Selective Transfer of Visual Working Memory Training on Chinese Character Learning

Bertram Opitz^{a,b}, Julia A. Schneiders^b, Christoph M. Krick^c, & Axel Mecklinger^b

^a School of Psychology, University of Surrey, Guildford, UK

^b Department of Psychology, Saarland University, Saarbrücken, Germany

^c Department of Neuroradiology, Saarland University Hospital, Homburg, Germany

Address correspondence to
Bertram Opitz
School of Psychology
University of Surrey
Guildford
GU2 7XH, UK
phone: +441483689449
e-mail: b.opitz@surrey.ac.uk

Abstract

Previous research has shown a systematic relationship between phonological working memory capacity and second language proficiency for alphabetic languages. However, little is known about the impact of working memory processes on second language learning in a non-alphabetic language such as Mandarin Chinese. Due to the greater complexity of the Chinese writing system we expect that visual working memory rather than phonological working memory exerts a unique influence on learning Chinese characters. This issue was explored in the present experiment by comparing visual working memory training with an active (auditory working memory training) control condition and a passive, no training control condition. Training induced modulations in language-related brain networks were additionally examined using functional magnetic resonance imaging in a pretest-training-posttest design. As revealed by pre- to posttest comparisons and analyses of individual differences in working memory training gains, visual working memory training led to positive transfer effects on visual Chinese vocabulary learning compared to both control conditions. In addition, we found sustained activation after visual working memory training in the (predominantly visual) left infero-temporal cortex that was associated with behavioral transfer. In the control conditions, activation either increased (active control condition) or decreased (passive control condition) without reliable behavioral transfer effects. This suggests that visual working memory training leads to more efficient processing and more refined responses in brain regions involved in visual processing. Furthermore, visual working memory training boosted additional activation in the precuneus, presumably reflecting mental image generation of the learned characters. We, therefore, suggest that the conjoint activity of the mid-fusiform gyrus and the precuneus after visual working memory training reflects an interaction of working memory and imagery processes with complex visual stimuli that fosters the coherent synthesis of a percept from a complex visual input in service of enhanced Chinese character learning.

Key words: Second language, Chinese, vocabulary learning, working memory, training

1. Introduction

Communicating with people around the globe is becoming more and more important in an increasingly globalized world. Thereby the ability to speak different languages is a condition precedent. Chinese is one of the languages, which are most frequently spoken all over the world. Thus, learning Chinese as a second language is vitally important for many Westerners. One of the most crucial aspects of second language learning is vocabulary acquisition. 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 et al. 1998). In contrast to alphabetic languages, little is known about how second language vocabulary acquisition can be improved in the most frequent and most prominent logographic language: Mandarin Chinese. Since the Chinese writing system decidedly differs in the design principles and the characteristics of visual appearance of the words compared to alphabetic languages (Perfetti et al. 2010), it provokes the question which processes underlie visual word i.e. character learning in Chinese and whether this process 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.

1.1. The Chinese writing system

Chinese is referred to as a logographic writing system. Hence, the basic unit of the script is the character that comprises a number of strokes packed into a square configuration. Unlike alphabetic scripts, visually complex stroke patterns in Chinese characters follow a left-right horizontal, top-bottom vertical or inside-outside orientation. The most striking difference in contrast to alphabetic languages is that characters map onto phonology at the syllable level, such that the usage of grapheme-phoneme correspondence rules as in alphabetic languages is not possible (Perfetti et al. 2005; Tan et al. 1996). Due to the differences in design principles and visual word forms between Chinese and alphabetic script the neural circuitry involved when

alphabetic native speakers learn Chinese characters is not readily inferred from the brain structures involved in learning alphabetic languages. The few available brain imaging studies investigating Chinese character learning in English native speakers consistently found a network that mimics the pattern for Chinese native character processing (Nelson et al. 2009; Liu et al. 2007; Deng et al. 2008) but contrasts with the one for alphabetic word reading (e.g. Tan et al. 2005a). In more detail, Nelson et al. (2009) demonstrated that native English speakers who were learning Chinese for one year activated bilateral fusiform gyri as well as the left middle frontal gyrus when reading Chinese characters. Those activations are usually not found when processing words in an alphabetic language. Similar activations were found in laboratory training studies of Chinese characters (Liu et al. 2007; Deng et al. 2008). For example, Liu et al. (2007) report comparable regions in bilateral fusiform gyri and the left middle frontal gyrus after native English speakers learned a set of 60 Chinese characters during a 3-day learning period. As the fusiform gyri are involved in the visual analysis of words and objects (e.g. Cohen et al. 2000, 2002; McCandliss et al. 2003; Riesenhuber and Poggio, 1999), these data suggest that alphabetic native speakers need to adopt additional visual procedures that process the detailed and complex stroke pattern of Chinese characters. Since the simpler left-right-oriented procedures during alphabetic reading are not sufficient for reading Chinese characters, neural resources for enhanced analysis of perceptual details seem to be accessorially recruited.

1.2. The role of working memory in vocabulary acquisition

Evidence that working memory processes underlie vocabulary acquisition comes from various studies demonstrating that vocabulary knowledge in alphabetic second languages correlates with phonological working memory capacity as measured by digit span and non-word repetition (e.g. Baddeley et al. 1998; Cheung, 1996; Kormos and Sáfár, 2008; Slevc and Miyake, 2006; Speciale et al. 2004). The implication is that second language learners in an alphabetic language have to rely on the phonological loop that provides short-term storage of novel unfamiliar sound patterns and enables the formation of more stable long-term phonological representations in the mental lexicon (Baddeley, 2003; Baddeley et al. 1998). As written words are automatically

transformed into a phonological code using grapheme-phoneme conversion rules, retention depends crucially on the acoustic and phonological characteristics for both visually and auditorily presented words (Baddeley, 2003).

Again, not much is known about the relationship between vocabulary acquisition and working memory in the case of logographic Chinese. Critically, a simple adoption of the auditory working memory mechanisms required for alphabetic languages seems unlikely due to decidedly different design principles of the Chinese language system. In the case of 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. Crucially, as those segments are visually more complex and cannot be converted into phonemes, additional visual-orthographic analysis and visual short-term storage are mandatory. While studies investigating visual working memory as a predictor for language learning, are scarce, a couple of developmental studies have examined determinants of reading ability in Chinese children focusing primarily on visual processing skills and phonological awareness (Ho and Bryant, 1997a; Huang and Hanley, 1995; McBride-Chang and Ho, 2005; Siok and Fletcher, 2001; Siok, Spinks, Jin, and Tan, 2009; Tong and McBride-Chang, 2010). Huang and Hanley (1995) 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 and Fletcher, 2001), or detecting and memorizing stroke patterns and recognizing abstract shapes among alternatives (Ho and Bryant, 1997b), predicted reading Chinese characters at early stages of learning to read. Contrarily, phonological skills correlated with reading abilities predominantly at higher grades. The strongest evidence for the assumption that visual-orthographic processes are mandatory for Chinese character reading comes from Tan et al. (2005b) who showed that the ability to read Chinese is predominantly related to a child's writing (and drawing) skills while phonological awareness plays a minor role. Taken together, these findings, though heterogeneous, suggest that visual orthographic processing skills as measured by working memory-like tasks are crucial especially in early stages of learning to read

in Chinese due to the demanding visual complexity of the characters system.

Following these lines of arguments, we assume that the language system's design principles impose constraints on the role working memory processes play for the acquisition of words in a second language. We argue that working memory skills in general predict vocabulary acquisition in a second language – also in Chinese. More specifically, we predict that – contrary to alphabetic languages – there is a unique contribution of visual working memory to Chinese character acquisition.

1.3. Working Memory Training and its Transfer

Capitalizing on the reasoning outlined above, an appropriate means to enhance Chinese second language learning could be the specific training of visual working memory processes. Working memory training has recently attracted a great deal of attention as a method to improve cognitive functioning in general (Melby-Lervag & Hulme, 2013). Although there is a large variation in methodology regarding sample characteristics, length and intensity of training and the use of transfer tasks, there is consensus that working memory can be trained. Despite rather mixed evidence it has been claimed that working memory training can – under specific conditions – transfer to various tasks that were not trained directly (for recent reviews see Klingberg, 2010; Boot, Blakely, and Simons, 2011; Diamond and Lee, 2011). Two of the conditions assumed to be met for such transfer to occur are that the criterion task and the transfer task (a) engage similar processing components and (b) recruit overlapping brain regions (Dahlin et al. 2008; Jaeggi et al. 2008; Jonides, 2004; Lövdén et al. 2010). Following this account, in the present study we aim at investigating whether visual working memory training can generally improve second language character acquisition in Chinese due to shared processing components (Sayala et al. 2006; Schneiders et al. 2011). We are also interested in how this training modulates the brain networks mediating learning Chinese vocabulary. As mentioned above short-term retention is necessary during novel word acquisition and should occur in modality-specific higher-order association cortices involved in language processing (Davis and Gaskell, 2009). The same higher-order visual association cortices were found to be

recruited by verbal working memory (e.g., Ranganath et al. 2004; Schneiders et al., 2011; Zimmer, 2008). Fiebach, Rissman, and D'Esposito (2006) for example demonstrated that during the retention period of a visual delayed cued recall task, pre-acquired (i.e., learned) words sustained greater activation in a language-sensitive left infero-temporal region relative to unlearned pseudo-words. This result provides some evidence for co-localized brain regions involved in both WM processing and word acquisition. Thus, we expect that transfer effects after visual working memory training on Chinese character acquisition should be accompanied by activation changes within the respective higher-order association cortex, namely in infero-temporal regions.

In addition to visual working memory training we employed an active as well as a passive control group. The employment of an active control group is essential insofar, as paradigms employing passive control groups tend to overestimate effects due to expectancy effects (Melby-Lervag and Hulme, 2013). That is, trained participants could improve their performance simply because they were treated. Thus, in the present study participants in the active control group were treated the same amount of time (in an auditory working memory task) as the visual working memory training group.

2. Methods

2.1. Participants and overall Procedure

Forty-eight native German students of Saarland University, 26 female and 22 male, mean age = 23.67 years (age range = 19-31 years), participated in this study. Participants did not have prior knowledge of any logographic language, 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.

Figure 1 A illustrates the overall experimental design. The study was separated into three stages, each lasting two weeks. The first and third stage consisted of the first and second Chinese vocabulary learning, each followed by an fMRI session that served as pre or posttest,

respectively. These two stages were equal for all participants. All participants learned the orthography and phonology of Chinese 2-character/syllable words and had to perform an orthographic and a phonological task on previously learned words in the following fMRI session. The second stage comprised the working memory training; participants were assigned to either the visual working memory training group (mean age = 23.94 years, age range = 21-29), the active auditory control 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 ($\chi^2(1, n=48) = .33, p = .56$), fluid intelligence as assessed by a speeded version of the Bochumer Matrizen-test (BOMAT) (Hossiep et al. 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: $p = .29$). The visual training group and the active auditory control group trained within two weeks on either a visual or auditory adaptive n -back task, respectively (see below). The passive control group did not receive any training.

2.2. Chinese Vocabulary Learning

The Chinese vocabulary learning in the first and third stage was adapted from a study by Deng et al. 2008 and began with a learning phase in the first week, in which participants acquired the orthography and phonology of 75 new Chinese words at each stage. These words were drawn from a total of 150 Chinese two-character/syllable nouns. The 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 and not 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 experienced male native speakers of Mandarin and German, respectively and recorded in a soundproof recording studio. 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 three. Both sets were divided into five learning lists of 15 characters each. The sequence of the five learning lists within each stimulus set was counterbalanced across participants. Mean number of strokes of the two-character words was held constant across all lists. 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.

On each of the first five sessions (learning units) participants learned a new list of 15 words. Within each trial of the learning units, 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). With a stimulus onset asynchrony (SOA) of 5000 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 presentation of the Chinese word and the following blank screen alternated 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. Even though, we were mainly interested in the visual orthographic aspects of Chinese vocabulary learning, participants learned the complete lexical information of Chinese words, i.e. orthographic, phonological and semantic information to hold the vocabulary learning ecologically valid.

From the second to the sixth learning session, each session started with an initial test unit, covering trained words from the last learning unit. The trial structure was analogous to the

learning units in terms of presentation times of the German and Chinese words. However, orthographic and phonological proficiency were tested separately, i.e. there were orthographic and phonological trials presented in random order. Only the results for the orthographic trials will be reported in the following. The Chinese word was presented only once and could match or could not match the German word. Each of the test units covered all 15 words from the preceding learning list. Each word appeared twice in the orthographic task and twice in the 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). Incorrect trials consisted of words that were learned in the previous learning unit, but did not represent the correct German- Chinese translation. Participants were asked to judge whether the word pair matched or did not match by pressing either the letter “M” or “C” of a standard computer keyboard. Response mappings were counterbalanced across participants and were maintained throughout vocabulary learning, working memory training and the fMRI sessions. 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. 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 or incorrect trials were held constant. Each test unit lasted about seven minutes.

In the second week of vocabulary learning (i.e., after the fifth learning session) review test units were applied (see Figure 1 B). Participants were tested on a subsample of all words they had learned. To accomplish the review test lists in a reasonable amount of time words in the review test units had to be taken from only four out of five learning lists. Thus each review test unit consisted of 240 trials and lasted about 28 minutes. 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. The trial structure was identical to that from the test units. From the eighth training session on, the training was terminated in case participants reached at least 80% correct responses 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 between the learning sessions, as measured by mean number of days, did not differ significantly between the groups in the pretest [working memory training group: $M = 1.25$, $SD = 0.03$; active control group: $M = 1.25$, $SD = 0.03$; passive control group: $M = 1.27$, $SD = 0.05$; $p > .10$] and the posttest [working memory training group: $M = 1.34$, $SD = 0.20$; active control group: $M = 1.23$, $SD = 0.06$; passive control group: $M = 1.32$, $SD = 0.18$; $p > .10$]. Mean spacing between the last Chinese vocabulary learning session and the following fMRI session did also not differ significantly between the groups in the pretest [working memory training group: $M = 2.50$ days, $SD = 1.03$; active control group: $M = 2.19$ days, $SD = 0.91$; passive control group: $M = 3.13$ days, $SD = 1.53$; $p > .10$] and posttest [working memory training group: $M = 1.88$ days, $SD = 0.96$; active control group: $M = 2.38$ days, $SD = 0.96$; passive control group: $M = 2.56$ days, $SD = 1.09$; $p > .10$].

2.3. Working Memory Training

An adaptive n -back paradigm was used for working memory training, which was adapted from the study of Jaeggi et al. (2008). For a detailed description of this paradigm see Schneiders et al. (2011). In the n -back task a sequence of stimuli is presented successively. Participants are requested to decide whether or not the current stimulus matches the one that appeared n positions back in the sequence. Stimuli were presented at a rate of 3 s (stimulus length = 500 ms, ISI = 2500 ms). To implement adaptivity, the level of n changed from one block of $20 + n$ trials to the next according to each participant's individual proficiency. Participants completed 40 blocks during each training session and eight to ten sessions during the working memory training.

The stimuli in the visual training task consisted of abstract visual black-and-white patterns presented on a computer screen whereas the stimuli for the active auditory control group consisted of bird voice tracks presented via headphones. A completely new set of eight stimuli was used for each session to prevent from high familiarization with specific stimuli and from verbal or semantic recoding.

2.4. fMRI Sessions

Participants were scanned after vocabulary learning in the first and third stage of the study, respectively. Participants were tested on all 75 Chinese words learned in the previous learning session. The task format was kept identical to the test and review test units of vocabulary learning, i.e. included separate tests of orthographic and phonological proficiency. This identical procedure was used to ensure that participants were familiar with the task and therefore could achieve a similar performance level despite the new environment in the scanner. To account for differences in the trial timing necessary for fMRI acquisition the feedback screen was replaced by a 1000 ms blank screen and the ITI was exponentially distributed and ranged 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 et al. 2001) (see Figure 1 C).

A visual discrimination task using unknown Chinese characters/syllables served as control task (see Figure 1 C). 120 single Chinese characters that were not included in the vocabulary learning were used to construct the 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. 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 orthographic and control tasks, the mean number of strokes of the control character pairs in each stimulus set was held constant between control character pairs and learned characters used in the vocabulary learning [$p > .10$]. The preceding German word was always either the word 'links' (left) or 'rechts' (right). The participants' task was to judge, whether the position cued by the German word corresponded to the position of the simple character within the character pair.

Experimental and control trials were employed in the same run with experimental trials being presented before respective control trials. This protocol was adapted from Deng et al. (2008) including the order of the experimental and control task being fixed. Furthermore we reasoned

that the more difficult orthographic task placed at the beginning of the rather long scanning session would ensure comparable performance for all participants that is not affected by changes in attention or vigilance. A working memory task was applied in an additional run subsequently to the lexical run. The results have been described previously (Schneiders et al. 2011).

2.5. Analysis of Behavioral Data

To compare participants' mean performance for each vocabulary learning task a repeated measure MANOVA (Pillai's trace) with the factors Time (pretest vs. posttest) and Group (working memory training vs. active control vs. passive control) was calculated on the discrimination index $Pr(p[\text{Hit}] - p[\text{FA}])$ (Snodgrass and Corwin, 1988) of the pre and posttest fMRI sessions. A multivariate approach was preferred as validity assumptions of the repeated measure analysis of variance are much less problematic compared to univariate procedures (Vasey and Thayer, 1987).

The participants' performance during the working memory training was quantified as the mean level of n for each session and subjected to a repeated measure MANOVA (Pillai's trace) with the factors Group (working memory vs. active control) and Session (Sessions one to eight).

2.6. Image Acquisition and fMRI Data Analyses

An event-related design with two repetitions was performed on a 1.5 Tesla scanner (Magnetom Sonata, Siemens Medical Systems, Erlangen, Germany). Participants lay comfortably on their spine and head motions were restricted by using a vacuum pillow. Visual stimuli were presented through a projector onto a translucent screen. Participants viewed the stimuli through a mirror attached to the head coil. Auditory stimuli were presented via MRI-compatible headphones. Responses were collected via 2-button response grips. A T2*-weighted gradient-echo planar imaging sequence was used for fMRI scans (matrix = 64, field of view = 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 consecutive axial slices

were acquired parallel to AC-PC line covering the whole brain. 960 volumes were acquired per run. An intra-session high-resolution structural scan was acquired using a T1- weighted 3D MPRAGE (1 mm³ voxel size).

The functional imaging data were analyzed using BrainVoyager QX (Brain Innovation, Maastricht, The Netherlands) (Goebel et al. 2006). The first four volumes of each subject's functional data set were discarded to allow for T1 equilibration. For the remaining 956 volumes, 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 per run. Functional slices were co-registered to the anatomical volume of the pretest session using position parameters and intensity-driven fine-tuning and were rescaled to a 3x3x3 mm resolution before they were transformed into Talairach coordinates (Talairach and Tournoux, 1988).

Functional time-series were analyzed using random-effects multi-subjects general linear model (GLM) (Friston et al. 1999). In a first analysis all levels of the factor Task (experimental and control) and Time (pretest and posttest) were modeled as separate predictors for each subject. 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). As predictors of no interest German words and L2 words of the phonological trials were added to the design matrix of each run. Also all six motion parameters described by the translation along the x, y and z-axes and rotation around these axes were modeled as predictors of no interest in the GLM to assure that residual movement artifacts did not obscure our results. Only correct trials were included in the analysis. Following the distinction of task practice effects on brain activation as recently proposed by Kelly and Garavan (2005) the effects of working memory training on initially task-relevant brain regions will be referred to as *redistribution* effects in the following. Such redistribution of functional activations implies a combination of increases and decreases in brain activity within the same areas before and after working memory training. To explore initially task-relevant activations after vocabulary learning independent of working memory training a random effects

contrast between the experimental task and the control task was calculated for the pretest data of all participants. 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 .

On the basis of these cluster activations in the pretest functional volumes-of-interest (VOI) were defined. Using VOIs representing greater activity in the experimental task as compared to the control task during pretest allowed us to specifically examine redistribution effects (i.e., effects that working memory training had on initially task- relevant brain regions) and provides a criterion for inclusion of regions in the pretest-posttest analysis (Erickson et al. 2007; Kelly and Garavan, 2005). To assess training-induced changes within VOIs we extracted the mean parameter estimates from pre- and posttest for each participant from the VOIs and performed a series of repeated measures MANOVAs focusing on Time (pre vs. posttest) by Group (working memory training vs. active control vs. passive control) interactions.

Another practice-related pattern that according to Kelly and Garavan (2005) has been frequently observed in brain imaging studies will be referred to as *reorganization* in the following. It describes the recruitment of new brain areas after working memory training associated with a change in the cognitive processes underlying task performance. Thus, a second analysis investigated whether working memory training led to new activations at posttest (i.e., reorganization effects, Kelly and Garavan, 2005) by examining contrast between the experimental task and the control task for the posttest data of the working memory training group. In order to reduce the possibility of a Type II error (Lieberman & Cunningham, 2009), i.e. not to miss any potentially relevant activation changes, a more liberal threshold set to $p < .0005$ (uncorrected) determined by the number of functional voxels > 25 was chosen. To test whether these regions were specific for the working memory training group, we defined significantly activated voxels in the experimental vs. control task contrast as VOIs and extracted mean parameter estimates from posttest of the experimental task only. These parameter estimates were subjected to an ANOVA with the Group between-subjects factor Group (working memory training vs. active control vs. passive control). To ensure that differences were not due to

differences in the pretest, the same VOIs and one-way ANOVAs were applied to the pretest extracted mean parameter estimates.

In addition, to estimate the functional connectivity during the experimental task at posttest, a psycho-physiological interaction (PPI) analyses (Friston, 1997) was conducted. PPI analysis is a brain connectivity method that characterizes the activity in one brain region by the interaction between activity in another region and a psychological (task) factor. Thus, brain areas which exhibit significantly greater covariance with the activity of the selected VOI during the Chinese character learning task compared to the control task can be considered as functionally connected to each other by the task. For each participant a PPI regressor was extracted. This regressor was the dot product of the BOLD time-course of a seed VOI and the task regressor for the experimental minus control task convolved with the hemodynamic response function. It was used to identify the individual effect of task modulation due to the Chinese character learning task on functional connectivity. As for the main analysis the results were thresholded at $p < .005$ (FDR corrected) using clusters determined by the number of functional voxels > 25 .

3. Results

3.1. Training Effects: Working Memory Training

The visual working memory training group as well as the active auditory control group improved their performance in the course of working memory training as revealed by a significant main effect of Session, [$F_{7,24} = 11.58, p < .001, \eta^2_p = 0.77$]. A marginally significant Group by Session interaction, [$F_{7,24} = 2.25, p < .10, \eta^2_p = 0.40$], indicated that the training effect tended to be larger for the visual training group than for the active control group.

3.2. Transfer Effects

Figure 2 shows the behavioral performance (*Pr* Scores) in the vocabulary learning task in the fMRI sessions. Performance improved from pre- to posttest as shown by the significant main effect of time [$F_{1,45} = 4.41, p < .05, \eta^2_p = .09$]. The Time by Group interaction was marginally

significant [$F_{2,45} = 2.71$, $p < .10$, $\eta^2_p = .10$]. In line with our predictions performance increased significantly from pre- to posttest only for visual working memory training [mean difference = .08, $SD = .13$, $t_{15} = -2.68$, $p < .05$] but not for the active [mean difference = .02, $SD = .12$, $t_{15} = -1.75$, $p = .10$] and passive control groups [mean difference = -.005, $SD = .10$, $t_{15} = 0.64$, $p > .10$].

3.3. Brain Imaging Results

3.3.1. Redistribution Effects

In the pretest, the contrast between the experimental and the control task revealed regions that were involved in Chinese character processing after the first vocabulary learning. These regions were in the left and right fusiform gyrus, the bilateral cerebellum, the right thalamus, and the right putamen (see Table I, for a list of regions and cluster peak coordinates).

[Table I about here]

With respect to VOI analyses, the main interactions of interest were Time (pretest vs. posttest) by Group (visual working memory vs. active control vs. passive control) as these interactions reveal differential pretest- posttest activation changes between the three groups. A significant Time by Group interaction was found in the left fusiform gyrus [1]¹ [$F_{2,45} = 6.47$, $p < .01$, $\eta^2_p = .22$]² (see Figure 3 A). Comparisons of pretest-posttest BOLD responses separately for each group indicated that activation changes were found only for the two control groups but not in the visual working memory training group: in the active control group there was a marginally significant activation increase [mean difference = .008, $SD = .017$; $t_{15} = -1.95$, $p < .10$], whereas in the passive control group [mean difference = -.013, $SD = .019$] activation in the left fusiform gyrus decreased significantly [$t_{15} = 2.77$, $p < .05$]. Descriptive activation decreases after visual working memory training [mean difference = -.005, $SD = .015$] did not reach significance [$p > .10$]. Notably, the Time by Group interaction within this VOI was still significant when reducing

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¹ Numbers in square brackets refer to numbers of the VOIs as indexed in Table I.

² 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.

the Group factor levels to the working memory training group and the active control group only [$F_{1,30} = 5.48, p < .05, \eta^2_p = .15$]. This indicates that the interaction does not trace back to the numerically largest activation decrease for the passive control group, but rather reflects the differential effect of visual working memory training and the active control group in the left fusiform gyrus. To make sure that effects did not arise from baseline (pretest) differences, a one-way ANOVA with the factor Group (three levels) was performed on the pretest % 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.

As differential fusiform gyrus activations at posttest for the active and passive control group were unexpected we performed a post-hoc correlation analysis between posttest performance and the corresponding fMRI measures. For the passive control group there was a positive correlation between posttest performance and the activity in the left mid-fusiform gyrus ($r_{16} = .49, p < .06$) that was not evident for the visual working memory training group and the active control group (visual working memory group: $r_{16} = .41, p > .15$, active control group: $r_{16} = .14, p > .60$). As similar activation decreases have been found to go in parallel with lowered task performance in a variety of other brain imaging studies (e.g., Milham et al. 2003), the correlation pattern in our data suggest that the low fusiform gyrus activation in the passive control group is a reflection of the low task performance.

[Figure 3 about here]

3.3.2. Reorganization Effects

To test for reorganization effects, regions were identified that were additionally active in the posttest comparison in the visual working memory training group. Those regions were the left and right fusiform gyrus and the right precuneus after visual training. No region was activated in the passive control group at posttest (see Table II).

[Table II about here]

The precuneus was the only region that additionally appeared in the posttest and was not already activated during pretest. Thus, in a second analysis, the precuneus-cluster was defined as a VOI. At posttest activations in this VOI differed significantly between the training and the control 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 working memory training group and both, the active control group [mean difference = .018, $SD = .006$] and the passive control group [mean difference = .020, $SD = .006$] were significant whereas the difference between the two control groups [mean difference = .002, $SD = .006$] was not (see Figure 4). Furthermore, the group effect at pretest within the precuneus VOI was non-significant [$F_{2,45} = .45, p = .64$], indicating that differences in the posttest do not trace back to group differences before working memory training.

[Figure 4 about here]

To evaluate whether this newly recruited brain area contributed to the increased performance in the experimental task the PR-scores of the posttest orthographic task were correlated with the activity in the right precuneus across all participants. A positive correlation between the two variables ($r_{48}=.495, p<.001$) was observed that remained significant when controlling for the posttest performance in the control task ($r_{45}=.342, p<.05$). Moreover, this analysis revealed a significant positive correlation for the visual working memory training group ($r_{13}=.529, p<.05$) but not for the two control groups (active control group: $r_{13}=.399$, and passive control group: $r_{13}=-.067$, both p -values $>.15$). This indicates that the additional recruitment of the precuneus benefits the Chinese character processing only after visual working memory training.

Furthermore, a PPI analysis was conducted, allowing to test whether the inter-regional correlation in neuronal activities between the precuneus and the mid-fusiform gyrus changes significantly as a function of the task condition (experimental vs. control task), independently of

activity due to task differences. This analysis used the precuneus VOI as seed region. At the significance level used in the main analysis, only for the visual working memory training group two brain regions emerged to be dynamically related to the right precuneus during the Chinese character learning task (see Table III).

[Table III about here]

4. 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. 2009; Wang et al. 2003), to the best of our knowledge, the present study is the first to explore the impact of visual working memory training on learning Chinese characters. We observed training gains in the *n*-back working memory tasks for the visual working memory training group that allowed us to compare the transfer effects on performance and neural activation changes in learning Chinese characters.

In line with our hypothesis that visual character learning in Chinese benefits from visual working memory training we observed superior learning selectively after visual working memory training, while both, the active and passive control groups did not show significant improvements, despite better performance in the active as compared to the passive control group. Most interestingly, the superior learning after visual working memory training was associated with a pattern of neural activation changes in the left mid-fusiform region – a brain area that is crucial for visual character processing – that was distinct from both control groups. In addition, visual working memory training only led to supplementary activation of the right precuneus during visual processing of learned Chinese characters in the posttest.

Our behavioral data are consistent with correlational and longitudinal studies reporting that especially visual and, to a minor extent, phonological working memory skills predict learning to read Chinese characters (Siok and Fletcher, 2001; Ho and Bryant, 1997b; Tan et al. 2005b). Thus, our data augment these findings by showing that visual working memory processes contribute to Chinese word learning to a larger extent than auditory/phonological working memory. By

this the data also imply that processing components of visual working memory and visual character recognition in Chinese vocabulary learning do overlap. The improvement in holding visually complex patterns in working memory (as revealed by improved performance in the visual n-back task) seems to be crucial for the recognition of visually complex Chinese characters when learning them as vocabulary in a second language.

The activation pattern of the experimental task in the pretest comparison comprised mainly the bilateral fusiform gyrus, bilateral cerebellum, right putamen and right thalamus. This finding is consistent with previous reports of Chinese second language processing (Deng et al. 2008; Liu et al. 2009; Nelson et al. 2009). Therefore, the present findings support our hypothesis that visual working memory training specifically affects the visual association cortex compared to the control conditions as the left fusiform gyrus is part of the ventral visual stream and critically involved in higher visual object recognition (Malach et al. 2002; Reddy and Kanwisher, 2006; Riesenhuber and 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 et al. 2003) as well as in Chinese (Liu et al. 2008), recent studies have revealed 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 et al. 2006, 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, we found pretest activation in all three groups already after the first 14-day Chinese vocabulary learning phase. This finding might suggest that such a short learning period is sufficient to lead to altered processing of at least the visual shapes of Chinese characters. This interpretation is in line with previous findings demonstrating that the ventral occipito-temporal cortex is highly responsive to a variety of visual stimuli (Price and Devlin, 2003, 2011; Starrfelt and Gerlach, 2007; Kensinger and Schacter, 2008). For example, Starrfelt and Gerlach (2007) investigated how stimulus type (words vs. pictures) and different tasks demands (e.g., categorization, color and object decision) affect activation in the left mid-fusiform gyrus. With increasing demands on shape processing activation differences

between words and pictures disappeared. These findings were taken to reflect the process of integrating shape elements into elaborated form descriptions in the left mid-fusiform gyrus for both visual objects and written words under task demands that emphasize visual processing like the orthographic task in the present experiment. Moreover, the left mid-fusiform gyrus was also found to be active in several visual working memory studies (Axmacher et al. 2009; Buchsbaum et al. 2005; Fiebach et al. 2006; Schneiders et al. 2011; Wager and Smith, 2003). It was argued that this involvement reflects visual analysis of objects held in working memory. Following this line of reasoning the present finding of mid-fusiform gyrus activation in the pretest can be taken to reflect the processing of visual properties such as shape configuration that are particularly suited for activating the left mid-fusiform gyrus.

Notably the left mid-fusiform gyrus was found to show differential activity changes after visual working memory training and both control conditions. After visual working memory training we observed sustained activity from pre to posttest that was associated with increased performance in the Chinese character learning task. This adds to an increasing body of evidence indicating that activity in the mid-fusiform gyrus is influenced by a complex relationship between task demands, emphasizing visual processing and proficiency with the Chinese writing system. For example, activation increases were found for English learners of Chinese when faced with novel transfer characters that were visually (but not semantically) similar to previously learned characters (Deng et al. 2008). Contrarily, a short period of visual form training significantly decreased the activation in the mid-fusiform gyrus to artificial Korean characters in Chinese native speakers (Xue et al., 2006). Together these studies underline the key role of the left mid-fusiform gyrus in learning visually complex stimuli by extracting more perceptual features in an advanced visual stage of learning (Xue et al. 2006, Xue and Poldrack, 2007). In light of these findings we suggest that in the present study the sustained activity in the mid-fusiform gyrus after visual working memory training accompanied by superior task performance might reflect the improved analysis of the complex visual stroke patterns of Chinese characters held in working memory. This facilitated encoding and maintaining of complex visual patterns in working memory could in turn be used by the trained participants to extract relevant shape

information from the visually complex Chinese characters more effectively resulting in improved performance in the posttest visual vocabulary learning task.

Interestingly, both the active and passive control group show opposed patterns of activation changes from pre to posttest in the fusiform gyrus which also differed from those in the active training group. The marginally significant increase of activity in the mid-fusiform gyrus in the active control condition resembles activation increases found in a variety of working memory training studies (see Klingberg, 2010 for a summary of these studies). We speculate that this increased activation results from improved tuning of Chinese character processing in mid-fusiform gyrus due to improvements in executive components of working memory. As executive components of working memory relying on different regions within the lateral prefrontal cortex are required in the *n*-back task, these components were presumably also trained by the active (auditory) control group (cf., Jaeggi, et al., 2010). Hence, it is conceivable that more attentional resources were allocated to the processing of the Chinese characters after cross-modal (auditory) working memory training, but that this enhanced processing was not yet sufficient to be also manifested in significant performance increases in the active control group. The visual working memory training group could, in principle, also allocate more attentional resources to the processing of Chinese characters as they equally trained executive control processes. However, it could be speculated that additional attentional resources may not facilitate an already efficient and optimized extraction of shape information from the Chinese characters. Consequently, the increase in mid-fusiform gyrus activity observed for the auditory group was not evident for the visual working memory training group.

Remarkably, the passive control group showed a reliable decrease in activation from the pretest to the posttest. As revealed by a follow up correlation analysis, this reduction in fusiform gyrus activation was associated with low post test task performance. This is qualitatively different from the activation increase in the active control group and the sustained activity found after visual working memory training and might point to less effort or allocation of attentional resources to vocabulary learning at posttest.

In addition to the aforementioned redistribution effects we found the right precuneus to be

uniquely active in the vocabulary learning task after visual working memory training. This reorganization pattern is in good agreement with previous studies commonly reporting bilateral precuneus activation in Chinese character processing (e.g. Kuo et al. 2004; Deng et al. 2008; Liu et al. 2008). More specifically, in these studies precuneus activation was higher for artificial than real and pseudo Chinese characters in native Chinese participants (Liu et al. 2008). In line with the present results of better performance in the orthographic task being associated with higher activity in the precuneus previous studies reported that precuneus activation was correlated with learning accuracy when native English speakers learned new Chinese characters (Deng et al. 2008). Based on these findings it has been argued that the precuneus is involved in the visual-spatial processing of sub-lexical components of Chinese characters (Deng et al. 2008). In this vein, we assume that in the current study the visual working memory training triggered additional visual-spatial strategies like the imagination of the complex stroke pattern to generate mental images of the learned characters in order to retrieve their respective visual-semantic representations. This view is in line with several proposals consistently linking activity in the precuneus to visual imagery (Cavanna and Trimble, 2006; Fletcher et al. 1995; Gardini et al. 2009). It is also consistent with recent results demonstrating that normal reading children but not dyslexic children exhibited similar precuneus activation when asked to compare the physical size of two simultaneously presented Chinese characters (Siok et al., 2009).

The precuneus also exhibited increased functional connectivity to posttest activation in the fusiform gyrus after visual working memory training as revealed by PPI analysis. PPI disambiguates inter-regional connectivity between the precuneus and the fusiform gyrus from differential task effects by evaluating the differential interactions on residual variance, i.e., after removing task-related effects (Friston, 1997). Therefore, this latter result implies that the enhanced extraction of visual shape features may have facilitated image generation as reflected in right precuneus activity. Most interestingly this reorganization effect was only found for the visual training group for which we solely found reliable behavioral improvements.

As precuneus activation was also associated with successful retrieval from episodic memory in prior studies (e.g. Wagner et al. 2005), we additionally tested whether enhanced activation was

only present when participants correctly recognized previously learned characters (hits) as compared with characters which were correctly identified as not learned (correct rejections). As the Response Type (hits vs. correct rejections) by Group (visual working memory vs. active auditory control vs. passive control) interaction was not significant [$F(2,45) = 0.43, p = .65$], we feel safe to conclude that the specific activation of the precuneus after visual working memory training does not reflect the matching process between the successfully imagined character and the presented probe character.

Taken together, the present findings speak for transfer of visual working memory training on Chinese orthographic vocabulary learning on the behavioral level. On the neural level these transfer effects are accompanied by sustained activation in the fusiform gyrus, presumably reflecting more efficient visual shape processing. Additionally, visual working memory training led to mental image generation as indicated by additional recruitment of the right precuneus. We, therefore, suggest that the conjoint activity of the mid-fusiform gyrus and the precuneus reflects an interaction of shape feature extraction and imagery processes with complex visual stimuli (cf. Dolan et al., 1997). This on-going dynamic interaction between the two brain areas fosters the coherent synthesis of a percept from a complex or insufficiently specified visual input as implicated by psychophysical experiments that demonstrate imagery-based facilitation of sensory representations (Ishai and Sagi, 1995).

4.1. Conclusions

In sum, the present findings demonstrate that visual working memory training improves visual Chinese vocabulary learning. Our data show that visual working memory training can modulate the recruitment of higher order visual regions for Chinese vocabulary learning, namely the left mid-fusiform gyrus and the precuneus. We observed sustained activation after visual working memory training in the left mid-fusiform gyrus along with behavioral transfer effects. This suggests that visual working memory training led to more efficient visual shape processing of Chinese characters and by this to more refined responses in brain regions involved in visual processing areas. Thereby, the present findings provide unique support for the idea that visual

working memory training might transfer to Chinese character acquisition by boosting multiple visual strategies, which can be recruited to encode and retrieve lately acquired Chinese characters.

Although the current study cannot solve the debate on heterogeneous evidence regarding transfer effects of working memory training in general, it nevertheless further underscores that overlapping processing components and brain regions are essential factors for transfer of working memory training. (Dahlin et al. 2008; Jaeggi et al. 2008; Jonides, 2004; Lövdén et al. 2010). Based on the current data it seems inevitable to exactly define the processing components and brain regions and to carefully choose training and transfer tasks accordingly.

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Table I:

Brain regions activated in the pretest contrast experimental task minus control task.

Brain region	BA	H	<i>t</i> value	Number of voxels	<i>x</i>	<i>y</i>	<i>z</i>
[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
	/	L + R	6.647	842	6	-46	-2
[4] Thalamus (Pulvinar)	/	R	5.927	944	24	-25	10
[5] 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 .005 (FDR corrected).

Table II:

Brain regions activated in the posttest contrast experimental task minus control task for the visual working memory training group

Brain region	BA	H	<i>t</i> value	Number of voxels	Talairach coordinates		
					X	Y	Z
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

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 .001 (uncorrected).

Table III:

Brain regions showing significant increases of connectivity to the right Precuneus in the posttest contrast experimental task minus control task as revealed by the PPI analysis.

Brain region	Voxel Level			t	p	Cluster Level	
	Talairach coordinates					p(cluster)	Number of voxels
	X	Y	Z				
right Fusiform Gyrus	41	-56	-15	10.61	10 ⁻⁷	.001	1133
left Fusiform Gyrus	-43	-53	-15	10.20	10 ⁻⁷	.001	3272

Voxel level results are listed based on cluster peak coordinates. Coordinates correspond to those from the Talairach & Tournoux reference brain.

Figure legends

Figure 1

(A) Schematic description of the experimental design. All three groups performed the same second language training and the fMRI session 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. (B) Schematic description of the Chinese character learning. 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. (C) Chinese Character Learning Task of the pre- and posttest fMRI sessions and its respective control task. Participants had to judge whether the German word matched to a learned Chinese character. In the control tasks participants performed a comparison task on features of the Chinese character.

Figure 2

Transfer effects as indicated by mean *Pr* scores of the Chinese Character Learning Task in the fMRI sessions during pre and posttest shown for the visual working memory training group, the active and the passive control group.

Figure 3

Working memory training-related activation changes during performance of the Chinese Character Learning task. The left panel depicts the respective VOI (left fusiform gyrus at BA 37 [1]). The right panel shows % signal change values within this VOI for the visual working memory training group versus both control groups. Numbers in square brackets refer to the numbers of the VOIs as indexed in Table I respectively.

Figure 4

Reorganization effect after visual working memory training. The left panel shows the VOI in the right Precuneus at BA 7/40. The right panel depicts % signal change values within this VOI for each group in the posttest comparison.

Figure 1.

Figure 2

Figure 3

Figure 4