.

6 CAN WORKING MEMORY BE TRAINED SPECIFICALLY WITHIN THE VISUAL MODALITY?

As the basic question of this thesis is whether two modality-specific working memory trainings result in differential transfer effects of Chinese orthographic and phonological learning, an open-ended question needs to be addressed previously: Can visual and auditory components of working memory actually be trained separately?

The focus of this thesis is on the unique contribution of visual working memory to Chinese character learning. Hence, I consider it necessary to show that improvements in a visual working memory task can be specifically improved by visual working memory training compared to auditory training or no training as a pre-condition for investigating this question. Thus, if such an intra-modal training effect can be demonstrated, it feels safe to assume that specifically visual components of working memory can indeed be trained separately. The dissociation between intra-modal and across-modal training effects shall be exemplified for the visual modality on the behavioral level. Furthermore, on a neural level, the separation between intra-modal and across-modal effects that are independent from the training modality shall be addressed.

6.1 MODALITY-SPECIFICITY IN WORKING MEMORY

As outlined previously the multi-component model by Baddeley et al. (Baddeley & Hitch, 1974; Baddeley, 2002, 2003b) comprises two subsidiary slave systems: the visuo-spatial sketchpad and the phonological loop. These independent and modality-specific systems form storage buffers for the processing and rehearsal of visuo-spatial and phonological materials and make these materials accessible for central control processes. The distinction between the two modality-specific slave systems has attracted a considerable amount of interest in the past years, but little is known to which amount they are plastic and can be trained specifically.

Studies have used various kinds of tasks to investigate working memory functions. Whereas classic span tasks (e.g. reading span) and recognition tasks (e.g. delayed matching tasks) primarily focus on the maintenance component of working memory, other tasks like the so-called *n*-back task additionally tap into higher order control processes (Cohen et al., 1997). The *n*-back task places high demands on various component processes within working memory namely maintenance, rehearsal, and especially manipulative processes such as the continuous updating of memory contents. Functional neuroimaging studies showed that the *n*-back task elicits bilateral fronto-parietal activations especially in the dorsolateral prefrontal cortex (PFC) and in superior and inferior parietal areas (e.g. Ragland et al., 2002; Druzgal & D'Esposito, 2001; Owen et al., 1999; Casey et al., 1998; Carlson et al., 1998; Nystrom et al., 2000; for a meta-analysis see Owen, McMillan, Laird, & Bullmore, 2005). This network is assumed to be largely independent of stimulus materials (Nystrom et al., 2000;

Owen et al., 2005) and is also found to be active in other working memory tasks such as item recognition or delayed matching (e.g. Mecklinger, Bosch, Gruenewald, Bentin, & von Cramon, 2000; for a meta-analysis see Wager & Smith, 2003).

Even though the important distinction between modality-specific storage systems can be found in the contemporary models of working memory as outlined previously, only few brain imaging studies have directly compared visual versus auditory working memory processes. One ERP study provided evidence for distinct visual and auditory working memory processes reflected in topographically and temporally different ERP slow waves (Ruchkin et al., 1997). In contrast, a positron emission tomography (PET) study by Schumacher et al. (1996) failed to find modality-specific differences between a visual and auditory verbal 2-back task, except for a greater activation in Broca`s area in the auditory task. Results were thus interpreted as largely reflecting amodal representations of verbal working memory contents.

The issue of modality-specifity of working memory was further investigated in recent fMRI studies. Direct comparisons of working memory for visually and auditorily presented single digit numbers revealed greater activations in the left posterior parietal cortex in a visual 2-back task and greater left dorsolateral PFC activations in the auditory version of the task (Crottaz-Herbette, Anagnoson, & Menon, 2004). Partly consistent with these findings Rodriguez-Jimenez et al. (Rodriguez-Jimenez et al., 2009) report greater bilateral activations in the dorsolateral PFC in the auditory compared to the visual condition of a verbal letter 2-back task along with modality-specific effects in sensory cortices. However, as both of the aforementioned studies used stimuli that are verbally recodable, it is possible that these dissociations were caused by factors other than input modality. The modified working memory model of Smith and Jonides (1997) assumes that all visually presented verbal materials are automatically transformed into a phonological code (see also Suchan, Linnewerth, Köster, Daum, & Schmid, 2006; Linden, 2007). Therefore it is arguable whether those effects can be ascribed to working memory modality, since they are confounded with recoding or semantic categorization processes. To prevent from this, it is necessary to use stimulus material, which cannot be abstracted from its sensory nature.

In a recent fMRI working memory study, Protzner and McIntosh (2007) tried to meet these requirements by using visually versus auditorily presented white noise bursts, i.e. stimuli that can neither be coded verbally nor converted into semantic representations. Using working memory tasks like temporal sequencing and stimulus comparison, they found modality-specific activations outside sensory cortices, located in the right middle frontal gyrus, right posterior superior temporal cortex, left middle cingulate, and left inferior parietal cortex for visual and right putamen and left posterior cingulate for auditory stimuli. These results point to a relative dissociation of working memory related activations according to the visual and auditory modality.

The data reviewed above support the hypothesis that working memory related activity in frontal and parietal cortices is partly modality specific and that the degree of the relative involvement of specialized areas varies with the degree of abstraction from the sensory nature of the stimulus materials and the transformation into conceptual i.e. verbalizable representations.

6.2 TRAINING OF SPECIFIC PROCESSING COMPONENTS IN WORKING MEMORY

Besides the approach of using working memory training to achieve transfer to untrained tasks, functional plasticity of process- or component-specific dissociations in working memory can be elegantly investigated using their specific training. Only a few studies followed this approach (Persson & Reuter-Lorenz, 2008; Sayala et al., 2006) and intended to disentangle components of working memory. Accordingly, they compared specific trainings, which differ only in terms of a processing component of interest (see also Lövdén et al., 2010). For these studies specific dissociations between different training groups are a matter of interest. Dissociations on the trained task indicate the trainability of a specific component or process in working memory, whereas dissociations on transfer tasks show that untrained tasks specifically benefit from the improvement of the component of interest. For example, the behavioral training study by Persson and Reuter-Lorenz (2008) provides evidence for training and transfer effects of a specified control process (i.e. interference resolution) as outlined previously. Notably, only one brain imaging study focuses on dissociations between specific and unspecific effects of working memory training contrasting visual-object versus visual-spatial working memory training. Sayala et al. (2006) report specific decreases in right superior frontal sulcus, right precuneus, and left postcentral sulcus during the delay period of a spatial recognition task after short-time training (five runs consisting of eight memory trials each) of the spatial version of the delayed recognition task compared to the training using object material. Moreover, decreased activations for both trainings were found in the right precentral sulcus and right insula during the delay period. Interestingly, these effects arose in the absence of any changes in performance. Thus, these domain-specific effects were taken to reflect increased efficiency in the representation of relevant spatial information and filtering of irrelevant object information over time, whereas the domain-unspecific effects reflect general changes in working memory control processes. For the first time it was shown that specific training can lead to specific activation decreases in the fronto-parietal working memory network. In the present study we used a similar approach, as it allows to dissociate intra-modal from general, across-modal training effects by comparing visual versus auditory working memory training.

6.2.1 NEURAL ACTIVATION CHANGES ASSOCIATED WITH WORKING MEMORY TRAINING

Studies attempting to characterize the neural correlates of training-related improvements by examining corresponding neural activation changes reveal an inconsistent pattern of results (Chein & Schneider, 2005), which can possibly be attributed to different training procedures varying in length and intensity. Olesen, Westerberg, & Klingberg (2004) reported increases in the left middle frontal gyrus and bilateral superior and inferior parietal cortices as well as decreases in the left inferior frontal gyrus using three types of visuo-spatial working memory tasks during training. In contrast Hempel et al. (2004) described an inverted u-shaped function in mainly comparable frontal and parietal regions during a more intense training of a spatial *n*-back task. Dahlin et al. (2008) found decreases in frontoparietal regions during a letter memory updating training lasting five weeks, which transferred to a 3-back task comprising similar updating characteristics. Studies examining practice effects during short-term repetition (within-session practice) consistently report decreases in activations in fronto-parietal regions although training effects on the behavioral level are not found consistently (Landau, Schumacher, Garavan, Druzgal, & D’Esposito, 2004; Sayala et al., 2006; Garavan, Kelley, Rosen, Rao, & Stein, 2000). It seems that short-term practice does not allow to differentiate between mere repetition effects and real training effects, because decreases in brain activation may also reflect priming due to repeated presentation of stimuli or changes in strategies. Effects arising from long-term training cannot be attributed to pure task repetition as long as the training is accompanied by behavioral training effects. Nevertheless, the shape of functional plasticity during intense long-term training is still a matter of controversy.

6.3 AIMS OF THE WORKING MEMORY TRAINING

Following those lines of research, the Working Memory Training Study aims (a) to explore whether working memory for visual materials can be trained by means of a visual *n*-back task and how any effects of visual working memory training are reflected in the functional neuroanatomy underlying task performance and (b) to examine the extent to which any such training effects and their neural correlates are intra-modal or attributable to the training of more general across-modal control processes. In more detail, it is explored whether improvements in visual working memory after visual training can be dissociated from the effects of *n*-back training in the auditory modality and how any across-modal training effects are also reflected in changes in the underlying neural circuitry.

By answering these questions the Working Memory Training Study serves – besides its research questions itself – as a test for the working memory paradigm to be used to investigate transfer effects to vocabulary acquisition in Chinese in the Language Training Study.

7 TRANSFER OF MODALITY-SPECIFIC WORKING MEMORY TRAINING TO VOCABULARY ACQUISITION IN CHINESE

Provided that the Working Memory Training Study can actually reveal a dissociation between visual and auditory working memory training, specific transfer to Chinese vocabulary acquisition in the visual and auditory modality can be investigated. According to the conditions for transfer effects as outlined previously, one needs to consider the functional overlap of involved brain regions besides overlapping processing components in order to deduce functional hypotheses.

7.1 OVERLAPPING PROCESSES AND BRAIN REGIONS

In pursuance of the model by Davis and Gaskell (2009) (see also Lindsay & Gaskell, 2010), short-term retention is necessary during novel word acquisition and should occur in modality-specific higher-order association cortices involved in language processing. Higher-level visual and auditory association cortices, namely the left mid-fusiform gyrus and regions around the left superior temporal gyrus, were also found when activations of visual versus auditory word recognition in native Chinese speakers were contrasted (Liu et al., 2009).

As outlined previously working memory is often understood as active memory conceptualizing working memory as an active state of long-term memory (e.g. Fuster, 1997; Cowan, 1999; Crowder, 1993; Ranganath, DeGutis, & D'Esposito, 2004; Zimmer, 2008) and working memory storage is assumed to use mechanisms and structures that comparably mediate perception (Jonides, Lacey, & Nee, 2005). Hence, in various brain imaging studies on working memory it was assumed that working memory makes use of systems that are intrinsically specialized for other processing domains such as motor planning or visual and auditory perception. For example, Mecklinger, Gruenewald, Besson, Magnié & von Cramon

(2002) investigated the effects of an object`s manipulablity on neural activation in a modified delayed matching to sample task to test these assumptions. In good correspondence with the prediction that short-term maintenance of manipulable objects is based on object-specific motor programs, they found a differential brain activation pattern for manipulable directly contrasted to non-manipulable objects in the ventral part of the premotor cortex and the anterior part of the intraparietal sulcus during the delay interval. With respect to the present study it is particularly relevant whether higher-order visual and auditory association cortices are also recruited by verbal working memory. Buchsbaum, Olsen, Koch, and Berman (2005) reported that the left superior temporal region in parallel with the left inferior frontal gyrus and the anterior insula showed auditory-selective activation during the retention period of a delayed bi-sensory verbal short-term memory task, whereas a region in the ventral temporal lobe comprising the fusiform gyrus showed visually selective memory responses. Similarly, Fiebach, Rissman, and D'Esposito (2006) clearly demonstrated that the language-sensitive left infero-temporal region contributes to the maintenance of visually presented words (but not pseudo-words) in working memory as indicated by sustained activation during the retention period of a visual delayed cued recall task.

Those lines of research reveal compelling evidence for overlapping processing components of working memory and successful word acquisition regarding the retention and analysis of incoming visual (written) information and acoustic (spoken) sound patterns. These processing components are likely to be accompanied by activations in higher-order visual and auditory association cortices.

7.2 FUNCTIONAL HYPOTHESES OF THE LANGUAGE TRAINING STUDY

In view of this evidence we expect that modality-specific working memory training leads to modulations in activation in those higher-order association cortices which are also involved in vocabulary acquisition. More specifically, transfer effects after intra-modal visual and auditory working memory training should be accompanied by stronger change of activation within the respective association cortex, namely areas in the infero-temporal cortex for learning visual written words and areas in the auditory dorsal stream (superior temporal cortex and adjacent prefrontal regions) for learning auditory spoken words.

WORKING MEMORY AND LANGUAGE TRAINING STUDY: OVERVIEW AND COMMON COMPONENTS

II WORKING MEMORY AND LANGUAGE TRAINING STUDY: OVERVIEW AND COMMON COMPONENTS

To investigate the research questions of the Working Memory Training Study and the Language Training Study as outlined previously, a nested pretest-training-posttest design was applied. In the following, an overview on the overall design will be given followed by methods and results of the stages and tasks within the overall design, which are shared by both the first and second training study. Thereafter, a short discussion is given on the impact the working memory training effects have for further investigating the research questions of the Working Memory Training Study and the Language Training Study.

1 OVERVIEW OF THE TRAINING STUDY DESIGN

Figure II-1 illustrates the overall experimental design. The nested training study procedure was separated into three stages, each lasting two weeks. The first and third stage consisted of the first and second Chinese language training (only relevant for the Language Training Study) followed by the fMRI session that served as pre- or posttest for both training studies, and were equal for all participants. In the Chinese language training participants learned the orthography and phonology of Chinese 2-character/syllable words and had to perform an orthographic and phonological task on previously learned words in the following fMRI session (for a detailed description of methods only relevant for the Language Training Study see Chapter IV-1). Participants additionally performed a visual working memory task in the fMRI sessions (only relevant for the Working Memory Training Study, for a detailed description of methods only relevant for the Working Memory Training Study see Chapater III-1). The second stage comprised the working memory training and served for both training studies. Participants were assigned to either the visual working memory training group (mean age = 23.94 years, age range = 21-29), the auditory working memory training group (mean age = 23.13 years, age range = 20-28), or the passive control group (mean age = 23.94 years, age range = 20-31). The groups were matched according to age (p = .59), gender (χ^2 (1, n=48) = .33, p = .56,), fluid intelligence as assessed by a speeded version of the Bochumer Matrizentest (BOMAT) (Hossiep, Turck, & Hasella, 1999) (p = .75) and working memory capacity as measured by two verbal and two visuo-spatial span tasks (adapted from Kane et al., 2004) (counting span: p = .59; reading span: p = .70; navigation span: p = .63; symmetry span: p = .29). Both training groups trained within two weeks on either a visual or auditory adaptive *n*-back task, respectively. The control group, however, did not receive any training.

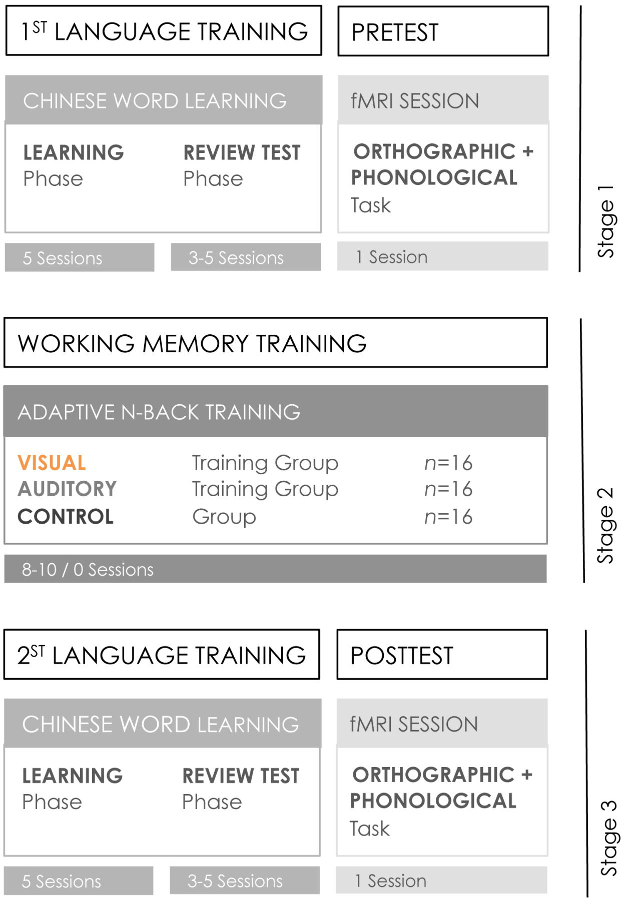

Figure II-1: Overall procedure of the Working Memory Training Study and the Language Training Study

All participants performed equivalent Chinese trainings and fMRI sessions in stage 1 and stage 3. In stage 2 participants trained either on a visual or auditory working memory task or did not receive any training (control group).

Participants were scanned after the first and second language training. Mean spacing measured by mean number of days between the language training sessions did not differ significantly between the training groups in the pretest, visual training group: M = 1.25; auditory training group: M = 1.25; control group: M = 1.27; p > .10, and the posttest, visual training group: M = 1.34 ; auditory training: M = 1.23; control group: M = 1.32; p > .10. Mean spacing between the last second language training session and the following fMRI session did not differ significantly between the training groups in the pretest, visual training group: M = 2.50; auditory training group: M = 2.19; control group: M = 3.13; p > .10, and posttest, visual training group: M = 1.88; auditory training group: M = 2.38; control group: M = 2.56; p > .10. Mean number of working memory training sessions did not differ between the visual, M = 9.38, and the auditory training group, M = 9.75, p > .10. Mean spacing between one training session and the next indicated by the mean number of days was held equal between the groups, visual training: $M = 1.30$, auditory training: $M = 1.25$, $p > .10$.

2 COMMON COMPONENTS OF THE TRAINING STUDIES

Basically participants and the working memory training were used for both training studies. Moreover, a single fMRI session at pre- and posttest was used to address the questions of both training studies in two different runs. In the following a description on the common methods will be given followed by a description, results and discussion of the working memory training.

2.1 COMMON METHODS

2.1.1 PARTICIPANTS

Forty-eight undergraduate and graduate students of Saarland University, 26 female and 22 male, mean age = 23.67 years (age range = 19-31 years), participated in the nested training study. All participants were right-handed as assessed by the Edinburgh Inventory (Oldfield, 1971) and indicated on a screening form to be physically and psychologically healthy, to have normal hearing, and normal or corrected to normal vision. They gave informed consent before testing and received 8 €/hour for their participation.

2.1.2 THE WORKING MEMORY TRAINING PARADIGM

The paradigm that was used for working memory training was adapted from the study by Jaeggi et al. (2008).

2.1.2.1 TRAINING TASK

Participants trained on an adaptive *n*-back working memory task. In the *n*-back task a series of stimuli are presented consecutively and participants have to decide whether the present stimulus matches the stimulus that was presented *n* positions back in the sequence. In this paradigm stimuli were presented sequentially at a rate of 3 s (stimulus length = 500 ms; interstimulus interval = 2500 ms). There were six targets per block with their positions determined randomly. To avoid non-targets that are most likely to distract participants` attention, non-targets immediately preceding or following a target had to be different from the target such that those trials could not function as lure trials. All other non-target stimuli were assigned randomly. A response was required on every stimulus. Participants responded manually by pressing either the letter ’M’ or ’C’ of a standard computer keyboard. Response mappings were counterbalanced across participants and were maintained throughout all training and fMRI sessions. Adaptivity was implemented by changing the level of *n* from one block of 20 + *n* trials to the next according to each participant`s individual proficiency. If the participant made more than 80% correct responses the level of *n* increased by 1, but decreased by 1 if accuracy was less than 67%. In all other cases *n* remained unchanged (see Figure II-2).

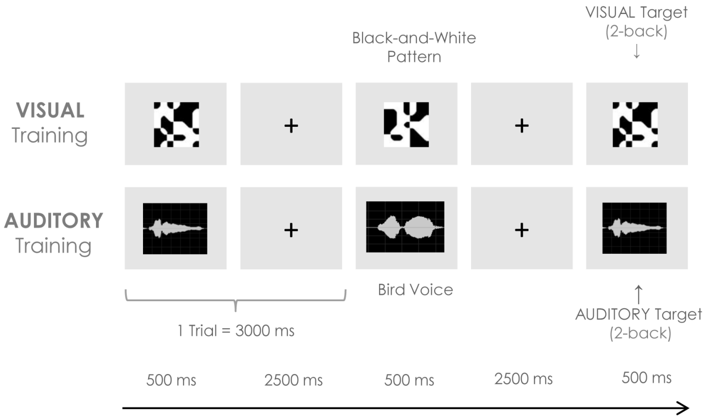

Figure II-2: The working memory training paradigm

Schematic description of the visual and auditory adaptive *n*-back task during training, illustrated for a 2-back condition. The visual training group trained with black-and-white pattern stimuli, whereas the auditory training group trained with bird voice stimuli.

Each training session started with the same level of *n* = 1 and comprised 40 blocks. The procedure was self-paced from one block to the next, so the amount of time to complete one training session varied between participants resulting on average 50 minutes per session. The training comprised ten sessions, which took place within a period of two weeks. The time lag between sessions was between one and three days. As not all participants completed the last two sessions, only the first eight training sessions were entered into the analysis.

2.1.2.2 STIMULUS MATERIAL

Abstract black-and-white patterns were employed for the visual training group. They were generated by randomly assigning black or white patches such that the proportions of colors within the pattern were kept constant. The auditory training group trained with bird voice stimuli presented via headphones (see Figure II-2). Samples were taken from a commercially available disc, normalized in volume, and removed from background noise. In a pilot study it was assured that the visual and auditory *n*-back tasks performed with these stimuli did not differ in difficulty. In each training session a completely new set of eight stimuli was used to ensure effects were not due to highly familiar stimulus material and to prevent verbal or semantic recoding.

2.1.2.3 DATA ANALYSIS

A repeated measures MANOVA (Pillai`s trace) with the factors Group (visual vs. auditory training group) and Session (sessions one to eight) was calculated on the mean level of *n* as an indicator of the participants` mean performance for each session. In the following we will refer to the outcome of this analysis as 'training effect', since this effect characterizes the improvement during the training procedure. From each training session the first 10 blocks were excluded from calculating the mean level of *n*, because participants had to pass those levels of *n,* which were below their individual performance level. Since validity assumptions of the repeated measure analysis of variance are much less problematic in the multivariate approach (Vasey & Thayer, 1987) in all of the following analyses MANOVAs (Pillai`s trace) were computed.

2.1.3 PRE AND POSTTEST FMRI SESSIONS

According to the classic pretest-training-posttest design the lexical tasks in the pretest fMRI session served to explore baseline activation for lexical processing after new visual and auditory Chinese words have been acquired in native German speakers (Language Training Study). By this it provides a basline for underlying language networks after second language vocabulary learning that is not affected by working memory training. Furthermore, the visual working memory task in the pretest fMRI session likewise acts as baseline to reveal the working memory network prior to training (Working Memory Training Study). In comparison with the pretest fMRI sessions the posttests can advice activation changes in the respective tasks according to the specific training conditions.

2.1.3.1 LEXICAL AND WORKING MEMORY TASKS

According to the research questions of the Language Training Study, an orthographic and phonological lexical task was applied in each of the pre- and posttest fMRI session as well as an orthographic and phonological control task (for a detailed description see Chapter IV-1.2). To allow for the research questions of the Working Memory Training Study, a visual 2-back working memory task was used as well as a visual 0-back control task (for a detailed description see Chapter III-1.1).

2.1.3.2 IMAGE ACQUISITION

An event-related design with two repetitions and two runs each (one lexical run and one working memory run) was performed on a 1,5 Tesla scanner (Magnetom Sonata, Siemens Medical Systems, Erlangen, Germany). Visual stimuli were presented through a projector onto a translucent screen. Participants viewed the stimuli through a mirror attached to the head coil and head motions were restricted using a vacuum pillow. Auditory stimuli were presented via MRI-compatible headphones (Resonance Technology, Los Angeles, CA). Responses were collected via 2-button response grips. A T2*-weighted gradient-echo planar imaging sequence was used for fMRI scans (matrix: 64, FoV = 224 mm, inplane resolution = 3.5 mm x 3.5 mm, slice thickness/gap thickness = 4 mm/1 mm, repetition time/echo delay time/flip angle = 2300 ms/50 ms/85°). Twenty-six contigual axial slices were acquired parallel to AC-PC line covering the whole brain. 960 volumes were acquired per lexical run, 300 volumes per working memory run. An intra-session high-resolution structural scan was acquired using a T1-weighted 3D MP-RAGE (1 mm^3 voxel size).

The order of the runs was fixed: first, the lexical run was applied, then the structural sequence was run followed by the working memory run.

2.1.3.3 DATA PREPROCESSING

The functional imaging data were analyzed using BrainVoyager QX (Brain Innovation, Maastricht, The Netherlands; Goebel, Esposito, & Formisano, 2006). For each run the first four volumes of each subject`s functional data set were discarded to allow for T1 equilibration. For the remaining volumes (956 in the lexical run, 296 in the working memory run), standard preprocessing was performed: The images were slice time corrected (sinc interpolation), motion corrected (trilinear interpolation) and spatially smoothed (isotropic Gaussian kernel at 6 mm FWHM). The data was high-pass filtered at 3 cycles. Functional slices were co-registered to the anatomical volume of the pretest session using position parameters and intensity-driven fine-tuning and were finally adjusted manually before they were transformed into Talairach coordinates (Talairach & Tournoux, 1988).

2.2 WORKING MEMORY TRAINING EFFECTS

Performance increases of the *n*-back task during training (mean level of *n* in each session) are shown in Figure II-3. The repeated measures MANOVA (Group X Session) revealed that both training groups improved their performance as indicated by a significant main effect of Session, $F(7,24) = 11.58$, $p < .001$, $\eta^2_p = 0.77$, and significant Session effects for both groups separately, visual training group: $F(7,9) = 5.64$, $p < .01$, $\eta^2_p = 0.81$, auditory training group: $F(7,9) = 6.37$, $p < .01$, $\eta^2_p = 0.83$. Although the visual and the auditory training group showed comparable performance levels in the beginning (collapsed across Session 1 and 2), $M = 2.66$ vs. $M = 2.61$, $p = .86$, the Group by Session interaction approached significance, $F(7,24) = 2.25$, $p < .10$, $\eta^2_p = 0.40$. Post hoc analysis showed significant differences between the training groups at the end of training (collapsed across Session 7 and 8), $M = 4.14$ vs. $M = 3.18$, $t(1,30) = 2.48$, $p < .05$, suggesting a greater training effect for the visual than for the auditory training group.

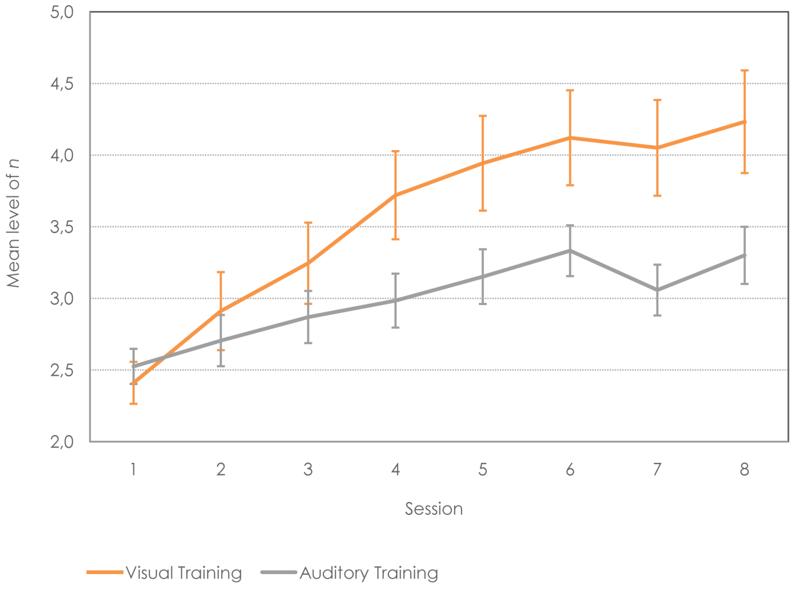

Figure II-3: Performance increases in the *n*-back task for the visual and auditory training group

The mean level of *n* as an indicator of the participants` mean performance for each session and corresponding standard errors of the mean.

2.3 DISCUSSION

Training-induced performance increases in the trained tasks were found for both the visual and the auditory training group. These findings converge with evidence from other working memory training studies reporting increased performance in the trained tasks using *n*-back training paradigms (Jaeggi et al., 2008, 2010b; Schmiedek, Lövdén, & Lindenberger, 2010; Hempel et al., 2004; Li et al., 2008) or other working memory training tasks such as letter updating or simple and complex span tasks (Dahlin et al, 2008; Holmes et al., 2009; Chein & Morisson, 2010; Jolles et al., 2010; Klingberg et al., 2005; Olesen et al., 2004; Schmiedek et al., 2010). For example the studies by Jaeggi et al. (2008, 2010b) report significant increases as indicated by increased mean *n*-back level in several groups of participants on a dual *n*-back task (Jaeggi et al., 2008; 2010b) and on a single visual *n*-back task (Jaeggi et al., 2010b). From this standpoint the training effects in both of the working memory training groups in the current study further enriches the host of studies showing that performance in working memory tasks can robustly be improved by a variety of training paradigms.

Beyond that, for the issues under investigation in this thesis the training effects in both training groups are a condition precedent to further investigate the research questions of both training studies. Only if it is ensured that the performance of the trained task is indeed increased, one can assume that relevant processes of the trained task are improved which is a precondition to test whether the training affects performance and processes of other tasks (Lövdén et al., 2010).

However, some caution may be needed in comparing and interpreting specific training or transfer effects between the visual and auditory training groups in the current study, because they differ in the degree of improvement as indicated by the marginally significant Time by Session interaction. As performance of the visual and auditory training group is comparable at the beginning of training and participants are matched according to several cognitive abilities such as fluid intelligence and working memory span tasks, it remains unsettled why the training effects in the visual training group are greater than in the auditory training group.

An explanation for the different training effects between the visual and auditory training group can be derived from the study by Jaeggi, Buschkuehl, Perrig, and Meier (2010a), that reports a greater dropdown of performance in the auditory *n*-back task compared to the visual as soon as difficulty exceeds $n = 2$. It seems that at higher working memory load levels, auditory versions of the *n*-back task become more difficult than visual versions, even if the performance is comparable at lower load levels. Thus, it was proposed that comparable difficulty does not necessarily coincide with the same levels of n in the visual and auditory version of the *n*-back task.

Following this line of evidence, the greater *n*-back level at the end of the visual training compared to the auditory training in this study is likely to trace back to inherent properties of the working memory tasks, i.e. differences in training effects might reflect differences in potentials for improvement which seems to be higher for visual material. Thus, the differences in training effects between the visual and the auditory training groups have to be kept in mind when it comes to the discussion of both training studies. Nevertheless, the fact that the visual as well as the auditory training reliably led to increased performance in the respective tasks - albeit perhaps to different degrees - permit to further test specific training effects in visual working memory (Working Memory Training Study) and transfer to second language vocabulary learning (Language Training Study).

WORKING MEMORY TRAINING STUDY

III WORKING MEMORY TRAINING STUDY

The Working Memory Training Study[1] was desgined to investigate whether working memory can specifically be trained for visual materials and how effects of visual working memory training are reflected in underlying brain networks. In the following methods and materials that are specific for the Working Memory Training Study and results are described followed by the discussion.

1 METHODS AND MATERIALS

The task that was specific to the Working Memory Training Study was the visual 2-back task in the pre- and posttest fMRI sessions.

1.1 TASKS AT PRE AND POSTTEST FMRI SESSIONS

To examine neural function changes in visual working memory after intra-modal and across-modal *n*-back training, a visual 2-back task was employed in the fMRI pre- and posttests. It was comparable to the visual training task except for the following changes: New sets of black-and-white patterns were used; stimuli were randomly assigned to the pre- and posttest sets and came from the same pool of stimuli used for the visual training sessions; block presentation was externally paced, and a constant *n*-level of 2 was used. A visual 0-back task using identical stimuli served as a control task. In this task a gray dot was added to the center of one of the stimuli. Similar to the 2-back task subjects were instructed to press one button upon the presentation of a target (i.e. whenever the gray dot was included in the stimulus) and another one if it was not. Five blocks of the visual 2-back task consisting of 22 trials and five blocks of the visual control task comprising 20 trials each were completed. Block order was constant for all participants, starting with the 2-back task. Experimental and control blocks alternated.

Before the pretest fMRI session participants performed one block of each task outside the scanner to familiarize them with the tasks.

1.2 BEHAVIORAL DATA ANALYSIS

A two-way MANOVA (Pillai`s trace) with factors Time (pretest vs. posttest) and Group (visual training vs. auditory training vs. control group) was performed on the visual 2-back task using the discrimination index *Pr* (*p*[Hit] - *p*[FA]) (Snodgrass & Corwin, 1988) as dependent variable.

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[1] This study was published in Schneiders, Opitz, Krick, & Mecklinger (2011).

In the following the outcome of this analysis will be referred to as ’training gain’, because it reflects the effect the training had on the visual 2-back task in the posttest.

1.3 BRAIN IMAGING ANALYSIS

Functional time-series were analyzed using random-effects multi-subjects general linear model (GLM) (Friston, Holmes, Price, Buechel, & Worsley, 1999). In a first analysis all levels of the factor Task (2-back vs. 0-back) and the factor Time (pretest vs. posttest) were modeled as separate predictors for each subject; motion parameters were added as predictors of no interest to the design matrix of each run. Only correct trials (targets and non-targets) were included in the analysis. Thus, the resulting GLM contained eight parameters of interest per subject: visual 2-back and visual 0-back for each of the pre- and posttest sessions. Predictor time courses were adjusted for the hemodynamic response delay by convolution with a double-gamma hemodynamic response function (Friston et al., 1998). To explore baseline activations elicited by the task without any training, the following random-effects contrast was calculated on all correct trials of the data of all participants: 2-back pretest vs. 0-back pretest. The results from this whole-brain analysis resulted in % signal change images thresholded at FDR < .01 using clusters determined by the number of functional voxels > 15. In a second analysis we defined functional volumes-of-interest (VOI) on the basis of cluster activations in the pretest. This hypothesis-driven approach allowed us to assess training-induced changes in activity on the basis of Time by Group interactions, with visual vs. auditory training group for intra-modal and collapsed across training groups vs. control group for across-modal activation changes. Importantly, using a priori VOIs from the activation during pretest allowed us to specifically examine effects that training had on initially activated brain regions and provides a criterion for inclusion of regions in the pre-posttest analysis (Kelly & Garavan, 2005; Erickson et al., 2007). All regions, which were significant in the first analysis and located within lateral prefrontal and parietal areas were entered in the VOI analysis. VOIs were defined as the overlap between significantly activated voxels and a 30 mm cube around local maxima (maximum peak distance of 30 mm) of each cluster. To assess training-induced changes within VOIs we extracted the mean parameter estimates from pre- and posttest for each participant and each predictor from the VOIs and performed a series of repeated measures MANOVAs (Pillai`s trace).

Numerous brain imaging training studies have reported different areas of activation in the posttest, which were not active before training (e.g. Poldrack, Desmond, Glover, & Gabrieli, 1998). To investigate this possibility in our data, we additionally examined the voxel-based statistical parameter map for the posttest contrast: 2-back posttest vs. 0-back posttest.

Analogously to the pretest analysis, % signal change images were thresholded at FDR < .01 using clusters determined by the number of functional voxels > 15.

2 RESULTS

2.1 BEHAVIORAL RESULTS

The critical analysis in the light of the predictions concerns the improvements (training gains) measured in the visual 2-back task from pre- to posttest after intra-modal (visual) and across-modal (auditory) training. The corresponding results are shown in Figure III-1. The two-way MANOVA with factors Time (pretest vs. posttest) and Group (visual training vs. auditory training vs. no training) revealed a main effect of Time, $F(1,45) = 36.25$, $p < .001$, $\eta^2_p = 0.45$, and a significant Group by Time interaction, $F(2,45) = 3.52$, $p < .05$, $\eta^2_p = 0.14$, indicating group-specific performance improvements.

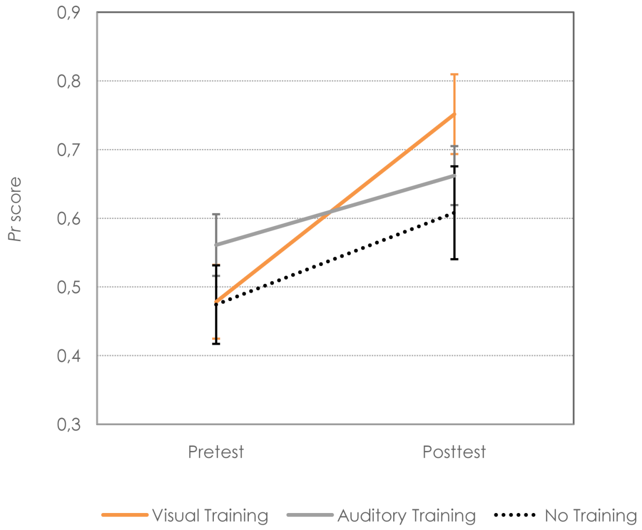

Figure III-1: Performance of the visual 2-back task in the pre- and posttest sessions

Mean *Pr* scores and corresponding standard errors of the mean for both training groups and the control group.

The improvement from pre- to posttest was reliable for the visual training group, $F(1,15) = 36.01$, $p < .001$, $\eta^2_p = 0.71$, and the control group, $F(1,15) = 7.75$, $p < .05$, $\eta^2_p = 0.34$, and marginally significant for the auditory group, $F(1,15) = 3.73$, $p < .10$, $\eta^2_p = 0.20$. Importantly, in two separate MANOVAs the Group by Time interaction was significant for the visual training vs. control group, $F(1,30) = 4.44$, $p < .05$, $\eta^2_p = 0.13$, but not for the auditory training vs. control group, $p = .65$. So the interaction of the initial two-way MANOVA reflects a larger training gain after visual training, which is also indicated by a considerably greater effect size compared to those of the auditory and control group.

2.2 BRAIN IMAGING RESULTS

2.2.1 REDISTRIBUTION EFFECTS

The comparison between the pretest 2-back and 0-back task revealed regions that were involved in visual working memory processing prior to training. These regions were in the left and right parieto-occipital cortex and in the left and right dorsolateral PFC and also in the left fusiform gyrus, left and right cerebellum, right thalamus, and left caudate nucleus (see Table III-1, for a list of peak cluster coordinates and local maxima coordinates).

Table III-1: Brain regions activated in the pretest contrast 2-back minus 0-back task

Number of VOI	Brain region	BA	H	t value	Number of Voxels	x	y	z
	IPS	**40**	**R + L**	**12.557**	**59940**	**-39**	**-46**	**40**
[1]	IPS anterior	40	L	12.557	13255	-39	-46	40
[2]		40	R	12.154	13465	39	-43	40
[3]	IPS posterior	7	L	11.777	14082	-33	-58	37
[4]		7	R	10.152	11644	27	-57	40
[5]	SOG	19	L	4.972	787	-24	-66	24
[6]		19	R	6.581	1613	27	-62	35
[7]	Precuneus	7	R + L	7.499	3113	-12	-73	52
	MFG	**6**	**R**	**11.257**	**44878**	**24**	**-4**	**61**
[8]	MFG	6	R	11.257	6755	24	-4	61
[9]	MFG	9	R	9.696	12241	42	26	31
[10]	MFG	9/46	R	7.506	9721	42	38	28
[11]	MFG	6	R	7.739	6682	48	8	43
[12]	Insula	/	R	9.320	4860	33	17	7
	MFG	**6**	**L**	**11.197**	**44208**	**-27**	**-7**	**58**
[13]	MFG	6	L	11.197	8012	-27	-7	58
[14]	medial SFG	6	L	10.819	9552	-3	8	49
[15]	PrCG	6	L	9.567	8708	-45	2	34
[16]	MFG	10	L	8.009	9348	-39	44	19
[17]	Insula	/	L	9.134	4640	-33	14	7
	Cerebellum	**/**	**L**	**7.396**	**6723**	**-39**	**-58**	**-32**
		/	**R**	**6.177**	**2277**	**27**	**-58**	**-29**
	Thalamus (av)	**/**	**R**	**4.782**	**862**	**9**	**-4**	**7**
	Caudate Nucleus	**/**	**L**	**5.578**	**643**	**-9**	**5**	**7**
	Fusiform Gyrus	**37**	**L**	**5.524**	**524**	**-48**	**-58**	**-11**

H, hemisphere; L, left; R, right; BA, Brodmann`s area; IPS, intraparietal sulcus; SOG, superior occipital gyrus; MFG, middle frontal gyrus; SFG, superior frontal gyrus. Clusters are listed based on cluster peak coordinates (in bold) and are more than 15 contiguous voxels surviving a threshold of $p < 0.01$ (FDR corrected). Local maxima within these clusters on which VOIs were defined (see Methods and Materials of the Working Memory Training Study) are listed and numbered for the sake of clarity. Note that some of these local maxima extend to adjacent brain areas. Coordinates correspond to those from the Talairach and Tournoux reference brain.

With respect to the second analyses (VOI analyses), the main interactions of interest were Group (visual vs. auditory) by Time (pre- vs. posttest) as these interactions reveal differential pretest-posttest activity changes in the visual and auditory groups. Significant Group by Time interactions were found in the right middle frontal gyrus (BA 9) [9][2], $F(1,30) = 4.84$, $p < .05$, $\eta^2_p = .014$, (see Figure III-2 A) and marginally significant in the anterior part of the right middle frontal gyrus (BA 9/46) [10], $F(1,30) = 2.89$, $p < .10$, $\eta^2_p = 0.09$ (see Figure III-2 B).

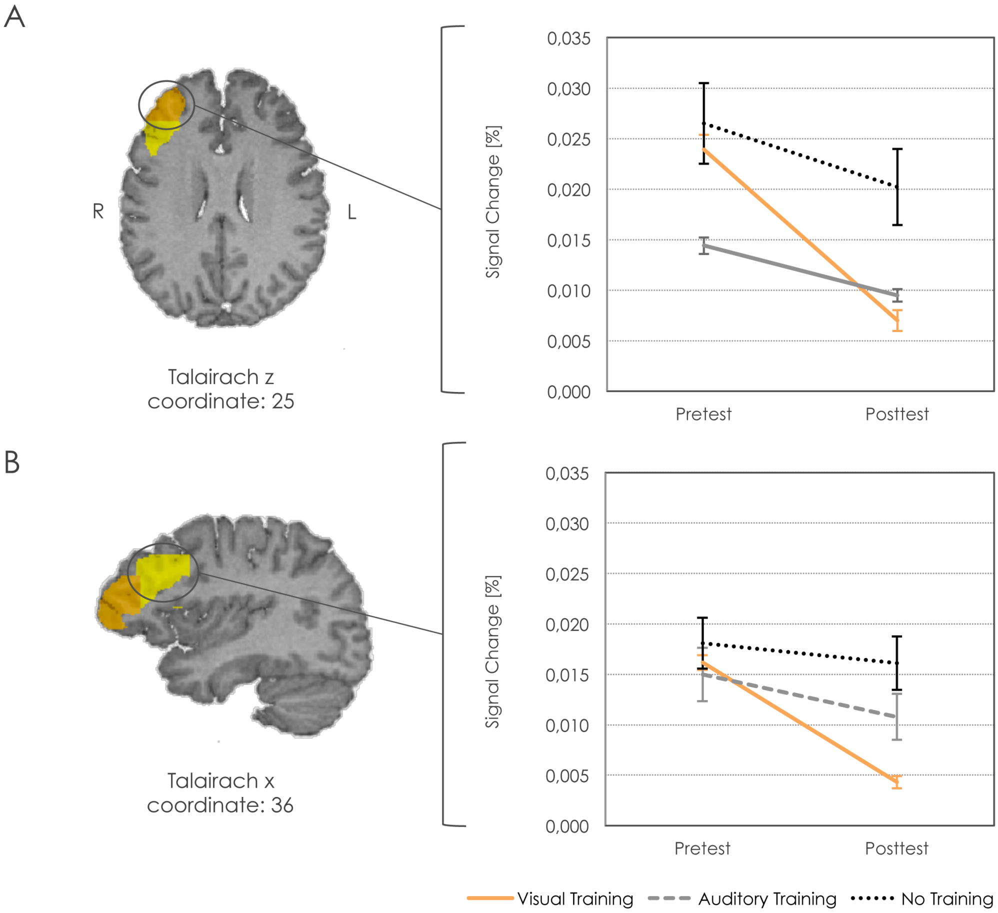

Figure III-2 Intra-modal training-related activation changes during the performance of a visual 2-back task

Percent signal change values of functional volumes of interests for the visual versus auditory training groups: right middle frontal gyrus at BA 9/46[10] (A) and right middle frontal gyrus at BA 9 [9] (B).

Post hoc analyses revealed that these interactions resulted from a significant reduction in activity from pre- to posttest for the visual training group, BA 9 [9]: $F(1,15) = 16.04$, $p < .001$, $\eta^2_p = 0.63$; BA 9/46 [10]: $F(1,15) = 12.37$, $p < .01$, $\eta^2_p = 0.45$, whereas this was not the case for the auditory training group, BA 9: $p = .27$, BA 9/46: $p = .18$.

Moreover, most of the VOIs in this analysis showed main effects of Time (pre- vs. posttest): banks of the right and left intraparietal sulcus (BA 40) [1 and 2], $F(1,30) = 11.74$, $p < .01$, $\eta^2_p = 0.28$, $F(1,30) = 9.86$, $p < .01$, $\eta^2_p = 0.25$, right superior medial frontal gyrus (BA 6) [8], $F(1,30) =$

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[2] Numbers in square brackets refer to numbers of the VOIs as indexed in Table III-1.

11.86, $p < .01$, $\eta^2_p = 0.28$, right middle frontal gyrus (BA 9) [9], $F(1,30) = 12.76$, $p < .001$, $\eta^2_p = 0.30$, right middle frontal gyrus (BA 9/46) [10], $F(1,30) = 16.02$, $p < .001$, $\eta^2_p = 0.35$, left middle frontal gyrus (BA 6) [13], $F(1,30) = 6.81$, $p < .05$, $\eta^2_p = 0.19$, and left medial superior frontal gyrus (BA 6) [14], $F(1,30) = 5.90$, $p < .05$, $\eta^2_p = 0.16$. These effects reflect activation decreases for all groups.

The aforementioned interactions revealed intra-modal training effects in visual working memory in the right lateral PFC. Next I examined, whether there are also across-modal training effects, activation changes that results from both training types relative to the control group, which would reveal training-induced alterations in general control functions. I performed repeated measure MANOVAs with factors Group (collapsed across trained groups vs. control group) and Time (pre- vs. posttest). These analyses revealed interactions in the banks of the right intraparietal sulcus (BA 40) [2], $F(1,46) = 4.83$, $p < .05$, $\eta^2_p = 0.10$, (see Figure III-3 A) and the right superior middle frontal gyrus (BA 6) [8], $F(1,46) = 4.18$, $p < .05$, $\eta^2_p = 0.08$, (see Figure III-3 B). The interactions resulted from reductions in activity for the two training groups, BA 40 [2]: $F(1,31) = 12.04$, $p < .01$, $\eta^2_p = 0.28$; BA 6 [8]: $F(1,31) = 12.10$, $p < .01$, $\eta^2_p = 0.28$, while activations for the control group remained stable over time, BA 40 [2]: $p = .90$; BA 6 [8]: $p = .76$.

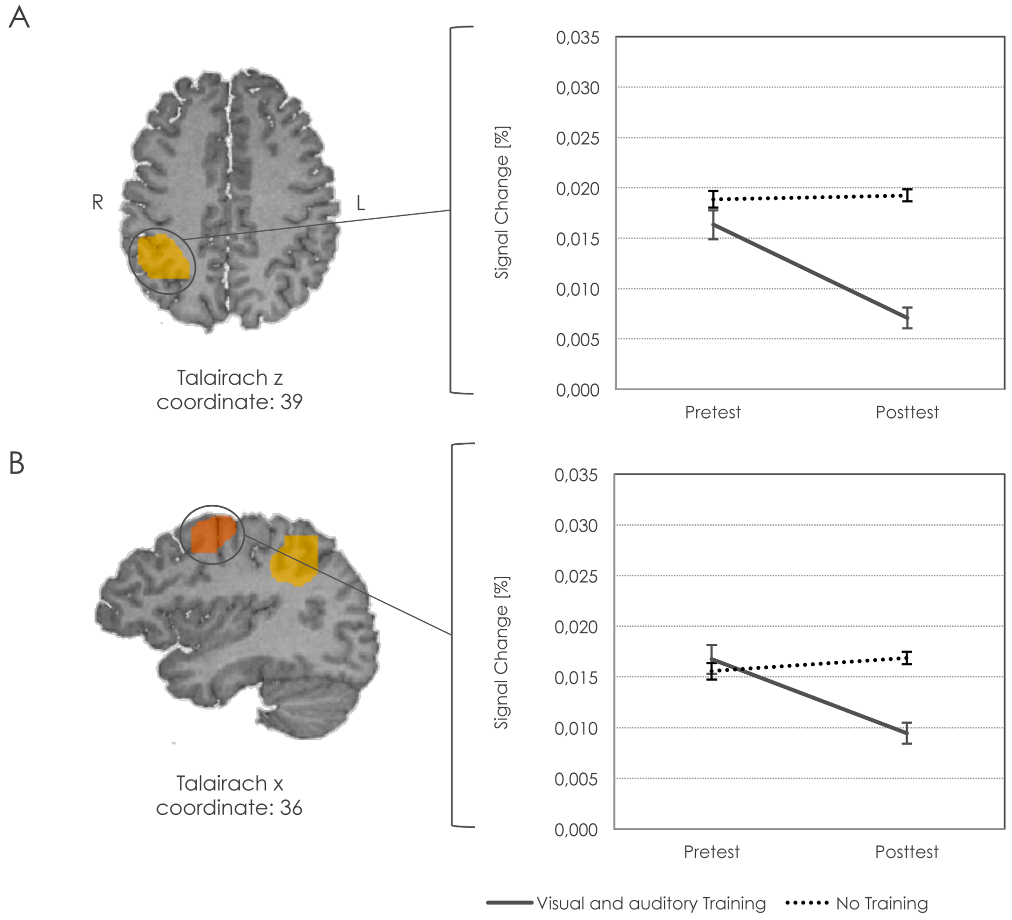

Figure III-3: Across-modal training-related activation changes during performane of a visual 2-back task

Percent signal change values of functional volumes of interests for both training groups (collapsed) versus the control group: right inferior parietal sulcus at BA 40 [2] (A) and right middle frontal gyrus at BA 6 [10] (B).

2.2.2 REORGANIZATION EFFECTS

The contrast between the posttest 2-back and 0-back task revealed regions that were involved in visual working memory processing in the posttest. These regions were in the left and right parieto-occipital cortex and in the left and right dorsolateral PFC and the left and right cerebellum (see Table III-2, for a list of peak cluster coordinates and local maxima coordinates). These areas were basically the same as those found in the pretest contrast. Nucleus caudatus, fusiform gyrus and thalamus were no more activated in the posttest. Notably, there was no region that was activated in the posttest but not in the pretest.

Table III-2: Brain regions activated in the posttest contrast 2-back minus 0-back task

Number of VOI	Brain region	BA	H	t value	Number of Voxels	x	y	z
	IPS	**19**	**R + L**	**10.382**	**44828**	**-30**	**-64**	**43**
[1]	IPS anterior	40	L	5.464	5119	-42	-38	34
[2]		40	R	9.134	10241	36	-46	43
[3]	Precuneus	19	L	10.382	11001	-30	-64	43
[4]		7	R	8.140	10130	18	-76	43
	MFG	**9**	**R**	**6.948**	**10763**	**39**	**23**	**31**
[5]	MFG	9	R	6.948	5410	39	23	31
[6]	PrCG	6	R	4.984	2640	42	-7	37
[7]	SFG	10	R	4.642	1842	36	53	16
	MFG	**6**	**R**	**9.207**	**4970**	**27**	**-7**	**61**
[8]	MFG	6	R	9.207	4970	27	-7	61
	Insula	**13**	**R**	**7.679**	**2507**	**33**	**17**	**7**
[9]	Insula	13	R	7.679	2496	33	17	7
	MFG/PrCG	**9**	**L**	**8.748**	**14892**	**-42**	**23**	**34**
[10]	MFG	9	L	8.748	5444	-42	23	34
[11]	PrCG	6	L	8.184	5890	-27	-10	52
[12]	PrCG	6	L	3.857	3906	-48	-4	22
	MFG/Insula	**13**	**L**	**10.141**	**6104**	**-30**	**17**	**10**
[13]	Insula	13	L	10.141	3066	-30	17	10
[14]	MFG	10	L	5.856	3200	-36	44	22
	Medial SFG	**6**	**L+R**	**8.668**	**5836**	**3**	**11**	**46**
[15]	Medial SFG	6	L+R	8.668	5478	3	11	46
	Cerebellum	**/**	**L+R**	**6.166**	**556**	**3**	**-73**	**-26**
		/	**R**	**4.527**	**441**	**30**	**-52**	**-29**

H, hemisphere; L, left; R, right; BA, Brodmann`s area; IPS, intraparietal sulcus; MFG, middle frontal gyrus; PrCG, precentral gyrus; SFG, superior frontal gyrus. Clusters are listed based on cluster peak coordinates (in bold) and are more than 15 contiguous voxels surviving a threshold of $p < 0.01$ (FDR corrected). Local maxima within these clusters on which VOIs were defined (see Methods and Materials of the Working Memory Training Study) are listed and numbered for the sake of clarity. Note that some of these local maxima extend to adjacent brain areas. Coordinates correspond to those from the Talairach and Tournoux reference brain.

3 DISCUSSION

The first aim of this study was to investigate whether working memory for visual materials can be trained by means of a visual *n*-back task and whether this training results in activation changes of underlying brain networks. Second, I examined the extent to which those training effects in visual working memory are intra-modal or across-modal i.e. can also be obtained by means of across-modal (auditory) working memory training.

3.1 SUMMARY

The training-induced performance increases in the trained tasks for both training groups allowed to compare the impact of the two training effects on performance in the visual 2-back task. The results indicated that (a) training of the visual *n*-back task was accompanied by a greater training gain in the visual 2-back task compared to auditory training and no training (b) BOLD activity within the right middle frontal gyrus (BA 9 and BA 9/46) decreased after the visual training only, whereas (c) both trainings led to decreased activation in the superior right middle frontal gyrus (BA 6) and posterior parietal region (BA 40) as compared to the control group.

3.2 SPECIFIC IMPROVEMENTS AFTER VISUAL WORKING MEMORY TRAINING

The specific improvement on the visual 2-back task after visual training suggests that there is indeed an advantage of modality-specific training. By using verbally and semantically devoid stimuli, which change from one training session to the next, we could ensure that participants could not abstract from their visual (or auditory) sensory nature and could not recode stimuli verbally or semantically. Thus they could not process them in a system other than input modality (Protzner & McIntosh, 2007; Smith & Jonides, 1997).

An objection against this interpretation could be that the greater training gain in the visual 2-back task from pre- to posttest after visual training compared to auditory training reflects the larger training effects during visual training as reflected in the training-induced increases of *n*. Accordingly, it could be argued that the training gains on the visual 2-back task are not intra-modal in the sense that similar effects could have also emerged after auditory training, if it would have been as efficient as the visual training. To address this issue I selected two training groups of $n = 10$ participants each, which were matched according to their training effects, i.e. the increase of *n* from the beginning (first and second session) to the end of training (seventh and eighth session). As assessed by an independent sample t-test there were no significant differences in the training effects between the two groups, $t(1,18) = 1.13$, $p > .05$. Paired-sampled t-tests revealed that the visual training group showed a performance increase from pretest to posttest, $t(1,9) = 3.75$, $p < .01$, whereas this was not the case for the auditory training group, $t(1,9) = 1.79$, $p > .05$. I performed equivalent post hoc analyses on activation changes in the right middle frontal gyrus for the subgroups equated for training effects to make sure that these activation decreases did not arise from differences in training effects. Paired-sample t-tests comparing pre- and posttest parameter estimates yielded significant activation decreases for the visual training group in both VOIs in the right middle frontal gyrus, BA 9: $t(1,9) = 2.99$, $p < .05$, BA 9/46: t(1,9) = 3.55, $p < .01$, while changes for the auditory training group did not reach significance, BA 9: $t(1,9) = 1.66$, $p > .05$, BA 9/46: $t(1,9) = 1.99$, $p > .05$. These data suggest that the specific increase in performance and activation decreases in the right middle frontal gyrus in the visual 2-back task after visual training were not a mere reflection of the general magnitude of the training effects and therefore most likely intra-modal effects within the visual modality. Even though the aforementioned post hoc analyses were based on a smaller sample size, the results support the hypothesis that visual working memory can be trained separately from other modalities.

However, if it is assumed that the different degree of improvement traces back to inherent properties of the task i.e. to different potentials for improvement (as already discussed in Chapter II-3), the visual and auditory training tasks are not exactly matchable according to the increase of *n*. Consequently, it can be postulated that, if the visual and auditory training are equalized according to the increase of *n*, the training effects, due to the higher difficulty levels for auditory large *n*, should be greater for the auditory training. Hence, our attempt to adjust the training effects could even have underestimated the intra-modal training gain of the visual training and provides even greater support for the view that this improvement is specifically driven by the sensory nature of the visual training.

Remarkably, the control group also showed a reliable improvement from the pre- to the posttest, indicating that even a small amount of within-session practice can result in improved performance (Garavan et al., 2000). This result is in agreement with a variety of working memory training studies that likewise found pure retest effects in a control group (Jolles et al., 2010; Mahnke et al., 2006; Owen et al., 2010; Smith et al., 2009) as well as in other training studies (Karbach & Kray, 2009; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). In an attempt to specify how repetition determines skill learning in mirror-reading Ofen-Noy, Dudai, and Karni (2001) showed that even a single item repetition within a limited time window can trigger procedural learning, if a certain degree of consistency between repeated practice trials is ensured. In line with the aforementioned results, the most parsimonious interpretation of the retest effect in the control group is that it reflects an effective formation of procedural memory for the visual 2-back task.

3.3 INTRA-MODAL AND ACROSS-MODAL REDISTRIBUTION EFFECTS IN THE WORKING MEMORY NETWORK

The pattern of activation of the brain regions during the pretest was generally consistent with previous reports of visual working memory tasks (Owen et al., 2005; Wager & Smith, 2003) and included mainly bilateral prefrontal and parietal areas.

The intra-modal activation decreases after visual training in the two adjacent VOIs in BA 9 and BA 9/46 both located in the right middle frontal gyrus are accompanied by the specific behavioral training gains on the visual 2-back task. These effects are in good agreement with the view that the right middle frontal gyrus is especially sensitive to visual working memory training, although it overlaps with the common modality independent working memory network that comprises the bilateral middle frontal gyri (BA 9/46) (Owen et al., 2005). In line with our findings, the meta-analysis conducted by Wager and Smith (2003) indicates the right BA 9 to be selectively activated by the requirements to maintain visual objects in working memory and to continuously update working memory contents. Although Nystrom et al. (2000), when contrasting letters, shapes, and locations in *n*-back tasks with different loads, do not find convincing support for stimulus type specific effects, their data speak for a stronger engagement of the right middle frontal gyrus in maintaining shapes than letters in memory and a greater activation for shapes compared to locations in high load conditions. Moreover, Protzner and McIntosh (2007) found that the right middle frontal gyrus showed greater activation with visual noise burst stimuli compared to auditory ones in simple working memory tasks, requiring sequencing and sequential comparisons of stimuli. Accordingly, the right middle frontal gyrus seems to be at least to some extent specific for the maintenance of visual object material in working memory as well as for manipulation of visual material such as updating processes.

To interpret the specific activation decreases in the two VOIs within the right middle frontal gyrus observed in the visual working memory training group, it is helpful to consider the results in the light of the general framework of functional plasticity as suggested by Kelly and Garavan (2005) (see also Poldrack, 2000) as outlined previously (see Chapter I-5.2). According to their approach, the present data suggest that visual training leads to a higher efficiency in storage, access and updating of purely visual material, mediated by the right middle frontal gyrus. With extensive training of these highly efficient processes, the scaffolding function of this region declines, which is reflected in activation decreases within this lateral prefrontal region.

Moreover, our data also provides evidence for across-modal training effects at the neural level i.e. effects that showed up likewise after visual as well as after auditory training. The activation decreases in the superior part of the right middle frontal gyrus (BA 6) and in the right posterior parietal cortex (BA 40) found for both training groups imply alternations in general control processes.

The right BA 6 is known to be one of the relevant regions for continuous updating processes (Wager & Smith, 2003), a set of operations that are crucial for the *n*-back task, irrespective of stimulus type. Furthermore, in a recent functional account of the lateral premotor cortex (BA 6), Schubotz (2007) outlines the potential involvement of this region in the prediction of motor actions and in the prediction of relevant dynamics of events i.e. prediction of change in serial prediction tasks. In these tasks subjects are asked to monitor a train of abstract stimuli for the repetition of a deviant sequence of stimuli and to judge whether the sequential order was correct or violated. In a series of fMRI experiments robust activations of the motor system, especially in the lateral premotor cortex, were found for different kinds of stimuli. The activation of the lateral premotor cortex was interpreted as reflecting the attempt of predicting a sequential pattern in the stimulus train. In this vein, a reasonable strategy for participants to solve the *n*-back task in the current study could have been to predict the target stimulus to be presented *n* stimuli after the current stimulus, a strategy that would impose high demands on change prediction. In turn, upon the presentation of the n^{th} stimulus, participants would judge whether or not this stimulus matches the predicted stimulus. Therefore, the processing requirements and their reflection in the right middle frontal gyrus activation are highly similar in serial predictions tasks and *n*-back tasks, irrespective of modality. The activation decreases in this brain region as a function of training might suggest that the sequencing and prediction process became more efficient in a modality-unspecific way such that less attentional control (scaffolding) is needed after training.

The activation decreases in the right inferior parietal lobule (BA 40) for both training groups coincide with the results of Hempel et al. (2004) and Dahlin et al. (2008) who also used updating training paradigms. The intraparietal lobule belongs to the common working memory network and is assumed to be especially involved in attentional control processes within working memory (Jonides et al., 1998). The decreases as a function of training can thus be interpreted as reduced scaffolding, since the processes of storage and continuous updating operate more effectively and consequently less attention is required.

It is noteworthy that activation decreases in the superior part of the right middle frontal gyrus (BA 6) and the right inferior parietal lobule (BA 40) are detected for both training groups although only for the visual group an improvement on the behavioral level arose. It seems that the degree of cross-modal training was not yet sufficient to be also manifested in significant performance increases in the auditory training group. Alternatively, it could be argued that changes in the neural substrate of performance cannot simply be attributed to changes in behavioral performance, since participants could have applied a strategy to maintain their performance level with reduced effort rather than to maintain their effort to achieve a higher level of performance (see Sayala et al., 2006, and Oleson et al., 2004, for similar arguments). In this framework, it could be argued that participants after auditory training applied such a strategy more extensively than after visual training and that this is reflected in the decreased activations in the superior part of the right middle frontal gyrus (BA 6) and the right inferior parietal lobule (BA 40). However, it needs to be acknowledged that on the basis of the present data we cannot decide whether such an effort preservation strategy is the result of the smaller training effects of the auditory group or the modality change from training to the posttest.

3.4 NO REORGANIZATION EFFECTS IN THE WORKING MEMORY NETWORK

In addition to the redistribution effects mentioned above, reorganization in terms of Kelly and Garavan (2005) was tested. The activation pattern for the posttest comparison shows a high overlap with the one obtained in the pretest comparison. No additional activation clusters appeared indicating that highly similar brain regions are active before and after training. These findings are in line with several other working memory training studies (e.g. Olesen et al., 2004; Landau et al., 2004; Garavan et al., 2000; Sayala et al., 2006). Training of working memory is less likely to evoke the same kind of neural/behavioral changes as for example training of tasks in which performance can become automatic with training such as visual skill learning and for which reorganization effects on the neural level are frequently reported (e.g. Poldrack et al., 1998). The information held in working memory differs for each trial and the stimulus response mapping for one trial may not be the same for the next trial. Therefore, working memory tasks after training still require cognitive control processes and thus may rely on highly similar brain areas before and after training.

3.5 CONCLUSIONS

In sum, behavioral as well as brain imaging results corroborate the hypothesis that intra-modal training of visual working memory is possible. To my knowledge, this is the first report to show that visual working memory can be trained specifically and those intra-modal training effects can be separated from alterations in general control processes resulting from across-modal working memory training. The visual training revealed greater training effects on the behavioral level and a specific pattern of reduced activation in two adjacent areas located in the right middle frontal gyrus. Furthermore, training of working memory in both modalities led to activation decreases in superior portions of the right middle frontal gyrus and the right inferior parietal lobule indicating more efficient general control processes after training.

3.6 IMPLICATIONS FOR THE LANGUAGE TRAINING STUDY

The findings of the Working Memory Training Study are crucial to further investigate the research questions of the Language Training Study. As the main research question of the

Language Training Study is to expore whether visual and auditory working memory exert differential effects on learning written and spoken words in Chinese, it was a pre-condition to demonstrate that visual processes in working memory can be trained separately from auditory. Thus, the results of the Working Memory Training Study are a vantage point both on a theoretical level and on an operational level.

On a theoretical level it was essential to show that visual working memory processes can indeed trained separately from auditory in particular, because visual working memory was assumed to uniquely underlie the acquisition of Chinese characters. For this reason, it was of highest priority to successfully exemplify intra-modal training effects within the visual modality. From an operational point of view, the adaptive *n*-back working memory paradigm has proven to be capable of training specific visual processes in working memory. Thus, the paradigm seemed most likely to be suitable for the purpose of the Language Training Study.

However, as an analogous dissociation for the audiotry modality was not examined, it is still an unresolved question whether equivalent effects can be expected for the auditory modality.

LANGUAGE TRAINING STUDY

IV LANGUAGE TRAINING STUDY

The Language Training Study aimed at exploring how visual and auditory working memory training affects learning visual and auditory Chinese words and how these trainings differ in their modulation of activation changes in underlying neural networks. In the following methods and materials that are specific for the Language Training Study and results are described. Thereafter, a detailed discussion is given.

1 METHODS AND MATERIALS

In the Methods and Materials chapter I will first focus on the Chinese language training and then at the tasks used in the pre- and posttest fMRI sessions.

1.1 CHINESE LANGUAGE TRAINING

The paradigm for the Chinese language training was adopted from the study by Deng et al. (2008).

1.1.1 PROCEDURE AND EXPERIMENTAL TASKS

The Chinese second language training included both a learning phase in the first week, in which participants acquired the orthography and phonology of 75 Chinese words, and a review test phase in the second week, in which learned words were reviewed and tested (see Figure IV-1). In the learning phase, participants learned a new list of 15 words on each of the first five sessions (learning units). Within each learning unit, participants first saw a German word in the center of the screen for 651 ms and simultaneously heard its German pronunciation via headphones (mean duration = 651 ms).

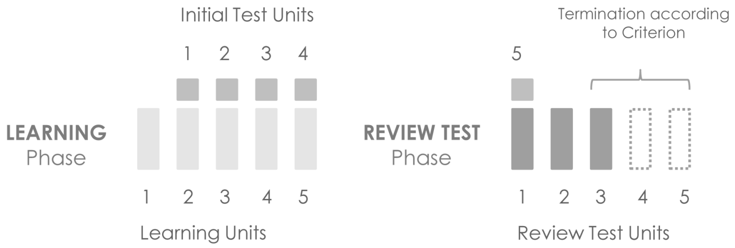

Figure IV-1: Schematic description of the Chinese language training

The learning phase comprised learning units in which new words were learned every other day with initial test units of previously learned words on the following session. The review test phase consisted of review test units in which all words from the previously learning phase were reviewed and tested.

After an inter-stimulus-interval (ISI) of 4349 ms, they saw the corresponding Chinese two-character word for 707 ms and simultaneously heard the Chinese pronunciation of this word via headphones (mean duration = 707 ms) followed by a 2293 ms blank screen. Within each trial the Chinese word was repeated for 10 times. After a 2200 ms inter-trial-interval (ITI) the next trial started. Each trial was repeated twice such that each Chinese word was repeated 20 times in each learning unit. Trials were presented pseudo-randomly ensuring that they were not contiguously repeated. Each learning unit took about 19 minutes. From the second to the sixth training session, each session started with an initial test unit, covering trained words from the last learning unit. Orthographic and phonological proficiency were tested separately. Within each orthographic trial, a German word was presented for 651 ms followed by a 1049 ms ISI, then a visual Chinese character was shown for 707 ms followed by a 1793 ms blank screen. Participants were asked to judge whether the word pair matched by pressing either the letter 'M' or 'C' of a standard computer keyboard. Feedback was given after each response by displaying a happy or sad smiley face for 600 ms. After a 2200 ms ITI, the next trial started. The trial structure of the phonological trials was analogous except that the German (mean duration = 651 ms) and the Chinese words (mean duration = 707 ms) were spoken and auditorily presented via headphones. Orthographic and phonological trials were pseudo-randomly presented, ensuring that within 30 consecutive trials the amount of trials presented in the visual and auditory modality and correct and incorrect trials were held equal. Incorrect trials consisted of words that were learned in the previous learning unit. Each test unit consisted of 60 trials lasting about seven minutes. From the fifth to the tenth training session review test units were applied. Participants were tested on a subsample of all words they had learned in the preceding learning phases. The trial structure was identical to that from the test units. Each review test unit consisted of 240 trials and lasted about 28 minutes. After 120 trials a self-paced break was given. From the eighth training session on, the training was terminated in case participants reached an accuracy of 80% correct or higher in both the orthographic and phonological task. This criterion was introduced to approximately equalize the performance between participants in the subsequent fMRI session. Mean spacing measured by mean number of days between the sessions did not differ significantly between the training groups in the pretest (visual training group: M = 1.25; auditory training group: M = 1.25; control group: M = 1.27; $p >$ .10) and the posttest (visual training group: M = 1.34 ; auditory training: M = 1.23; control group: M = 1.32; $p >$ .10).

1.1.2 MATERIALS

150 Chinese two-character/syllable nouns were selected from 21 categories of the Chinese-American category database (Yoon et al., 2004), which showed fewest cross-cultural differences in the standardized Chinese and American sample of younger adults. No homophones on the syllable level were included (i.e. identical syllables with different meanings) and no more than five characters/syllables were repeated within different words. Each Chinese word was given a one-word unambiguous German translation in meaning with a word frequency below ten per million (Wortschatzportal, Universität Leipzig, http://wortschatz.informatik.uni-leipzig.de). Chinese characters were 165 x 99 pixel size and displayed in Sim Sun black font and German words were presented in Arial black font with a size of 36 on a light gray

screen. Auditory Chinese and German words were spoken by a male native Mandarin and German native speaker and recorded in a soundproof recording studio using a digital recorder and a high-quality stereo microphone. Sound files were normalized such that they were equal in mean amplitude. In all sessions volume was individually adjusted before auditory stimulus presentations.

Words were evenly divided into two stimulus sets at a total of 75 words, which were counterbalanced across participants for stage one and stage two. Words were broken up into ten learning lists of 15 characters each. The sequence of the five learning lists within each stimulus set was counterbalanced between participants. Mean number of strokes of the two-character words, as an indication of visual complexity, was 17.16 and was held constant across lists, $F(1,9) = .062$, $p > .10$. Same tone combinations of the two-syllable words (e.g. lexical tone of the first and second syllable) did not emerge more than twice within each list. No more than two words of the same category were included and no character/syllable was repeated within each list.

Each of the test units covered all 15 words from the latest learning list. Each word appeared twice in the visual (orthographic task) and twice in the auditory modality (phonological task) summing up to 60 trials. Half of the German-Chinese word pairs were correct (German word corresponded to its Chinese translation), the other half was incorrect (German word did not correspond to its Chinese translation).

Words in the review test units were taken from four out of five learning lists. Correct and incorrect pairs were constructed analogously to the test units, except that words of three out of the four learning lists were assembled across learning lists for constructing incorrect trials. The sequence of the five review test lists within each stimulus set was counterbalanced between participants.

1.1.3 DATA ANALYSIS

A repeated measure MANOVA with the factors Group (visual training vs. auditory training vs. no training) and Time (pretest vs. posttest) was calculated on the mean discrimination index *Pr* (*p*[Hit] - *p*[FA]) (Snodgrass & Corwin, 1988) of the first three review tests of the second week of each language training as an estimate of the participants` mean performance for each language training.

1.2 TASKS AT PRE AND POSTTEST FMRI SESSIONS

Participants were scanned after each language training and were tested on all 75 Chinese words learned in the previous language training. An orthographic and phonological task using the same task format as in the test and review test units of the language training was employed, except that the feedback screen was replaced by a 1000 ms blank screen and the ITI was exponentially distributed and ranked from 4000 to 9000 ms (mean duration = 5000 ms) varying in steps of 1000 ms to achieve an optimal tradeoff between detectability and estimation efficiency of the BOLD response (Hagberg, Zito, Patria, & Sanes, 2001) (see Figure IV-2).

Figure IV-2: Orthographic and phonological tasks of the pre- and posttest fMRI sessions and their respective control tasks

Participants had to judge whether the German word matched to the learned Chinese word either in the visual (orthographic) or the auditory (phonological) modality. In the control tasks participants performed a comparison task on features of the Chinese word either in the visual or the auditory modality.

A visual and an auditory discrimination task using unknown Chinese characters/syllables served as control tasks for the orthographic and the phonological task, respectively (see Figure IV-2). In the visual comparison task, participants had to discriminate between two unknown characters from which one consisted of more strokes than the other. In the auditory comparison task, participants had to judge whether two unknown Chinese syllables either increased or decreased in volume. The preceding German word was always either the word ‘links’ (left) or ‘rechts’ (right) written in the orthographic task and spoken in the phonological task, respectively. In the orthographic task participants were instructed to associate the simple character with the position cued by the German words, whereas in the phonological task participants were instructed to associate left with ascending and right with descending volume. The task was to judge, whether the cue (German word) corresponded to the Chinese word.

Experimental and control trials were employed in the same run. In a first block 75 orthographic and 75 phonological trials were pseudo-randomly presented, ensuring that within 30 consecutive trials the amount of visual and auditory trials and correct and recombined trials were held equal. In a following second block 30 orthographic and 30 phonological control trials were employed in a pseudo-random order using the same constraints as in the experimental tasks. The run lasted 35 minutes.

Before the pretest fMRI session participants performed 10 trials of each control task outside the scanner to familiarize them with the tasks.

1.2.1 MATERIALS

120 single Chinese characters that were not included in the language training were used to construct the orthographic control task. Character pairs were constructed by randomly assembling simple (three to six strokes) and complex characters (13 to 15 strokes) resulting in 60 character pairs, in half of the pairs the simple character was placed on the left position and the complex on the right and vice versa. As in the language training, pairs were evenly split up into two stimulus sets of 30 character pairs, which were counterbalanced across participants for the pre- and posttest fMRI sessions. In order to minimize perceptual differences between experimental and control tasks, the mean number of strokes of the control character pairs in each stimulus set was 18.00 ($SD = .28$) such that complexity was held constant between control character pairs and learned characters used in the language training, $t(1,208) = 1.16$, $p > .10$. For the phonological control task, the character`s corresponding pronunciations were used. All Chinese and German spoken words/syllables for the control task were recorded in the same way as the words of the language training. Chinese 2-syllable pairings were edited to increase or decrease in volume.

1.2.2 BEHAVIORAL DATA ANALYSIS

A repeated measure MANOVA with the factors Group (visual training vs. auditory training vs. no training) and Time (pretest vs. posttest) was calculated on the discrimination index *Pr* (p[Hit] - p[FA]) (Snodgrass & Corwin, 1988) of the pre- and posttest fMRI sessions.

1.2.3 BRAIN IMAGING DATA ANALYSIS

Functional time-series were analyzed using random-effects multi-subjects GLM (Friston et al., 1999). In a first analysis all levels of the factor Task (orthographic, phonological, orthographic control and phonological control) and Time (pretest and posttest) were modeled as separate predictors on the presentation of the Chinese words for each subject. Motion parameters and activations on the German words were added as predictors of no interest to the design matrix of each run. Only correct trials were included in the analysis. Thus, the resulting GLM contained eight parameters of interest per subject: Orthographic, phonological, orthographic control and phonological control for each of the pre- and posttest sessions. Predictor time courses (duration = 707 ms) were adjusted for the hemodynamic response delay by convolution with a double-gamma hemodynamic response function as implemented in Brain Voyager QX (see Friston et al., 1998, for further details).

To explore baseline activations elicited by the orthographic and the phonological task after learning and independent of working memory training, the following random-effects contrast was calculated on all correct trials of the data of all participants: Orthographic pretest vs. orthographic control pretest for the orthographic task and phonological pretest vs. phonological control pretest for the phonological task. The results from this whole-brain analysis resulted in % signal change images thresholded at $p < .005$ (FDR corrected) using clusters determined by the number of functional voxels > 25. In a second analysis I defined functional VOI on the basis of these cluster activations in the pretest. Importantly, using a priori VOIs from the activation during pretest permitted to specifically examine effects that training had on initially activated brain regions (referred to as redistribution effects) and provides a criterion for inclusion of regions in the pretest-posttest analysis (Erickson et al., 2007; Kelly & Garavan, 2005). This hypothesis-driven approach allowed to assess training-induced changes in activity by means of Time (pretest vs. posttest) by Group (visual training vs. auditory training vs. no training) interactions. All voxels which were significant in the first analysis located within the cerebrum where entered in the second analysis. To assess training-induced changes within VOIs I extracted the mean parameter estimates from pre- and posttest for each participant and each predictor from the VOIs and performed a series of repeated measures MANOVAs.

To investigate whether visual and auditory working memory training led to new activations at posttest, referred to as reorganization effects (Kelly & Garavan, 2005), I examined the voxel-based statistical parametric maps in the fMRI posttest separately on the multi-study GLM for each training group and the orthographic and phonological task. Because of smaller sample sizes the threshold was set to $p < .0005$ (uncorrected) determined by the number of functional voxels > 25. To test whether regions that were only activated in the posttest were specific for the respective group, I defined significantly activated voxels as VOIs and extracted mean parameter estimates from pre- and posttest for each participant and each predictor from the VOIs and performed one-way ANOVAs with the between-subjects factor Group. To ensure that differences were not due to baseline differences in the pretest, the same VOIs and one-way ANOVAs were applied to the pretest extracted mean parameter estimates.

2 RESULTS

First the behavioral results of the first and second Chinese language and of the fMRI pre- and posttests will be described. The description of the brain imaging results follows the taxonomy of Kelly and Garvan (2005): Redistribution effects are first presented followed by the description of reorganization effects.

2.1 BEHAVIORAL RESULTS

2.1.1 CHINESE LANGUAGE TRAINING

Figure IV-3 shows the behavioral performance (*Pr* Scores) on the review test phases of the first and second language training for the orthographic (Figure IV-3 A) and phonological tasks (Figure IV-3 B).

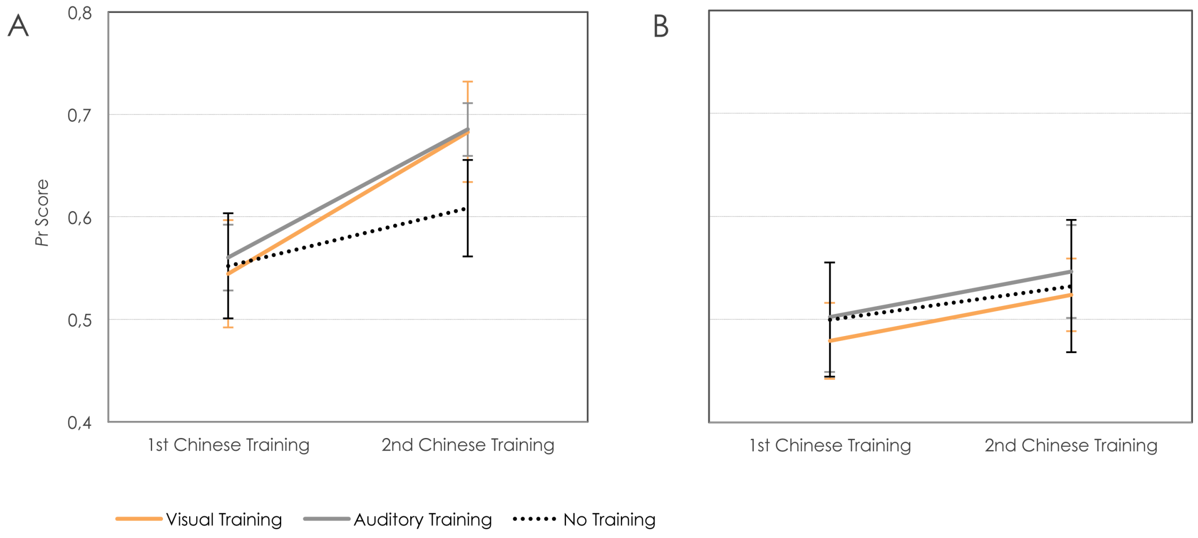

Figure IV-3: Behavioral performance on the orthograhic (A) and the phonological task (B) in the review test phases of the first and second Chinese training

Mean *Pr* scores and corresponding standard errors of the mean for the visual and auditory training groups and the control group.

The two-way MANOVAs with the factors Time (first vs. second language training) and Group (visual training vs. auditory training vs. no training) allow to test for transfer effects the intra-modal (visual) and cross-modal (auditory) training had on learning Chinese characters and spoken words. In the orthographic task, performance increased from the first to the second language training, as indicated by a significant main effect of Time, $F(1,45) = 50.57$, $p < .001$, $\eta^2_p = .53$. The Time by Group interaction was marginally significant, $F(2,45) = 2.88$, $p < .10$, $\eta^2_p = .11$.

Planned contrasts of pretest-posttest differences indicated that performance increases after visual training, mean difference = .14, *SD* = .09, were significant, $t(1,15)= -5.86$, $p < .001$, performance increases after auditory training were likewise significant, $t(1,15)= -5.05$, $p < .001$, and performance was marginally significant after no training, mean difference = .06, *SD* = .12, $t(1,15)= -1.93$, $p < .10$. A one-way ANOVA with the factor Group was performed on the first training and revealed no significant differences between the groups, $F(2,45)= .05$, $p > .10$, $\eta^2_p = .00$, ensuring that effects were not caused by baseline differences prior to working memory training. In the phonological task, no significant main effect or interaction was obtained, $p > .10$.

2.1.2 FMRI SESSIONS

Performance on the orthographic and phonological tasks in the pre- and posttest fMRI sessions was basically equivalent to performance in the language training (see Figure IV-4 A and B).

In the orthographic task, performance improved from pre- to posttest as shown by the significant main effect of Time, $F(1,45) = 4.47$, $p < .05$, $\eta^2_p = .09$. The Time by Group interaction was marginally significant, $F(2,45) = 2.51$, $p < .10$, $\eta^2_p = .10$. Performance increases from pre- to posttest after visual training, mean difference = .07, $SD = .12$, were significant, $t(1,15)= -2.34$, $p < .05$, and marginally significant after auditory training, mean difference = .02, $SD = .12$, $t(1,15)= -1.75$, $p = .10$, whereas performance did not change after no training, mean difference = -.05, $SD = .10$, $t(1,15)= 0.64$, $p > .10$. In the phonological task, neither main effect, $p > .10$, nor interaction was significant, $p > .10$.

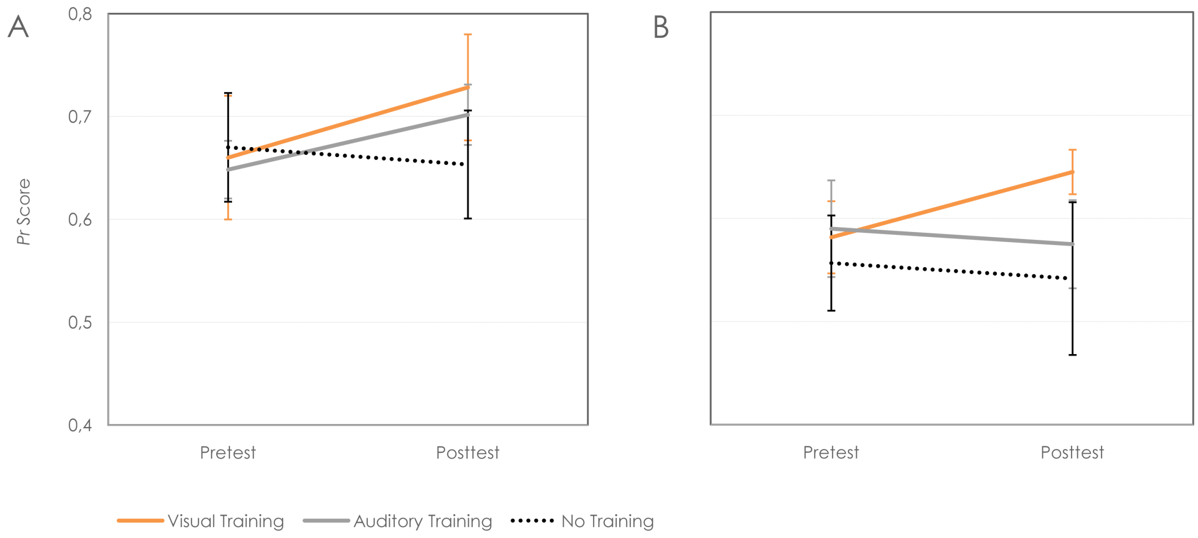

Figure IV-4: Behavioral performance on the orthographic task (A) and phonological task (B) in the pre- and posttest fMRI sessions

Mean *Pr* scores and corresponding standard errors of the mean for the visual and auditory training groups and the control group.

Together with the transfer effects in the first and second Chinese language training, these results show that inta-modal as well as across-modal working memory training transferred to performance on the orthographic task whereas contrary to our hypothesis none of the trainings transferred to performance on the phonological task.

2.2 BRAIN IMAGING RESULTS

2.2.1 REDISTRIBUTION EFFECTS

In the pretest, the contrast between the orthographic task and the orthographic control task revealed regions that were involved in orthographic character processing after the first language training. These regions were in the left and right fusiform gyrus, the left and right cerebellum, the right thalamus, and the right putamen (see Table IV-1, for a list of regions and cluster peak coordinates).

Table IV-1: Brain regions activated in the pretest contrast orthographic task minus orthographic control task

Number of VOI	Brain region	BA	H	t value	Number of Voxels	x	y	z
[1]	Fusiform Gyrus /Cerebellum	37	L	9.559	7292	-48	-58	-14
[2]	Fusiform Gyrus /Cerebellum	37	R	6.943	4695	36	-46	-14
[3]	Cerebellum	/	L	7.479	2250	-6	-73	-29
[4]	Cerebellum	/	L + R	6.647	842	6	-46	-2
[5]	Thalamus (Pulvinar)	/	R	5.927	944	24	-25	10
[6]	Putamen	/	R	6.011	701	15	-10	19

H, hemisphere; L, left; R, right; BA, Brodmann`s area. Clusters are listed based on cluster peak coordinates. Coordinates correspond to those from the Talairach & Tournoux reference brain. Clusters presented are more than 25 contiguous voxels surviving a threshold of $p < .005$ (FDR corrected).

With respect to VOI analyses, the main interactions of interest were Time (pretest vs. posttest) by Group (visual training vs. auditory training vs. no training) as these interactions reveal differential pretest-posttest activation changes between the training groups. A significant Group by Time interaction was found in the left fusiform gyrus [1][3], $F(2,45) = 6.47$, $p < .01$, $\eta^2_p = .22$ (see Figure IV-3 A).

Comparisons of pretest-posttest performance separately for each group indicated that activation increases after auditory training, mean difference = .008, $SD = .017$, were marginally significant, $t(1,15)= -1.95$, $p < .10$, activation decreases after visual training, mean difference = -.005, $SD = .015$, did not reach significance, $p > .10$; however, after no training, mean difference = -.013, $SD = .019$, activation decreased significantly, $t(1,15)= 2.77$, $p < .05$.

Notably, the Group by Time interaction within this VOI was still significant when reducing the Group factor levels to visual and auditory working memory training only, $F(1,30) = 5.48$, $p < .05$, $\eta^2_p = .15$. This

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[3] To eliminate the possibility that this effect could have arisen from voxels belonging to the cerebellum, this analysis was performed on the basis of a sub-VOI including only voxels belonging to the temporal/occipital cortex [cluster size: 2678 voxels, peak voxel: -45, -58, -18]. The interaction of the original VOI was also significant, $F(2,45) = 3.43$, $p < .05$, $\eta^2_p = .13$, but less pronounced as indicated by a smaller effect size. Note that numbers in square brackets refer to numvers of the VOIs as indexed in Table IV-1.

indicates that the interaction does not trace back to the dropdown in activation for the control group, but rather reflects the differential effects of auditory and visual working memory training in the left fusiform gyrus in the orthographic task.

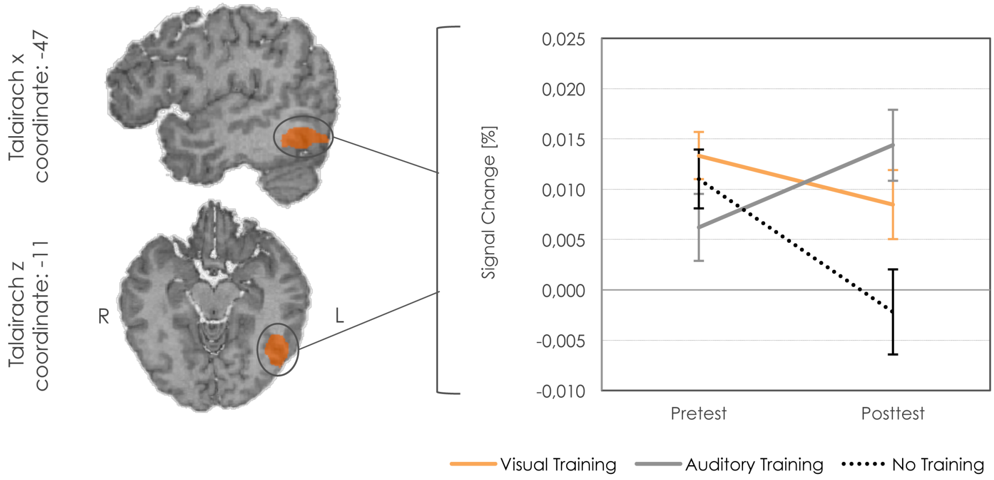

Figure IV-5: Working memory training-related activation changes during performance of the orthographic task

Percent signal change values for the orthographic task within the left fusiform gyrus at BA 37 [1] for visual training versus auditory training versus no training.

To make sure that effects did not arise on account of baseline differences, a one-way ANOVA with the factor Group (three levels) was performed on the pretest percent signal change values within this VOI and revealed no significant differences between the groups, $F(2,45) = 1.58$, $p > .10$, $\eta^2_p = .07$. No other significant Time by Group interaction was found for any other VOI of the orthographic task.

Regions that were involved in auditory phonological processing after the first second language training as indicated by the contrast between the phonological task and the phonological control task during pretest were in the left and right inferior frontal gyrus, superior temporal gyrus and anterior insula as well as in the left and right putamen, and left cerebellum (see Table IV-2, for a list of regions and cluster peak coordinates).

Table IV-2: Brain regions activated in the pretest contrast phonological task minus phonological control task

Number of VOI	Brain region	BA	H	t value	Number of Voxels	x	y	z
[1]	IFG/STG /Insula	44/22/13	L	5.003	1023	-29	-7	16
[2]	IFG/STG /Insula	44/22/13	R	6.204	702	45	11	7
[3]	Putamen	/	L	5.856	1457	-18	2	10
[4]	Putamen	/	R	5.675	937	21	7	7
[5]	Cerebellum	/	L	4.384	806	-21	-55	-20

H, hemisphere; L, left; R, right; BA, Brodmann`s area; IFG, inferior frontal gyrus; STG, superior temporal gyrus. Clusters are listed based on cluster peak coordinates. Coordinates correspond to those from the Talairach & Tournoux reference brain. Clusters presented are more than 25 contiguous voxels surviving a threshold of $p < .005$ (FDR corrected).

The Time by Group interactions of the VOI analyses reached significance in the anterior insula, $F(2,45) = 3.79$, $p < .05$, $\eta^2_p = .14$,[4] (see Figure IV-3 B).

Activation after visual training, mean difference = .022, $SD = .036$, decreased significantly, $t(1,15)= -2.26$, $p < .05$, whereas activation increased significantly after auditory training, mean difference = -.016, $SD = .026$, $t(1,15)= 2.49$, $p < .05$. In the control group activation did not change, $p > .10$. As for the orthographic task, the Time by Group interaction was still significant when the Group factor was confined to the two training groups, $F(1,30) = 11.84$, $p < .01$, $\eta^2_p = .28$. This again indicates that both working memory trainings exert differential effects in the anterior insula in the phonological task. To make sure that effects did not arise on account of baseline differences, a one-way ANOVA with the factor Group was performed on the pretest percent signal change values within this VOI and revealed no significant differences between the groups, $F(2,45)= 1.26$, $p > .10$, $\eta^2_p = .05$.

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[4] The original VOI comprised the left inferior frontal gyrus, superior temporal gyrus, and anterior insula [1] and likewise showed a significant Time by Group interaction, $F(2,45) = 4.06$, $p < .05$, $\eta^2_p = .15$. Since functionally distinct brain regions were included within this VOI, we separated voxels according to Brodmann`s areas resulting in the following three sub-VOIs: inferior frontal gyrus (BA 44) [cluster size: 18 voxels, peak voxel: -48, 12, 1], superior temporal gyrus (BA 22) [cluster size: 219 voxels, peak voxel: -48, 8, 1], and anterior insula (BA 13) [cluster size: 121 voxels, peak voxel: -45, 8, 1]. Time by Group interactions in the inferior frontal gyrus and superior temporal gyrus were not significant, $p > .10$. Note that numbers in square brackets refer to numbers of the VOIs as indexed in Table IV-2.

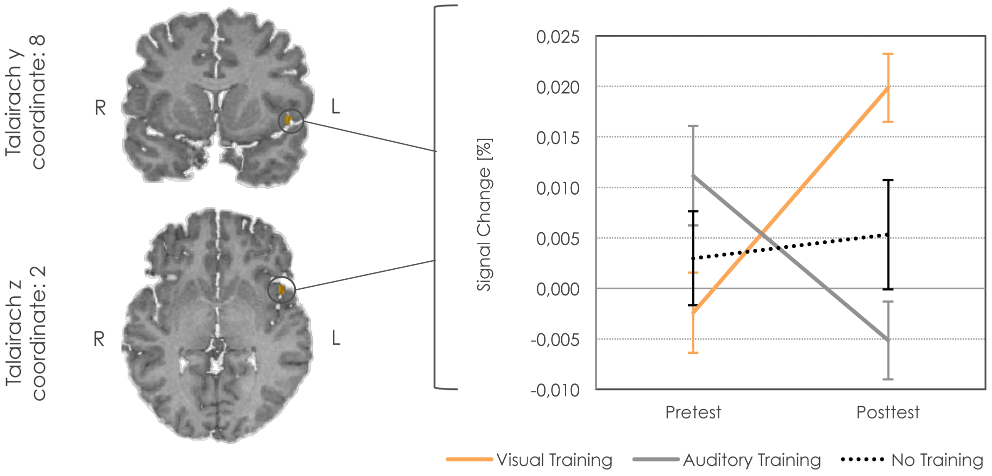

Figure IV-6: Working memory training-related activation changes during performance of the phonological task

Percent signal change values for the phonological task within the anterior Insula at BA 13 for visual training versus auditory training versus no training.

Although the analysis of the behavioral data in the phonological task did not reveal a significant Time by Group interaction on *Pr* scores, visual inspection of Figure IV-4 B suggests that there was a larger improvement after visual than after auditory training. To ensure that activation changes in the anterior insula in the visual training group were not due to performance differences a MANCOVA with performance during the phonological task in the fMRI session as a covariate was performed in the sub-VOI comprising the left anterior insula. The Time by Group interaction was still significant, $F(2,44) = 4.58$, $p < .05$, $\eta^2_p = .17$. In no other VOI of the phonological task a significant Time by Group interaction was obtained.

Taken together, a similar pattern of activation changes was observed in the left mid-fusiform gyrus in the orthographic task and in the left anterior insula in the phonological task. Activation decreased/sustained after intra-modal training where as activation increased after across-modal working memory training.

2.2.2 REORGANIZATION EFFECTS

Regions that were active in the posttest comparison in the orthographic task after visual and auditory training were located in the left and right fusiform gyrus and the right precuneus (visual training group) and in the left and right fusiform gyrus (auditory training group). No additional region was activated in the control group at posttest (see Table IV-3).

Table IV-3: Brain regions activated in the posttest contrast orthographic task minus orthographic control task separated for the visual and auditory training group

Training-group	Brain region	BA	H	t value	Number of Voxels	x	y	z
Visual	Fusiform Gyrus /Cerebellum	37	L	7.227	1559	-39	-52	-11
	Fusiform Gyrus /Cerebellum	37	R	9.365	1623	42	-55	-14
	Precuneus	7/40	R	6.540	2369	27	-67	34
Auditory	Fusiform Gyrus /Cerebellum	37	L	6.999	3434	-48	-58	-17
	Fusiform Gyrus /Cerebellum	37	R	5.917	1100	48	-55	-11

BA, Brodmann`s area; H, hemisphere; L, left; R, right. Clusters are listed based on cluster peak coordinates. Coordinates correspond to those from the Talairach & Tournoux reference brain. Clusters presented are more than 25 contiguous voxels surviving a threshold of $p < .001$ (uncorrected).

In the orthographic task the precuneus was the only region that accrued in the posttest and was not already activated during pretest (see Figure IV-7).

Activations in this VOI differed significantly between the training groups as indicated by a significant main effect of Training Group, $F(2,45) = 6.70$, $p < .01$, $\eta^2_p = .23$. Tukey HSD post hoc comparisons of differences between parameter estimates of the groups revealed that the activation differences between the visual and auditory training group, mean difference = .018, *SD* = .006, and the visual training group and the control group, mean difference = .020, *SD* = .006, were significant whereas the difference between the auditory training group and the control group, mean difference = .002, *SD* = .006, was not reliable. As the analysis to test reorganization effects was based on the three groups separately I computed a one-way ANOVA on the pretest activations within the precuneus VOI. The main effect of Group was not significant, $F(2,45) = .45$, $p = .64$, ensuring that differences in the posttest do not trace back to baseline differences before working memory training.

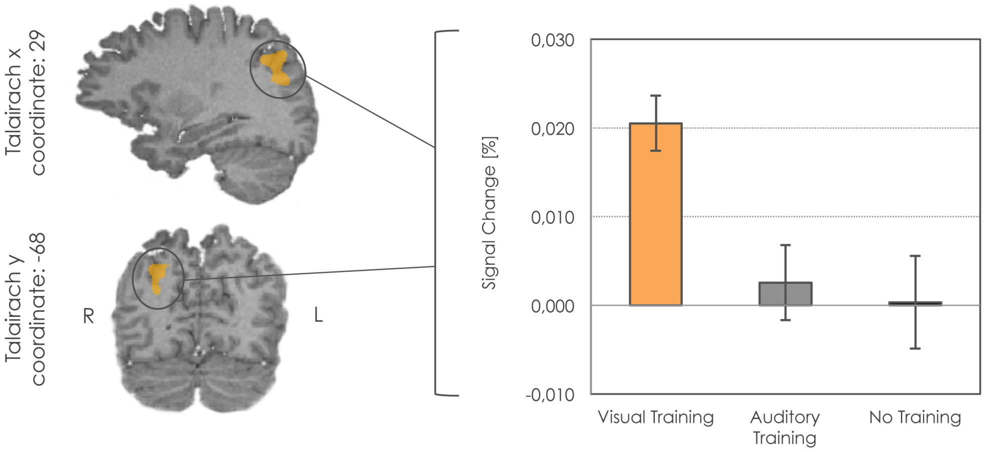

Figure IV-7: Reorganization in the orthographic task after visual training

Percent signal change values for the orthograhic task within the precuneus at BA 7/40 for each training group in the posttest comparison.

In the phonological task no region was activated in the posttest comparison separately for the groups.

3 DISCUSSION

Although there have been various studies investigating the neural correlates of Chinese second language learning (e.g. Deng et al., 2008; Liu et al., 2007; Wang et al., 2003), this study is the first to investigate vocabulary learning in the visual and auditory modality and to explore the impact of auditory and visual working memory training as a means to elucidate underlying processes in Chinese word learning.

3.1 SUMMARY OF THE RESULTS

Training effects were found in the *n*-back working memory tasks for both training groups, which allowed to compare the transfer effects of both trainings on performance and neural activation changes in learning Chinese visual and auditory words. The behavioral results indicated that both visual and auditory working memory training led to increased performance in the orthographic tasks compared to no training, while no reliable improvements in the phonological tasks were found. Most interestingly, the visual and auditory working memory training elicited diametrically opposed patterns of neural activation changes in brain areas which are crucial for visual and auditory language processing, i.e. the left infero-temporal cortex for the visual modality and the left anterior insula for the auditory modality. As only the orthographic tasks revealed behavioral improvements after working memory training, these latter effects were not modulated by differential behavioral transfer effects from visual and auditory working memory training. In addition, visual working memory training specifically led to supplementary activation in the right precuneus.

3.2 TRANSFER EFFECTS OF WORKING MEMORY TRAINING ON CHINESE VOCABULARY ACQUISITION

The prediction that visual and auditory vocabulary acquisition should generally be improved by working memory training was not supported by our data as I found transfer effects only for the orthographic task but not for the phonological task. The improvements on the orthographic task during the second language trainings and in the fMRI sessions after visual as well as auditory working memory training demonstrates that orthographic learning in Chinese benefits likewise from visual and auditory working memory training and are by this in line with our specific hypothesis on learning written Chinese characters. However, visual training did not result in additional gains compared to auditory training. These data complement correlational and longitudinal studies reporting that both visual and phonological working memory skills predict learning to read Chinese characters (Siok & Fletcher, 2001; Ho & Bryant, 1997b; Tan et al., 2005b). Thus, the current data augment these findings by providing evidence for underlying visual working memory processes to contribute specifically to Chinese character learning besides auditory working memory. As the *n*-back task not purely trains modality-specific processes but also taps into executive components such as updating, those aspects cannot be clearly separated in our paradigm although abstract visual and auditory materials were used which were verbally and semantically devoid. As the visual training showed specific training effects in the visual 2-back task in the Working Memory Training Study, it is likely that visual training indeed improved modality-specific processes and thereby led to transfer to orthographic learning. However, on the basis of the behavioral data, it needs to be unresolved to which subcomponents of the *n*-back task the transfer effects trace back, especially because comparable transfer effects were found for auditory training.

In contrast, against my assumptions none of the working memory trainings improved the acquisition of spoken Chinese words, neither in the language trainings nor in the fMRI sessions. Notably, the behavioral results are contradictory insofar as the auditory working memory training transferred to the across-modal orthographic task but not to the intra-modal phonological task for which specific improvements were expected. To account for this pattern of results, it is helpful to consider the framework for cognitive plasticity by Lövdén et al. (2010). As already outlined in the introduction (Chapter I-5.1) the authors proposed that cognitive plasticity is induced by a prolonged mismatch between functional supplies and environmental demands. In this vein, the level of intrinsic plastic capacity i.e. the capacity for changes within the possible range of cognitive performance is a necessary condition. I speculate that the level of plastic capacity might be more strongly limited for phonological learning compared to orthographic learning. On account of the simpler syllable structure in Mandarin Chinese, to-be-learned syllables are difficult to distinguish from each other. Aside from that they do not bear any possibility to link the sound pattern to meaning whereas linking stroke patterns to meaning is likely in the orthographic task as semantic radicals, i.e. stroke patterns that provide information about the meaning of the character, are commonly ideographic (Tsang & Cheng, 2009). If the range of functional capacity was indeed restricted in the phonological task, the alternation of auditory working memory processes, as a function of training might not have been sufficient to be manifested in transfer in the phonological task.

3.3 WORKING MEMORY TRAINING-RELATED ACTIVATION CHANGES

The activation pattern of the visual orthographic task in the pretest comparison comprised mainly the bilateral fusiform gyrus, bilateral cerebellum, right putamen and right thalamus and was generally consistent with previous reports of Chinese second language processing (Deng et al., 2008; Liu et al., 2007; Nelson et al., 2009). The left mid-fusiform gyrus was found to show opposed activation changes after visual and auditory working memory training. Therefore, the findings on the first glance support the hypothesis that visual working memory training should specifically affect the visual association cortex as the left fusiform gyrus is a part of the ventral visual stream and a center for higher visual object recognition (Malach, Levy, & Hasson, 2002; Reddy & Kanwisher, 2006; Riesenhuber & Poggio, 1999). Although the region is discussed to be exclusively involved in processing one`s native visual word forms in alphabetic languages (e.g. Cohen et al., 2000; 2002; McCandliss, Cohen, & Dehaene, 2003) as well as in Chinese (Liu et al., 2008), recent studies have implicated an important role of the left fusiform gyrus in processing and learning visual words in a new writing system, especially in visually complex logographic languages like Chinese (e.g. Deng et al. 2008; Liu et al., 2007; Nelson et al., 2009; Xue, Chen, Jin, & Dong, 2006a, 2006b; Xue et al., 2010). The mid-fusiform gyrus has been shown to be already activated in early phases of Chinese character learning (Liu et al., 2007; Nelson et al., 2009). In line with these findings, the pretest activation across all three groups likewise demonstrate that the first 14-day Chinese language training was sufficient to result in robust activation in the mid-fusiform gyrus, suggesting that lexically relevant visual information could be extracted from Chinese characters. Moreover, in previous studies activation in this region changed in the course of learning Chinese characters and artificial logographic characters (Deng et al., 2008; Xue et al., 2006b). The pattern of increases and decreases was nevertheless inconsistent. More specifically, activation increases were found for transfer characters, which did not share a previously learned radical (Deng et al., 2008), and were attended by enhanced memory for artificial Korean characters that share visual complexity with Chinese characters (Xue et al., 2006b). Contrarily, Xue et al. (2006a) reported decreased activation in the mid-fusiform gyrus after a short period of visual word training using artificial Korean characters but increased activation in subsequent phonological and semantic learning in Chinese native speakers. To the extend to which learning artificial Korean characters engage the same visual processes as learning Chinese characters these studies speak for the prominent role of the left mid-fusiform gyrus in learning visually complex written words and enhanced activity in this region seem to reflect greater perceptual encoding in an advanced visual stage of learning (Xue et al., 2006a).

From the viewpoint of working memory, the left mid-fusiform gyrus was found to be active in several visual working memory studies (Axmacher et al., 2009; Buchsbaum et al, 2005; Fiebach et al., 2006; Wager & Smith, 2003; Wang, Yang, Shu, & Zevin, 2011). Taking those data into account, the finding of sustained activation after visual working memory training together with improved performance in the orthographic task, suggests that visual working memory training specifically sharpened encoding and maintaining of complex visual patterns in working memory. This honed process could promptly be used to extract relevant information from visually complex Chinese characters more effectively and thus allowed for better access to lexical knowledge. The antipodal pattern of increased activation after auditory working memory training is similar to the pattern found in the majority of training studies showing more activity related to better performance (Deng et al., 2008; Xue et al., 2006a, 2006b). As the mid-fusiform gyrus is assumed to be involved in verbal multi-modal integration (Cohen, Jobert, Le Bihan, & Dehaene, 2004; Xue et al., 2006a; Fiebach et al., 2006) even auditory working memory training was capable of shaping the mid-fusiform gyrus to engage short-term maintenance such that similar behavioral improvements as after visual training could be achieved. Accounting that the *n*-back task taps into executive components of working memory and that working memory serves to control visual selective attention in the fusiform gyrus (de Fockert, Rees, Frith, & Lavie, 2001; Fiebach et al., 2006), I speculate that increased activation in the mid-fusiform gyrus reflects increased selective visual attention in the orthographic task presumably guided by modality-unspecific improvements in executive components of working memory after auditory training. Remarkably, the control group showed a reliable decrease in activation from the pretest to the posttest although no behavioral improvements were found and experience with Chinese characters was exactly the same across the groups, indicating that learning visual words in Chinese without any influence of working memory training results in activation decreases over time. These findings are in agreement with two studies on perceptual learning of Chinese characters (Xue et al., 2010; Xue & Poldrack, 2007). Activation decreases in the control group thus are likely to reflect similar perceptual familiarization with Chinese characters. However, it was not efficient enough to significantly improve task performance.

In addition to changes in activation within activated brain regions prior to working memory training, the right precuneus was found to be uniquely active in the orthographic task after visual training. Bilateral precuneus activation is commonly found in Chinese character processing (e.g. Kuo et al., 2004; Deng et al., 2008; Tan et al., 2005a; Bolger et al., 2005). More specifically, it showed solely activation for artificial characters in native Chinese participants in contrast to real and pseudo Chinese characters (Liu et al., 2008) and stronger activation was correlated with greater increase in accuracy when learning new characters in English native speakers (Deng et al., 2008). It is likely that in both studies a higher demand on visual-spatial analysis was required since artificial characters were new for Chinese natives in the Liu et al. (2008) study and better accuracy in the Deng et al. (2008) study involved visual-spatial analysis of the newly acquired radical`s stroke pattern. In this vein, I assume that in the current study the visual working memory training triggered additional visual-spatial strategies. As the precuneus is consistently linked to visual imagery (Cavanna & Trimble, 2006; Fletcher et al., 1995; Gardini, Cornoldi, De Beni, & Venneri, 2009), this activation is likely to reflect visual mental image generation of the learned characters to retrieve its respective visual-semantic representation.

As precuneus activation was also associated with successful retrieval of previously encountered items (e.g. Wagner, Shannon, Kahn, & Buckner, 2005), I additionally tested whether enhanced activation was only present when participants correctly recognized previously learned characters (hits) as compared with characters which were falsely identified as correct (false alarms). As the Response Type (hits vs. false alarms) by Group (visual training vs. auditory training vs. no training) interaction was not significant, $F(2,45) = 0.43$, $p = .65$, I feel save to conclude that the specific activation of the precuneus after visual training does not reflect the matching process between the successfully imagined character and the presented probe character. Instead it most likely mirrors the generation of a visual image of the character independent of performance. Collectively, findings of sustained activation in the fusiform gyrus after visual training and additional recruitment of the right precuneus provide unique support for multiple visual strategies, which were boosted by visual working memory training to encode and retrieve the characters.

The activation pattern elicited by the auditory phonological task in the pretest comparison included primarily bilateral inferior frontal and superior temporal cortices, bilateral putamen and left cerebellum. Thus, the findings converge with findings from studies of Chinese (Liu et al., 2009) as well as alphabetic auditory word processing (e.g. Price, 2010; Fiez & Petersen, 1998).

Diverging activation changes between training groups were found in the VOI comprising the left superior temporal gyrus, anterior insula and inferior frontal cortex after visual and auditory training and by this support our prediction that auditory working memory training should specifically affect the auditory association cortex involved in auditory language processing. These areas belong to the dorsal stream within the dual-stream model of speech processing which is involved in perception and articulatory representation of spoken words (Hickock & Poeppel, 2004, 2007). The adjacent left anterior insula likewise belongs to the speech network (Ardila, 1999; Bamiou, Musiek, & Luxon, 2003; Mutschler et al., 2009) and was linked amongst others to articulatory-based phonological analysis (Fiez & Petersen, 1998). Moreover, insula activation was consistently found in discrimination tasks of phonological contrasts in auditory language learning studies (Golestani & Zatorre, 2004; Callan et al., 2003). In addition, the anterior insula is known to play a major role in phonological working memory (Augustine, 1996; Buchsbaum et al., 2005; Paulesu, Frith, & Frackowiak, 1993; Gaab, Gaser, & Schlaug, 2006). Importantly, Chee et al. (2004) found that bilinguals who were as fluent in Chinese as in English compared to those who were not recruited the left insula more strongly in a phonological working memory task. Thus, the more facile engagement peri-sylvian regions seems to be required to incorporate novel speech-like sounds into long-term phonological representations. Accordingly, in the present data, intra-modal (auditory) training might have tapped exactly those processes, which became more effective in the course of auditory working memory training predominantly due to articulation processes. As a consequence, less cognitive effort was needed to perform the phonological task, as improved auditory processes could be more effectively applied in the phonological task. Since the insula is assumed to be a multi-modal integration area mediating temporally defined cross-modal interactions (Sterzer & Kleinschmidt, 2010), across-modal (visual) training led to enhanced engagement of the predominantly auditory insular cortex reflected in increased activation. Improved executive processes after visual training might have accelerated flexibility to direct attention to sound patterns for incorporating them into long-term representations. This mechanism thus was reflected by increased activation. Importantly, no change of activation was observed for the control group indicating that activation changes in the training groups indeed trace back to working memory training.

If one considers the patterns of activation changes in the orthographic and phonological task in conjunction, it becomes evident that they are strikingly similar. To begin with, the effects are located in multi-modal association cortices, the left infero-temporal cortex and regions around the superior temporal gyrus with its core region in the anterior insula. Those areas are by definition associated with higher-order visual or auditory sensory information processing and multi-sensory integration. Thereby, they are appendant to specified ‘storage’ areas for visual and auditory word processing. I assert that intra-modal working memory training led to more effective encoding and retrieval of lexical information in the respective modality accompanied by a sharpening of the corresponding neural network. This might be reflected in activation decreases in areas involved in sensory information processing and multi-sensory integration or preserved activation accompanied with behavioral improvements. Contrarily, across-modal training further triggered pronounced recruitment of the relevant modality-specific region by enabling its flexible recruitment depending on the affordances of the to-be-recognized stimulus.

However, on the basis of these findings it cannot be unambiguously decided whether this mechanism was induced by multi-modal interaction or by modality-independent working memory control processes that might have facilitated to directed attention to the relevant process. It is also conceivable that the additional recruitment of these regions reflects increased motivation since participants might have invested more effort in the task modalities they were not trained in. In opposition to activation changes after visual and auditory working memory training, activation pattern in the control group did not change (phonological task) or activation changes resembled most the one elicited by mere perceptual habituation (orthographic task). As differential activation patterns occurred independently of behavioral improvement, more advanced processing might not be sufficient for changes on the behavioral level.

3.4 CONCLUSIONS

To sum up, the present findings demonstrate, that visual and auditory working memory training likewise improve learning Chinese visual words whereas for learning Chinese auditory words no such effects were found. In addition the present data demonstrate that the recruitment of modality-specific language-related brain regions can be differentially modulated by modality-specific working memory training in learning Chinese. Specifically, the (predominantly visual) left infero-temporal cortex and the (predominantly auditory) left anterior insula showed analogous activation changes after intra- compared to across-modal working memory training which were independent from training-related performance increases. Intra-modal training restulted in sustained or decreased activation in contrast to across-modal training leading to activation increases. This pattern of increases and decreases within the same language-related regions suggests that the kind of activation changes during vocabulary acquisition do not simply follow a mere pattern of increases or decreases commensurate to whether they belong to the ‘scaffolding’ network or task-specific regions. Rather working memory training can lead either to more precise functioning or flexible engagement of overlapping processes. More generally, the findings corroborate the view that short-term retention is needed during the acquisition of new words in Chinese and that these mechanisms are most likely modality-specific.

GENERAL DISCUSSION

V GENERAL DISCUSSION

The global aim of this thesis was to investigate underlying working memory processes and neural correlates of visual and auditory vocabulary acquisition in Chinese. As an additional question and pre-condition for examining the main goal I questioned whether visual working memory can be trained separately from auditory and whether intra-modal can be distinguished from across-modal training effects in visual working memory on the behavioral and on the neural level.

In the following, I will first give a short summary of the goals, research questions and interpretations of both training studies. Further on, I will discuss the results in a broader realm of current models in the field. Next, I will continue with limitations and caveats of the training studies followed by an outlook and considerations about further directions. Finally, I will put the major findings in a nutshell and end with some concluding remarks.

1 SUMMARY

1.1 WORKING MEMORY TRAINING STUDY

The Working Memory Training Study was designed to test whether visual working memory processes can be trained specifically on the behavioral and neural level and whether those effects can be separated from across-modal training effect. Decidedly larger training gains after visual working memory training compared with auditory or no training on a visual 2-back task were found. These effects were accompanied by specific training-related decreases in the right middle frontal gyrus arising from visual training only. Likewise, visual and auditory training led to decreased activations in the superior portion of the right middle frontal gyrus and the right posterior parietal lobule. I infer that the combination of effects resulted from increased neural efficiency of intra-modal (visual) processes on the one hand and of across-modal (general control) processes on the other hand. Therefore, visual processes of working memory can be trained specifically, and these effects can be functionally dissociated from alterations in general control processes common to both working memory trainings. These results offered a good starting point to use the training paradigm in the Language Training Study. As exemplified for the visual modality, the working memory training paradigm was successful in training a modality-specific process. Thus, the paradigm was applicable to investigate different transfer effects of visual and auditory working memory training on visual and auditory vocabulary learning in Chinese.

1.2 LANGUAGE TRAINING STUDY

The Language Training Study aimed at investigating whether visual working memory training exerts unique influence on learning Chinese visual words (orthographic learning) due to the greater complexity of the Chinese writing system, and, conversely, whether auditory working memory training has a specific impact on learning Chinese auditory words (phonological learning). In addition, training induced modulations in language-related brain networks were examined using fMRI in a pretest-training-posttest design. Both working memory trainings led to positive transfer effects on orthographic learning as compared to no training, whereas for phonological learning no transfer effects were obtained. Differential activation changes after visual and auditory working memory training were found in areas engaged in visual and auditory word processing: Activation sustained/decreased after intra-modal (visual) training in the left mid-fusiform gyrus in the orthographic task. Similarly, activation decreased after intra-modal (auditory) training in the anterior insula in the phonological task. These findings are consistent with the view that working memory training in the equivalent modality enhances the efficiency of perceptual encoding in the orthographic task and incorporating novel sound patterns into long-term phonological representations in the phonological task. Surprisingly, activation increases after across-modal training emerged in both tasks within the same brain regions: Activation increased after auditory training in the mid-fusiform gyrus in the orthographic task and likewise after visual training in the anterior insula in the phonological task, suggesting that working memory training in the complementary modality reflects selective attention to the respective tasks presumably guided by modality-unspecific improvements in executive components of working memory. Moreover, visual training led to additional recruitment of brain regions in the orthographic task, i.e. the right precuneus, presumably mirroring the generation of a mental visual image of the to-be-retrieved character.

2 DISCUSSION WITH RESPECT TO CURRENT MODELS IN THE FIELD

The findings of the Working Memory Study and Language Training Study have already been discussed in Chapter III-3 and IV-3, respectively. However, there is still need view them with respect to current models in the field. Thus, I will next consider the results of both training studies in the light of working memory models as well as models for language processing and word learning.

2.1 WORKING MEMORY TRAINING STUDY

Although none of the working memory models addressed the trainability of components in working memory, the findings of the Working Memory Training Study can be reconsidered in light of the assumptions made by the models outlined in the introduction and the functional architecture of working memory they propose.

The models by Baddeley (2002, 2003b), Cowan (1999), and Zimmer (2008) agree partially about sensory-specific maintenance in working memory. As visual and auditory primary cortices are clearly separated in the brain, all of the models assume that the maintenance of sensory features occurs in separated brain regions corresponding to their input modality. The current findings further complement the assumptions proposed by the models as it could be shown that training an adaptive purely visual *n*-back task uniquely enhanced performance in a visual 2-back task after training in contrast to the equivalent training in the auditory modality or no training.

With respect to neural correlates of visual working memory, the models decidedly differ from each other. Baddeley and Logie`s module of the visual-spatial sketchpad (Baddeley & Logie, 1999; Logie, 1995) was attributed to the left inferior temporal cortex and bilateral anterior occipital lobe for maintaining object information (visual cache) and right parietal areas for visual-spatial information (inner scribe) (e.g. Müller & Knight, 2006; Henson, 2001). In contrast, Zimmer (2008) assumed that primary, secondary, and associative visual cortices accomplish the maintenance of visual features and objects, but the location i.e. spatial information is coded in an amodal way by the parietal cortex especially the intraparietal sulcus. Cowan (1995) similarly speculates that visual sensory and association cortices should be involved in the maintenance of visual information and the inferior parietal cortex that functions as an attentional 'spotlight' as it shifts attention to activated memory representations. In the current study intra-modal training effects for visual materials were found in the right middle frontal gyrus. This result cannot be accounted for by any of the working memory models as none of them assumed the dorsolateral PFC to be specialized for any specific material. Instead, the models link the dorsolateral PFC with functions of the central executive such as active manipulation of relevant information. However, there is generally more uncertainty about the role of the PFC in working memory. Models on the functional organization of the PFC might be helpful to bridge that gap. In this context, several conflicting distinctions on its functional role have been proposed: one group of models suggests a 'content-specific' organization for the PFC, with the ventrolateral PFC to be engaged by maintaining object information in working memory and the dorsolateral PFC being recruited by visual-spatial material (e.g. Goldman-Rakic, 1987). Otherwise, another group of models assumed a 'process-specific' organization of the PFC (e.g. Petrides, 1994) i.e. the ventrolateral PFC is suggested to be required for the pure maintenance of information over short periods of time, whereas dorsolateral areas are concerned with manipulating and monitoring information in working memory. More recent meta-analyses (Owen et al., 2005;

Wager & Smith, 2003) revealed that the majority of brain imaging studies on this issue confirms the latter view. In light of these findings, the activation decreases in the middle frontal gyrus after visual training broadens the understanding of working memory functions in the PFC. Beyond of a specialization for manipulation in the dorsolateral PFC, the middle frontal gyrus seems to manipulate purely visual material in a more efficient way after visual *n*-back training. Thereby, the current data speaks for a modality-specific (visual) subdivision within the process-specific organization of the PFC.

According to Cowan (1995) the intraparietal cortex is responsible for attentional scanning within working memory. In a similar vein, in Zimmer`s framework (2008) the intra-parietal cortex was comparably associated with amodal representations in working memory related to attentional and spatial task demands. Consistent with this assumption the intraparietal lobule was found to be engaged in attentional control processes in working memory (Jonides et al., 1998). Thus, as outlined previously (Chapter III-3.3), the decreased activation in this region after visual as well as auditory working memory training was taken to reflect reduced scaffolding such that less attentional control was needed for storage and continuous updating after *n*-back training. Notably, my interpretation that the intra-parietal cortex functions as an attentional controller is in line with a vast amount of findings that associate parietal areas to attentional functioning beyond working memory tasks (e.g. Corbetta, Miezin, Shulman, & Petersen, 1993; Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). Moreover, Cowan (1995) explicitly alludes that cognitive training of working memory allows attentional search to become more effective. Thus, the present observation that activity decreased in the intraparietal lobule after both working memory trainings is further in good agreement with its proposed role in attentional scanning.

However, the current findings speak against the functional mapping of Baddeley`s Multiple-Component Model onto brain regions as inferior-parietal regions including BA 40 were addressed to the phonological store. Evidence that the phonological store component was associated with inferior parietal cortex came from two early brain imaging studies (Paulesu et al., 1993; Awh et al., 1996). In these studies subtracting activity in a silent repetition condition from that in a verbal working memory condition to remove activation engaged in sub-vocal rehearsal identified the storage component of verbal working memory. Thus, remaining activation in the inferior parietal cortex was thought to reflect pure storage of phonological information. However, several findings demonstrated that the left parietal cortex does not reliably reflect the characteristics that were addressed to the phonological store: For example, this region is not selective for phonological material held in working memory, but likewise active for non-verbal stimuli (e.g. Smith, Jonides, & Koeppe, 1996; Nystrom et al., 2000; Owen et al., 2005). Furthermore, the region was not active during passive listening of speech (e.g.

Friederici, Meyer, & von Cramon, 2000; Petersen, Fox, Posner, Mintun, & Raichle, 1988), which has to be assumed for the phonological store, as auditory verbal information should have obligatory access to the store. Akin to studies that are inconsistent with the mapping of the phonological store onto the inferior parietal cortex, the observed data in the Working Memory Training Study cannot be accounted for by the proposed mapping of Baddeley`s components onto the brain.

Taken together, viewing the present data of the Working Memory Training Study with regard to current working memory models could reveal that they more strongly support neural correlations of working memory as suggested by Cowan and Zimmer in comparison to Baddeley`s mapping onto the brain. Furthermore, the findings specifically broaden the understanding of neural activation changes related to working memory training.

2.2 LANGUAGE TRAINING STUDY

In the following I will assign the findings of the Language Training Study in the wider context of models on language processing and learning as well as their implications for working memory models.

2.2.1 MODELS OF LANGUAGE LEARNING AND PROCESSING

As the view that vocabulary acquisition builds on working memory processes is central to this thesis and was first proposed in the Model of New Word Learning (Baddeley et al., 1998), I will first discuss the current data with respect to this model. After that, I will reconsider the present findings in light of the Complementary System Account for Word Learning (Davis & Gaskell, 2009; Lindsay & Gaskell, 2010), the Processing Framework for Chinese in Second Language Learners (Liu et al., 2007), the System Accommodation Hypothesis (Perfetti et al, 2007, 2010), and the Visual Word Form Area Hypothesis (Cohen et al., 2000; 2002; McCandliss et al., 2003).

In Baddeley`s Model of New Word Learning the role of one module of the Multiple-Component Model - the phonological loop - was specifically ascribed to new word learning. When unfamiliar spoken words are to be learned, the learner has to rely on the phonological loop to retain the sound pattern temporarily while lexical representations are constructed. For visual input the same mechanism is assumed because written words are automatically transformed into phonological codes via grapheme-phoneme conversion. However, grapheme-phoneme conversion is not possible in Chinese. Thus, deriving phonology from Chinese characters and entering the new sound pattern into the phonological store by means of sub-vocal articulation is not possible. Thus, in line with these assumptions, the present findings that visual training led to increased performance in Chinese character acquisition akin to auditory training points to a special role of maintaining visual word information for the acquisition of Chinese logographic characters. Therefore, the present data shows that the Model for New Word Learning cannot be viewed as a universal model that can be applied to every language system. Especially the assumption that the articulatory system can automatically transform phonology derived from visual input and enter it into the phonological system does only hold true for those writing systems that use grapheme-phoneme conversion i.e. alphabetic languages. Consequently, the model cannot analogously be applied to Chinese. However, concerning the auditory modality the proposed mechanism should be universal although in the current study no transfer neither after auditory nor after visual training was found to acquiring the phonology of Chinese words.

Davis & Gaskell (2009) and Lindsay & Gaskell (2010) proposed a model for word learning that additionally takes neural underpinnings into consideration. For learning novel spoken words the model assumes that cortical systems specialized for speech perception are involved in building up long-term representation of the new words. More specifically, short-term storage of the new speech sounds is necessarily required. The present results on learning the phonology of new Chinese words clearly speak in favor of this mechanism as the demand for short-term storage of the new speech sounds is reflected in the current data. In particular, the anterior insula seems to be differentially shaped by visual and auditory training in the process of incorporating novel speech-like sounds into long-term representations of the spoken words. After intra-modal (auditory) working memory training this process presumably became more efficient, whereas across-modal (visual) working memory training contrarily was capable of flexibly directing attention to this process as reflected in increased activation. However, although the model was only specified for the auditory modality, comparable short-term storage would likewise be assumed for retaining visual features in visual association cortices to build up the new orthographic representations of the to-be-learned characters. The differential impact of visual and auditory working memory training on activation in the infero-temporal cortex further corroborates this assumption analogously to the auditory modality. Generally, the present findings are in good agreement with the assumptions made by the Complementary System Account of Word Learning (Davis & Gaskell, 2009; Lindsay & Gaskell, 2010). Beyond that, the present data adjoin neural underpinnings for the model`s assumption of maintaining modality-specific i.e. visual and auditory language-relevant information during the acquisition of written and spoken words. Specifically, as differential activation changes after visual and auditory working memory training followed an antipodal pattern in the mid-fusiform gyrus for learning written Chinese characters and in the left anterior insula for learning spoken Chinese words – regions belonging to the visual and auditory association cortices -, the mechanisms are most likely modality-specific as suggested by the model.

Despite the fact that the models proposed by Baddeley et al. (1998) and Davis and Gaskell (2009) on learning new words are useful for understanding the current findings, they do not address vocabulary acquisition particularly in Chinese. In contrast, the only model that directly addresses learning Chinese words is the Processing Framework for Chinese as Second Language Learners (Liu et al., 2007). One critical assumption of the model is that character recognition is threshold-like i.e. a specific character reaches full activation through being activated by visual stroke patterns and radicals. However, the proposed threshold assumption cannot be tested with the methods used in this study. Nevertheless, the findings in the mid-fusiform gyrus speak in favor of the model as the extraction of visual-orthographic information from the characters is assumed to have become more effective after visual working memory training. By this, the current data indirectly support the assumptions made by the model. Moreover, the model assumes that the reliance on visual-orthographic analysis is especially pronounced in early stages of learning Chinese characters, because as vocabulary size is small connections from orthography to meaning and from orthography to phonology are still weak. The present data can only account for an early stage of learning to read characters, since in the first and second Chinese language training participants acquired only 75 words each. In sum, behavioral and brain imaging findings of the Language Training Study are in good correspondence with the view that visual-orthographic analysis is especially needed during an early stage of Chinese character acquisition as suggested by the Processing Framework for Chinese as Second Language Learners.

To the best of my knowledge, Perfetti et al. (2007, 2010) are the only researchers who hypothesized about the brain network activated when second language learners read words in a foreign language. Thus, the neural network which was found for the German participants during the pretest fMRI session while performing the orthography task can be reconsidered with respect to Perfetti`s distinction between assimilation and accommodation patterns. In the current study, the activation pattern found for German participants in the pretest highly resembles the network that is typically found for native Chinese character reading, namely the activation of bilateral mid-fusiform gyri. In the first instance, a strikingly similar pattern of accommodation was previously shown for native English speakers reading Chinese characters (Nelson et al., 2009; Liu et al., 2007). Thus, the present data further supports the notion that alphabetic native speakers – as they cannot process the unique demands of the Chinese writing system with their native reading network – need to recruit additional brain regions to recognize the complicated visual form of the characters.

The striking findings that the mid-fusiform gyrus is at all activated even after a relatively short laboratory Chinese language training and that visual and auditory working memory training differentially alternated activation within this region need to be viewed in the light of the Visual Word Form Area (VWFA) Hypothesis formulated by Dehaene, Cohen and others (Cohen et al., 2000, 2002; Dehaene, 2005; Dehaene & Cohen, 2010, 2011; McCandliss et al., 2003). Although the current study does not target at testing the VWFA hypothesis, it nevertheless can provide further insights on it's understanding and vice versa. Dehaene, Cohen, and colleagues assume a reproducible cortical area located in the mid-part of the left fusiform gyrus being selectively active during visual word recognition in skilled readers. As this region seems to possess the characteristics of case and location invariance, they suggested labeling it VWFA. Moreover, it was claimed that the VWFA hosts functionally specialized neural circuits for letter and word recognition, which are attuned to the requirements of a specific script. Importantly, the location is thought to be reliably reproducible throughout all cultures and writing systems including non-alphabetic scripts like Chinese (Dehaene & Cohen, 2010). The functional specialization of the VWFA for reading is assumed to stem from a partial 'recycling' of the visual cortex that originally evolved for other purposes of object recognition (Dehaene & Cohen, 2007). Thereby, the cortex – as it is to some extent plastic - can get attuned to the requirements of reading a specific script progressively in the course of ontogenesis (McCandliss et al., 2003). The building of visual word forms and its neural underpinning in the VWFA through perceptual expertise was thought to require no less than five years when children acquire literacy in their native language (Dehaene & Cohen, 2010; Aghababian & Nazir, 2000). However, a recent training study on Chinese adult illiterates to learn Chinese characters reported stronger activation to character compared to faces in a brain region that was identified as the VWFA in skilled readers already after one month of character training (He et al., 2009). In this regard, the current findings that the VWFA was even activated after the first 14-day Chinese language training in German participants have to be reviewed. To begin with, the acquisition of literacy in the native language does not only lead to build up a VWFA but also to sharpen the organization of the ventral occipito-temporal cortex in the way that cortical responses to non-lexical visual categories such as faces and houses become less dispersed (Dehaene et al., 2010). Thus, it is likely that acquisition of literacy in their native language in participants of the present study resulted in a better differentiated category-specific organization of the ventral occipito-temporal cortex providing an advanced starting point for learning a new writing system. Thus, in addition to the native specialization for the Latin alphabet in German participants, the operations within the VWFA namely the extraction of visual-orthographic information from visual word forms in the newly acquired Chinese writing system can be attuned to more readily. One might speculated that, as perceptual learning and internalization of any script- and language-specific regularities has already taken place, the VWFA can more quickly adapt to the new demands of the visually more complex

Chinese characters for which neurons must become attuned to stroke patterns within characters, including radicals and whole characters (Ding, Peng, & Taft, 2004). Accordingly, as compared to a situation in which no plastic change due to the acquisition of literacy has occurred such as in illiterates or children (He et al., 2009), the VWFA of German Chinese second language learners is already 'tuned' and thus responded to learned characters even after a short 14-day Chinese language training.

Beyond that, the modulation of activation in the mid-fusiform gyrus after visual and auditory working memory training during the orthographic task likewise can be viewed in the light of the VWFA hypothesis. In this context, it is critical to state that the VWFA was originally claimed to be unimodal i.e. only involved in visual word processing. By this, the stable activation in combination with increased performance on the orthographic task after visual working memory training provides support that the process of visual encoding and maintenance in working memory was sharpened in the fusiform gyrus and could be applied to extract visual orthographic information from the characters more efficiently – as already outlined previously (see Chapter IV-3.3). In contrast, the effect of increased activation in the same region after auditory working memory training was more surprising. To account for this data within the framework of the VWFA hypothesis is more complex, as there is a debate in progress on whether the VWFA might also play a role in multi-modal lexical or semantic processing. Evidence is mounting that the VWFA is also activated on the presentation of auditorily presented words (Cohen et al., 2002). In this controversy, the notion came up that words in modalities other than visual also recruit the VWFA, but that the location is more anterior (Buechel, Price, & Friston, 1998; Booth et al., 2002). Thus, the more anterior a region, it was suggested to be increasingly engaged in cross-modal and semantic computations. To test this assumption Cohen et al. (2004) contrasted visual versus auditory words in a phoneme and grapheme detection task and in fact found a left posterior infero-temporal activation on the presentation of spoken words in both of the tasks. Notably, the activation overlapped with the VWFA but the regions could be isolated in a single subject analysis. Thus, the more lateral and slightly more anterior region that was activated likewise by spoken and written words was labeled the Left Inferotemporal Multimodal Area (LIMA), as it appeared to be distinct but very close to the VWFA. Nevertheless, it is not well understood under which conditions the LIMA is recruited. Furthermore, the spatial limitations of brain imaging methods call into question that any activation can be clearly attributed to the LIMA. Contrariwise, activations might overlap with the VWFA and could thereby reflect top-down orthographic recruitment during the processing of spoken words (e.g. Price, Winterburn, Giraud, Moore, & Noppeney, 2003; Price & Devlin, 2011; Yoncheva, Zevin, Maurer, & McCandliss, 2010). As the orthographic VOI in the present study is relatively large and comprises patches of the cortex attributed to the VWFA as well as the peak coordinate of the LIMA (x = -48, y = -60, z = -16), increased activation after auditory working memory training cannot be attributed to either location. Nevertheless, as working memory training used non-lexical material and increases were found on the presentation of written Chinese characters it is most likely that auditory working memory training improved amodal executive function that might have resulted in an attentional top-down recruitment of the VWFA to extract visual-orthographic features of the Chinese characters. However, taking into account that increased activation in the auditory training group might trace back to the LIMA, auditory working memory training could have boosted the retrieval of the character`s respective phonology. Due to the fact that working memory is capable of controlling visual selective attention in the fusiform gyrus – as already outlined in the discussion part of the Language Training Study (see Chapter IV-3.3) – and the additional retrieval of auditory phonology on the presentation of the character might not be successful to solve the task, I assume that the first possibility is most likely the case.

To conclude, it has to be acknowledged that although all of the models provide meaningful approaches to the understanding of vocabulary acquisiton in a second language, none of the models can account for the present data in a satisfactory manner. In detail, the current findings are in good agreement with Davis & Gaskell`s Complementary System Account for Word Learning (Davis & Gaskell, 2009) as the current data further provides neural underpinnings for their assumption of required short-term storage in the respective visual and auditory language-relevant brain regions. The Processing Framework for Chinese as Second Language Learners as proposed by Liu et al. (2007) mainly focuses on the threshold assumption for reading Chinese characters and pronounced visual-orthographic analysis in early stages of character acquisition. However, the model does not account for neural correlates and is restricted to character acquisition only. Moreover, the present findings are in line with Perfetti`s Accommodation Hypothesis (Perfetti et al., 2007; 2010) which is the only framework that takes into consideration how the nature of the native language system affects learning second languages. Furthermore, Baddeley`s Model for New Word learning (Baddeley et al., 1998) is capable to announce a wide variety of findings, but it seems to be limited to alphabetic languages since it does not take language system into account that do not make use of grapheme-phoneme conversions. Finally, the hypotheses raised on the functions of the VWFA (e.g. Dehaene & Cohen, 2010, 2011) are crucial for understanding how the brain can cope with new writing systems. However, the characterstics of the VWFA are still too vague as to clearly account for the complex activation pattern that was found in the present study after visual and auditory working memory training. As a synthesis, future models that target to account for the acquisition of a new lexicon in a second language should regard intrinstic characteristics of written and spoken words in the native as well as the to-be-learned language system, resultant demands on visual and auditory working memory processes, and a detailed specification of underlying brain regions.

2.2.1.1.1 WORKING MEMORY MODELS

The findings of the Language Training Study can also be viewed from the perspective of working memory training, its transfer, and working memory models. Thus, I will next attempt to fit them in the current working memory models that were already introduced previously (see Chapter I-4.1).

To begin with, the prominent Multiple-Component Model assumes distinct modules dedicated to specific working memory functions. Accordingly, brain imaging was used to identify specific brain regions on which those modules might operate. Neural correlates of the main structural and processing components of the model were mainly attributed to regions in the ventro-lateral and dorso-lateral PFC as well as the inferior parietal cortex. According to the model, one would assume that visual *n*-back training should have trained the functioning of the visual-spatial sketchpad whereas the auditory *n*-back training should have trained correspondingly the phonological loop system, besides a general training of the central executive. Following the logic that common or at least overlapping brain regions need to be involved in the trained and transfer tasks, activation should be present in those brain regions that are associated with the specific modules. However, the activation changes after visual and auditory working memory training in the orthographic and phonological task was found in the inferior-temporal cortex and the anterior insula. Notably, both regions are not explicitly associated to a specific module of the Multiple-Component Model. Instead activation in the language-specific left fusiform gyrus is modulated outside the regions that were proposed for the visual-spatial sketchpad. Analogously, the anterior insula – although known to be involved in the phonological working memory – was not explicitly associated to the phonological loop system. Similarly, the model cannot account for the finding that the visual working memory training triggered activation in the right precuneus in the orthographic task. Thus, the modules in Baddeley`s model and their restricted mapping onto the brain can hardly converge with the present data.

Contrariwise, Cowan (1995) and Zimmer (2008) hold the view of a widely distributed working memory network that operates on representations also relevant for long-term memory representations. Cowan (1995) specifically assumes that the encoding and maintenance of sensory features might be performed by those regions that are also involved in perceiving the stimulus i.e. sensory primary, secondary and associative cortices. Zimmer (2008) even specifies the neural structures of major components of visual and auditory working memory in more detail: Lateral occipital, inferior temporal, and fusiform cortices are hypothesized to maintain visual objects in working memory whereas auditory associative cortices in the superior temporal lobe are thought to retain auditory objects in working memory. The current findings are in good correspondence with those assumptions as visual and auditory working memory training resulted in activation changes in the left mid-fusiform gyrus in the orthographic task – a region located in the visual associative cortex, namely the visual ventral stream – and in the left anterior insula in the phonological task – a region correspondingly belonging to the auditory associative cortex. Furthermore, Zimmer`s framework especially covers the relation between working memory and visual imagery. In this vein, the model is additionally capable to account for the current finding of the unique recruitment of the precuneus after visual working memory training only. As the precuneus is known to be both active in visual working memory and in various imagery and mental simulation tasks (Cavanna & Trimble, 2006), Zimmer assumed the precuneus to provide a "workplace for processing the visual appearance of perceived and generated images" (Zimmer, 2008, p. 1390). Thus, these considerations converge well with the interpretation that visual *n*-back training might have triggered the generation of a mental image of the to-be-retrieved characters during the orthographic task at posttest (see Chapter IV-3.3).

In sum, the present findings seem to be in good correspondence with the models proposed by Zimmer and Cowan, whereas they cannot be accounted for by the mapping of Baddeley`s modules onto brain regions. By this, the current findings further support the idea that complex cognitive systems such as working memory and language are not supported by discrete and specialized modules but rather by neural networks operating all over the brain and in accordance to the demands of the particular tasks (e.g. Cowan, 1996, 1999; Zimmer, 2008).

3 LIMITATIONS AND CAVEATS

Although the present training studies provide important contributions to a better understanding of the trainability of visual processes in working memory and the impact of visual and auditory working memory to Chinese vocabulary acquisition, they nevertheless bear a couple of limitations and caveats which are addressed in the following.

3.1 WORKING MEMORY TRAINING PARADIGM

In general, *n*-back working memory training has turned out to be a fruitful paradigm for the training of working memory functions as various working memory studies effectively found improvements in the course of training *n*-back tasks (Jaeggi et al., 2008; Hempel et al. 2004, Schmiedek et al., 2010, for reviews see Jaeggi et al., 2010b; Buschkuehl & Jaeggi, 2010). Furthermore, it was also powerful in leading to transfer effects on fluid intelligence (Jaeggi et al., 2008). It might be especially advantageous that adaptivity can easily be implemented in the task by increasing or decreasing the level of *n* in accordance to the participant`s current performance as adaptivity was proposed to be a necessary condition for cognitive plasticity (Lövdén et al., 2009). Moreover, the *n*-back task taps into a variety of processing components involving encoding, maintenance and retrieval of the stimuli as well as manipulating and updating of the contents as well as memory for temporal order. Thus, all of those components might be affected by training the task. However, although this advantage seems plausible on the first glance, it might also bear essential limitations: As numerous processing components are engaged during training there is no possibility to disentangle training and transfer effects on a more fine-grained level i.e. different processing components engaged in the task cannot be separated. Thereby, no conclusions can be drawn about the specific component the training and transfer effects might trace back. With respect to the present training studies, the *n*-back training paradigm was capable of separating intra-model and across-modal training effects in the visual modality and resulted in a differential modulation of brain activation after training the visual compared to the auditory version of the task. Nevertheless, effects cannot be disentangled in terms of encoding, maintenance, retrieval or manipulative processes in working memory.

Furthermore, comparing visual and auditory *n*-back trainings bore another limitation. As already outlined previously in the discussion part of the working memory training effects (see Chapter II-2.3), the working memory training paradigm used for both training studies led to greater training effects for visual compared to auditory training. Since the amount of improvement was confounded with the modality of working memory training, this problem had to be addressed especially for answering the research questions of the Working Memory Training Study (for a detailed discussion see Chapter II-2.3). For the Language Training Study this issue was less problematic insofar as behavioral transfer effects did not differ between the visual and auditory training groups neither in the orthographic tasks nor in the phonological task despite of a different degree of improvements between the groups. This fits well with the idea that the different training effects do not reflect different improvements between the groups but rather reflect different potentials of the task to be improved i.e. visual training seems to be easier to be improved compared to auditory (Jaeggi et al., 2010a) (see Chapter II-2.3). Moreover, complementary patterns of activation changes after visual and auditory working memory training were found in the orthographic and the phonological task respectively, which independently arose from the amount of improvement during the *n*-back training.

In conclusion, the working memory training paradigm used in the current studies was successful as a tool to investigate the research question of both training studies although the aforementioned limitations have to be acknowledged and were met in each of the discussion parts.

3.2 WORKING MEMORY TRAINING STUDY

The Working Memory Training Study convincingly demonstrated that visual working memory training led to a specific improvement compared to auditory working memory training or no training and that intra-modal training effects can be separated from across-modal training effects on the neural level. However, the major shortcoming of this study is that the results cannot account for general modality-specific dissociations. As the dissociation was only demonstrated for the visual modality, it cannot readily be assumed that comparable effects would be evident for the auditory modality. Thus, to speak of modality-specific dissociations on a general level, equivalent effects need to be reported also for training in the auditory modality.

Furthermore, it needs to be admitted that the auditory working memory training group might have been disadvantaged in comparison to the visual group to show improvements in the visual 2-back task. As the visual material used in the 2-back task was taken from the same pool of stimuli that were used in the visual *n*-back training, participants in the visual group did not have to switch from one modality to another between the last training session and the posttest fMRI session, whereas the auditory training group had to switch from training with auditory bird voices to visual abstract black-and-white pattern stimuli. Thus, this switch of modality could have prevented the auditory training group from showing comparable increases in the task on the behavioral level. Although this possibility cannot be excluded, the findings that specific training gains in the visual modality were accompanied by specific activation decreases strengthens the line of arguments that training gains on the behavioral level indeed trace back to improvements in visual working memory.

3.3 LANGUAGE TRAINING STUDY

One major shortcomming of the Language Training Study refers to an fMRI related methodological issue i.e. the trial structure of the orthographic and phonological tasks and their respective control tasks used during the fMRI sessions. In event-related fMRI designs variable intervals between the events (jitter) are by default used to isolate item-related activation (e.g. Donaldson, Petersen, Ollinger, & Buckner, 2001). In the current study I likewise applied this method to isolate activation between randomly presented trials. However, the interval between the German word and the subsequent Chinese word within the same trial was constant. Thus, activity related to the German word probably summated to the activity related to the Chinese word. To keep this effect as small as possible activation on the German words was entered as regressors of no interest into the GLM (see Chapter IV-1.2.3). Although the way the GLM was modelled is likely to have prevented any activation take-over, this possibility needs to be considered for the experimental tasks as well as for the control tasks. In the experimental tasks - orthographic and phonological tasks - each German word was presented only once, whereas in the control tasks, each of the two words (the German words for 'left' and 'right') were presented in half of the trials. Thus, one might speculate about the effect this issue might have for the activation pattern measure on the presentation of the Chinese words. For the experimental tasks the presentation of a single high frequent German word would presumably activate regions known to be involved in visual and auditory word comprehension. German words in the control tasks would likewise activate this network, but repetition suppression effects could have emerged due to its repeatedly presentation in the course of the experiment. Repetition priming of single words i.e. repeated stimulus presentation has been shown to result in decreased activation (repetition suppression) in the bilateral auditory cortical areas for familiar spoken words (Gagnepain et al., 2008) and in the occipito-temporal cortex for familiar written words (Fiebach, Gruber, & Supp, 2005). In the present study activation from the control trials was subtracted from the experimental trails. Hence, the subtraction of activity related to the German control word from activity related to the German experimental word, might have resulted in an activation pattern usually found for processing written and spoken alphabetic words - as repetition suppression is likely for the control word and by this would activate the respective network less strongly. Furthermore, this activation pattern might have overlapped the activation elicited by the Chinese network due to the fixed interval.

Against this background, I will firstly reconsider the activation pattern for the orthographic and the phonological task in the fMRI pretest sessions and secondly effects of activation changes due to visual and auditory working memory training in the orthographic and phonological tasks. With respect to activation patterns in the orthographic task, one would expect a purely left laterized network for the German words that might be summated to the network elicited by the Chinese word. The pretest in the orthographic task revealed mainly the bilateral fusiform gyri besides cerebellar activations. The only regions for which an activation take-over seems likely is the left mid-fusiform gyrus as the right fusiform gyrus is usually not expected to be activated on alphabetic words. On this basis, it is not unequivocal whether the activation in the left mid-fusiform gyrus purely traces back to the processing of the Chinese characters. However, as the bilateral fusiform gyri were likewise activated in a previous training study on Chinese characters after only a 3-day training (Liu et al., 2007) and the fact that activation of the German words was modelled as regressors of no interest, it is most likely that the activation in the left fusiform gyrus is not solely induced by a possible take-over activation from German words. Analogously, similar considerations might prevail for the activation pattern in the phonological task at pretest. As activation patterns for spoken alphabetic and Chinese words might basically overlap, I cannot exclude the possibility that a summation of activity from the German words might have occurred. Nevertheless, in view of the aformentioned arguments and the findings in the orthographic task, I do not expect the activation pattern in the phonological to be exclusively driven by coactivation of the German words. Moreover, in the face of activation changes in the left fusiform gyrus in the orthographic task and the left anterior insula in the phonological task after visual and auditory working memory training, the same logic can to be applied. In these analyses activation during the pre- and posttest fMRI sessions were compared as a function of working memory training. Thus, the possibility of an activation take-over from the German word to the Chinese words might hold in an analogous manner for both the pre- and the posttest as far as one assumes that the repetition of high frequent native words does not lead to additional repetition suppression effects in the control task due to the repetition after a delay of four weeks. Critically, as the impact of visual and auditory working memory training is unlikely to have altered the processing of high-frequent native words, the activation changes – in contrast to the pattern itself – cannot have emerged from the lack of separating activation corresponding to the German and Chinese words respectively. Taken together, it has to be admitted that the activation patterns need to be interpreted with caution due to a possible but unlikely take-over of activation from the German words to the Chinese words. Nevertheless, activation changes after working memory training are unambiguously independent from this limitation.

Furthermore, additional limitations form an experimental psychological perspective need to be mentioned. In regard to the activation pattern of the orthographic task in the pretest session, the present activation converges well with previous studies that found the bilateral fusiform gyrus activated in Chinese second language learning (Nelson et al., 2009) and in a laboratory training study in which participants had to learn 60 characters within three days (Liu et al., 2007). However, both of the studies report consistent activation in the left middle frontal gyrus on the presentation of learned Chinese characters in alphabetic learners, whereas no frontal activation was found in the pretest contrast of the current data. It might be possible that due to a relatively restrictive threshold activation in the left middle frontal gyrus could not reach significance. Moreover, the lack of activation might originate from the nature of contrast. In the previous studies by Nelson et al. (2009) and Liu et al. (2007) Chinese characters were contrasted against English words. In comparison in the present contrast learned Chinese characters were contrasted against unfamiliar Chinese characters. Therefore, it has to remain unresolved why activation in the middle frontal gyrus was absent in the present study.

Although the current study was capable to broaden the knowledge of processes underlying vocabulary acquisition in Chinese, the role of specific features of the Chinese language system were not particularly addressed. For example, the major components of Chinese characters are radicals that in most cases bear semantic information (Tsang & Chen, 2009). For this reason it might be that the extraction of morphological information in addition to the extraction of visual-orthographic information might be particularly important for Chinese character reading (McBride-Chang & Ho, 2005). This question however, cannot be accounted for by this study. Similarly, lexical tones are in particular characteristic for Chinese phonology (Ho & Bryant, 1997a). However, in the present study the discriminability and acquisition of lexical tones within Chinese words was not addressed.

Finally, the Language Training Study requires a narrow interpretation as participants learned only a restricted set of characters and thus need to be classified as beginning learners. Moreover, they acquired Chinese written and spoken words in isolation, as words never appeared in any sentential context. Thereby, ecological validity of learning Chinese vocabulary as a second language has to be rated as low, because the way participants learned Chinese vocabulary did not approximate real-life situations.

4 OUTLOOK AND FURTHER DIRECTIONS

On the basis of the limitations and caveats just outlined above, an outlook and further directions for future studies and research questions will be given in the following.

4.1 WORKING MEMORY TRAINING STUDY

As already brought up in the limitations and caveats section (see Chapter V-3.1), it would be even more convincing to demonstrate a double dissociation on the behavioral as well as on the functional level to show that intra-modal training gains can be comparably found for the auditory just like for the visual modality. For this reason it would be preferable to conduct a complementary study with an auditory pre- and posttest 2-back condition. The findings of specific improvements in the auditory 2-back task after auditory working memory training in addition to intra-modal training effects reflected by activation decreases in regions distinct from those which are found for the visual modality, would add even stronger evidence for the view that working memory can be trained modality-specifically. Furthermore, comparable across-modal training effects as found in the current study could further strengthen evidence for improved modality-unspecific executive processes in working memory.

4.2 LANGUAGE TRAINING STUDY

Although the current data adds important insights into the link between visual (and auditory) working memory and visual word processing in the infero-temporal cortex especially in Chinese, there is nevertheless some uncertainty about the particular role of the infero-temporal cortex in verbal working memory also in alphabetic languages. The study by Fiebach et al. (2006) convincingly demonstrated that the left infero-temporal cortex is involved in active maintenance of written alphabetic words in working memory. A patch of the infero-temporal cortex covering the VWFA showed significant activation during the retention period of a delayed cued recall working memory task for written words and a trend for pseudowords. Critically, the interaction between stimulus type (words vs. pseudowords) and working memory load (two vs. five items) arose due to a stronger activation for words in the high load condition compared to pseudowords. The data was taken to confirm the idea that activation of the language-sensitive left inferior-temporal cortex is not exclusively driven by visual-perceptual processing but is also found for non-perceptual visual verbal working memory even in the absence of any visual input. However, as pseudowords activated the region to a lesser degree under high load conditions, it was suggested that activation in the left fusiform gyrus reflects predominantly semantic aspects of word recognition and maintenance. A possible reason could be that maintaining pseudowords over short intervals more strongly relies on the phonological loop system, because no semantic representation is available. However, it needs to be considered that pseudowords differ from words not only in terms of the lack of entry in the mental lexical. Pseudowords and words also vary in the familiarity of word forms as well as in the likelihood to recode them phonologically. Therefore, it is still not unequivocally clear from that data, whether the contribution of the fusiform gyrus to maintaining words under high load conditions is indeed due to its semantic nature. Contrariwise, it could also be attributed to an enhanced reliance on visual-orthographic form whereas for pseudowords phonological recoding and rehearsal strategies could have prevented from a similar degree of activation in the infero-temporal cortex. In this vein, a conductive approach would be to further explore this issue – complementary to the study by Fiebach et al. (2006) – by using Chinese characters, pseudocharacters and native Chinese participants. The Chinese writing system takes the advantage that no grapheme-phoneme mappings are possible. Chinese pseudocharacters cannot be transformed into a phonological code that can be maintained by the phonological loop system. Hence, if a similar word type by working memory load interaction would be found for Chinese characters and pseudocharacters, the weaker activation cannot be explained by an enhanced reliance on the phonological loop system but has to be attributed to the lack of semantic information. By this, the interpretation given by Fiebach et al. (2006) would be reconfirmed. If Chinese pseudocharacters would elicit the same degree of activation in the infero-temporal cortex as real characters do, the activation in the word condition can no more be attributed to semantics. Instead, the equivalent activation on Chinese characters and pseudocharacters would most likely reflect short-term maintenance of visual-orthographic information independently of semantic content. Beyond that, such a finding could state the interpretations of the Language Training Study even more precisely, because activation changes in the infero-temporal VOI could more clearly be interpreted in the way that visual working memory training most likely sharpened encoding, retaining and retrieval of visual orthographic information to character recognition.

Furthermore, it has to be addressed that the current findings and conclusions concerning the acquisition of Chinese phonology do not take into account the role of lexical tones. Interestingly, the left anterior insula is known to be specifically involved in linguistic pitch processing. In the study by Wong, Parsons, Martinez, and Diehl (2004) native Chinese and native English speakers had to discriminate pitch patterns embedded either in Mandarin Chinese or English words. Only when Chinese speakers discriminated pitch patterns in Mandarin words the left anterior insula was activated whereas in all other conditions the homologue region in the right hemisphere responded. Moreover, in Mandarin Chinese speakers - no matter whether they were natives or second language speakers - the left anterior insula had significantly greater gray and white matter density as compared to native speakers of non-tonal European languages that could not speak Chinese (Crinion et al., 2009). These findings were taken to corroborate the hypothesis that linking pitch patterns of spoken words to their meaning is performed by the left anterior insula. As in the present study auditory working memory training resulted in increased neural efficiency in the phonological task in the left anterior insula, it might be of considerable interest to further explore whether learning lexical tones can be improved by auditory working memory training and how it alters functioning and structure of the left anterior insula.

Ultimately, it would be particularly interesting to examine underlying working memory processes of learning alphabetic words as a new language system that could be addressed in a complementary training study in non-alphabetic participants such as Chinese. The hypotheses can be derived from the well-known relationship between phonological working memory capacity and second language proficiency for alphabetic languages for learning written and spoken words. For learning auditory spoken words it can be assumed that short-term retention of the foreign sound pattern is required to build up new phonological representation of words. The relationship for visual written words though is likely to trace back to specific properties of the alphabetic writing system namely grapheme-phoneme mappings. The conversion from written graphemes to phonological phonemes can be directly derived from the script via grapheme-phoneme conversion rules because an inherent property of the alphabetic writing system is that letters and letter combinations code the phonemes of words. As this transformation is suggested to be highly automatic, auditory-phonological working memory should uniquely predict performance to phonological as well as orthographic learning in non-alphabetic native speakers. Similarly to the approach in the current training study, a useful tool would be to test the impact of auditory working memory training on the acquisition of alphabetic written and spoken words. Beyond that, corresponding training induced activation changes in language-related brain networks could broaden the understanding of underlying mechanisms. However, as the auditory working memory training in the current Language Training Study was not successful to result in transfer effects on learning the phonology of Chinese words, it might be advisable to modify the auditory working memory paradigm. Presumably acoustic non-lexical stimulus material is preferable from which is known that it strongly correlates with reading skills and that has been proven to be suitable for training (Foxton et al., 2003; Foxton, Brown, Chambers, & Griffiths, 2005). Such a complementary training study would complete the understanding of underlying working memory processes for second language vocabulary acquisition across alphabetic and logographic language systems.

5 CONCLUDING REMARKS

With two nested training studies addressing separate research questions it could successively be demonstrated that (a) visual working memory processes can be trained specifically and these effects can be separated on the neural level from alternations in general control processes independent of modality and (b) although visual and auditory working memory training transferred to learning Chinese characters but not to learning the phonology of Chinese words, the trainings resulted in a complementary pattern of activation increases and decreases in modality-specific language-related regions in learning Chinese.

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APPENDIX

VII APPENDIX

1 ABBREVIATIONS

AC-PC	anterior commissure – posterior commissure
ANOVA	analysis of variance
BA	Brodmann area
BOLD	blood oxygen level dependent
ERP	event-related potential
FDR	false discovery rate
fMRI	functional magnetic resonance imaging
FoV	field of view
FWHM	full-width at half-maximum
GLM	general linear model
H	hemisphere
IFG	inferior frontal gyrus
IPS	inferior parietal sulcus
ISI	inter-stimulus-interval
ITI	inter-trial-interval
L	left
LIMA	left inferotemporal multimodal area
MANOVA	multivariate analysis of variance
MANCOVA	multivariate analysis of covariance
MP-RAGE	magnetization prepared rapid gradient echo
MRI	magnetic resonance imaging
PET	positron emission tomography
PFC	prefrontal cortex
PrCG	precentral gyrus
R	right
SFG	superior frontal gyrus
SOG	superior occipital gyrus
VOI	volume-of-interest
VWFA	visual word form area

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3 ACKNOWLEDGEMENTS

I gratefully thank

Prof. Dr. Axel Mecklinger, my supervisor and instructor, who supported my ideas and my work, taught me to think like a researcher and - most importantly – showed me how fascinating the world of neuroscientific research actually is.

Prof. Dr. Hubert Zimmer, for lending me his ear on various issues on working memory and its training and for being my second reviewer,

PD Dr. Bertram Opitz, my co-supervisor, for numerous fruitful discussions, helpful comments, and any kind of support especially concerning methodological and fMRI related issues,

Dr. Christoph Krick for technical support during fMRI scanning and for providing the stimulus material for the visual working memory tasks,

Thorsten Brinkmann, who kindly introduced me to the mysteries of Brain Voyager Software and fMRI scanning,

Anna-Lena Scheuplein for making the acquisition and analysis of more than 1000 training sessions and more than 100 fMRI sessions possible,

Fabian Löwenbrück, Franka Niederwald, and Saida Awad for their support in preparing, organizing, and acquiring the training and fMRI sessions during their internships,

Jörg Vogel and Rui Wang for borrowing their voices to the auditory versions of the German and Chinese stimulus material,

Dr. Uta Schneiders and Manuel Ruf for proofreading and support with formatting,

various loved people around me for their individual nonscientific contributions to this work.