Separating Intra-Modal and Across-Modal Training Effects in Visual Working Memory: An fMRI Investigation

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Working memory training is a useful tool to examine dissociations between specific working memory processes. Although current models propose a distinction between modality-specific working memory processes, to our knowledge no study has directly examined the effects of visual versus auditory working memory training. Functional magnetic resonance imaging was used to investigate whether visual working memory processes can be trained specifically and whether those effects can be separated from across-modal training effects. We found decidedly larger training gains after visual working memory training compared with auditory or no training on a visual 2-back task. 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. We 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.

Keywords: auditory, *n*-back task, training, visual, working memory

Introduction

Working memory refers to the ability to maintain and manipulate information for a short period of time (Baddeley 2002). The original multicomponent model by Baddeley and Hitch (1974) as well as the current working memory model of Baddeley (2002, 2003) proposes a system that consists of a central executive aided by 2 subsidiary slave systems: the visuospatial sketchpad and the phonological loop. These independent and modality-specific systems form storage buffers for the processing and rehearsal of visuospatial and phonological materials and make these materials accessible for central control processes. Besides the model comprises a forth component, the episodic buffer, which is assumed to be a limited capacity store that binds information to form integrated episodes. The distinction between the 2 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 show that the *n*-back task elicits bilateral frontoparietal activations especially in the dorsolateral prefrontal cortex (PFC) and in superior and inferior parietal areas (e.g., Carlson et al. 1998; Casey et al. 1998; Owen et al. 1999; Nystrom et al. 2000; Druzgal and D'Esposito 2001; Ragland et al. 2002; for a meta-analysis, see Owen et al. 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 et al. 2000; for a meta-analysis, see Wager and Smith 2003).

Even though the important distinction between modality-specific storage systems can be found in contemporary models of working memory, only few brain imaging studies have directly compared visual versus auditory working memory processes. One event-related potential (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 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 functional magnetic resonance imaging (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 et al. 2004). Partly consistent with these findings, Rodriguez-Jimenez et al. (2009) report greater bilateral activations in the dorsolateral PFC in the auditory compared with 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 et al. 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, that is, 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, that is, verbalizable representations.

A useful tool for examining the functional plasticity of those content-specific dissociations is their specific training. Recently working memory training has attracted a great deal of attention because it has been shown that it does not reduce to simple retest effects (for a review, see Klingberg 2010) and can, under specified conditions (Jonides 2004), even lead to transfer effects on various cognitive skills such as fluid intelligence (Jaeggi et al. 2008).

Most of the studies aim at using working memory training as a tool to generally improve higher cognitive abilities and thus target at providing an applicable and effective intervention which should result in enhanced performance in nontrained tasks (transfer effects). For this purpose, they use only one training group that trains a battery of working memory tasks (e.g., Klingberg et al. 2005; Mahnke et al. 2006; Li et al. 2008; Holmes et al. 2009; Chein and Morrison 2010) or only one working memory task (e.g., Hempel et al. 2004; Dahlin et al. 2008; Jaeggi et al. 2008; Jolles et al. 2010).

In contrast, only a few studies (Sayala et al. 2006; Persson and Reuter-Lorenz 2008) intend to disentangle components of working memory and accordingly compare 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 the training and transfer effects of a specified control process (i.e., interference resolution). Training effects of the high-interference versions of 3 different working memory tasks were compared with those of the corresponding noninterference versions. Only the high-interference training led to increased efficiency in proactive interference resolution in the trained and also nontrained tasks involving interference resolution. 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 (5 runs consisting of 8 memory trials each) of the spatial version of the delayed recognition task compared with 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 frontoparietal working memory network. In the present study, we used a similar approach, as it allows to dissociate modality-specific from general, modality-unspecific training effects by employing 2 different kinds of working memory trainings which only differ in the sensory modality of stimuli, that is, visual versus auditory.

Furthermore, it needs to be mentioned that studies attempting to characterize the neural correlates of training gains by examining corresponding neural activation changes reveal an inconsistent pattern of results (Chein and Schneider 2005), which can possibly be attributed to different training procedures varying in length and intensity. Olesen et al. (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 3 types of visuospatial 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 5 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 frontoparietal regions although training effects on the behavioral level are not found consistently (Garavan et al. 2000; Landau et al. 2004; Sayala et al. 2006). 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. In line with this view, Klingberg (2010) concludes in a recent review paper that a total amount of at least 8 h of working memory training or a training period of 3 weeks is required to achieve substantial training effects. Nevertheless, the shape of functional plasticity during intense long-term training is still a matter of controversy. Moreover, there is some consensus that adaptiveness is a crucial factor for the effectiveness of working memory training (Lövdén et al. 2010). The studies of Klingberg et al. (2005) and Holmes et al. (2009) report 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 with nonadaptive training.

Combining both lines of research mentioned above, the present study's first goal was 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. The second goal was 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, we 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.

Materials and Methods

Participants and Procedure

Forty-eight undergraduate and graduate students of Saarland University, 26 females and 22 males, mean age = 23.67 years (age range = 19–31 years), participated in this 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 €/h for their participation.

As shown in Figure 1, 16 participants were assigned to either the visual training group (mean age = 23.94 years, age range = 21–29), the auditory 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, $P = 0.59$, gender, χ^2 (1, n = 48) = 0.33, $P = 0.56$, fluid intelligence as assessed by a speeded version of the Bochumer Matrizentest (BOMAT) (Hossiep et al. 1999), $P = 0.75$, and working memory capacity as assessed by 2 verbal and 2 visuospatial span tasks which were adapted from Kane et al. (2004) (counting span: $P = 0.59$; reading span: $P = 0.70$; navigation span: $P = 0.63$; symmetry span: $P = 0.29$).

Before training all groups participated in an initial fMRI session. Both training groups received 8–10 training sessions within 2 weeks following the initial fMRI session on either a visual or auditory adaptive *n*-back task; the control group, however, did not receive any training. Mean number of training sessions did not differ between the visual, $M = 9.38$, standard deviation [SD] = 0.72, and the auditory training group, $M = 9.75$, SD = 0.58, $P = 0.11$. Mean spacing between one training session and the next indicated by the mean number of days was held equal between the groups (visual training: $M = 1.30$, SD = 0.11; auditory training: $M = 1.25$, SD = 0.10, $P = 0.30$). Four weeks after the initial fMRI session all participants took part in the fMRI posttest. The lag between the last training session and the fMRI posttest as indicated by the mean number of days was equal for the visual, $M = 15.44$, SD = 1.09, and auditory training group, $M = 15.44$, SD = 0.63, $P = 1.00$.

Tasks and Materials

Training Tasks

For the training tasks, we used an adaptive *n*-back paradigm, which was adapted from Jaeggi et al. (2008). 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 our paradigm, stimuli were presented sequentially at a rate of 3 s (stimulus length = 500 ms; interstimulus interval = 2500 ms). There were 6 targets per block with their positions determined randomly. To avoid nontargets that are most likely to distract the participants' attention, nontargets 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 nontarget 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 the 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 Fig. 2). Each training session started with the same level of $n = 1$ and comprised 40 blocks.

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. 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 8 stimuli was used to ensure effects were not due to highly familiar stimulus material and to prevent verbal or semantic recoding. 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 min per session. The training comprised 10 sessions which took place within a period of 2 weeks. The time lag between sessions was between 1 and 3 days. As not all participants completed the last 2 sessions, only the first 8 training sessions were entered into the analysis.

A repeated measures multivariate analysis of variance (MANOVA) (Pillai's trace) with the factors Group (visual vs. auditory training group) and Session (sessions 1–8) 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 and Thayer 1987) in all of the following MANOVAs (Pillai's trace) were computed.

Pretest and Posttest Tasks

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 pretest and posttest. 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 pretest 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,

Figure 1. Schematic description of the experimental design. All 3 groups performed the same visual 2-back task and a 0-back control task in the pretest and posttest fMRI session. During the training interval, the visual training group was trained on an adaptive *n*-back task using visual stimuli, the auditory training group was trained on the same task using auditory stimuli, whereas the control group did not receive any training.
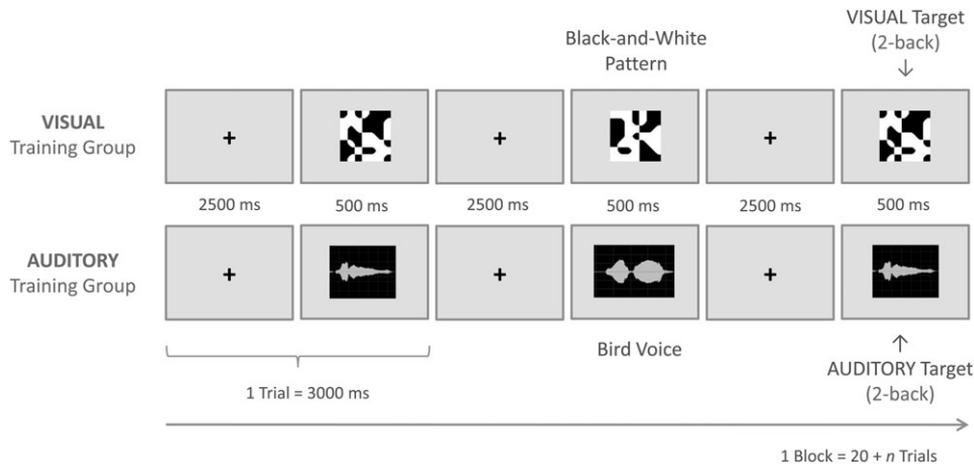
Figure 2. Schematic description of the visual and auditory adaptive *n*-back task during training, illustrated for a 2-back condition. The visual training group trained with black-and-white pattern stimuli, whereas the auditory training group trained with bird voice stimuli.

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 5 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.

A 2-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 and Corwin 1988) as dependent variable. 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.

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

fMRI Acquisition and Analyses

An event-related design with 2 repetitions was performed on a 1.5 T scanner (Magnetom Sonata, Siemens Medical Systems). 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 by using a vacuum pillow. Responses were collected via 2-button response grips. A T_2^*-weighted gradient-echo planar imaging sequence was used for fMRI scans (matrix: 64, field of view = 224 mm, in-plane resolution = 3.5 × 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 contiguous axial slices were acquired parallel to AC–PC line covering the whole brain. 300 volumes were acquired per run. An intra-session high-resolution structural scan was acquired using a T_1-weighted 3D magnetization prepared rapid gradient echo (1 mm^3 voxel size).

The functional imaging data were analyzed using BrainVoyager QX (Brain Innovation; Goebel et al. 2006). The first 4 volumes of each subject's functional data set were discarded to allow for T_1 equilibration. For the remaining 296 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 full-width at half-maximum). The data were high-pass filtered at 3 cycles. Functional slices were coregistered 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 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 (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 nontargets) were included in the analysis. Thus, the resulting GLM contained 8 parameters of interest per subject: visual 2-back and visual 0-back for each of the pretest 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 versus 0-back pretest. The results from this whole-brain analysis resulted in % signal change images thresholded at *P* < .01 (false discovery rate [FDR] corrected) using clusters determined by the number of functional voxels > 15. In a second analysis, we defined functional volumes of interest (VOIs) 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 versus auditory training group for intra-modal and collapsed across training groups versus 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 and 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 pretest 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 et al. 1998). To investigate this possibility in our data, we additionally examined the voxel-based statistical parameter map for the posttest contrast: 2-back posttest versus 0-back posttest. Analogously to the pretest analysis, % signal change images were thresholded at FDR < 0.01 using clusters determined by the number of functional voxels > 15.

Results

Behavioral Results

Performance increases of the *n*-back task during training (mean level of *n* in each session) are shown in Figure 3*a*. The repeated measures MANOVA (Group × Session) revealed that both
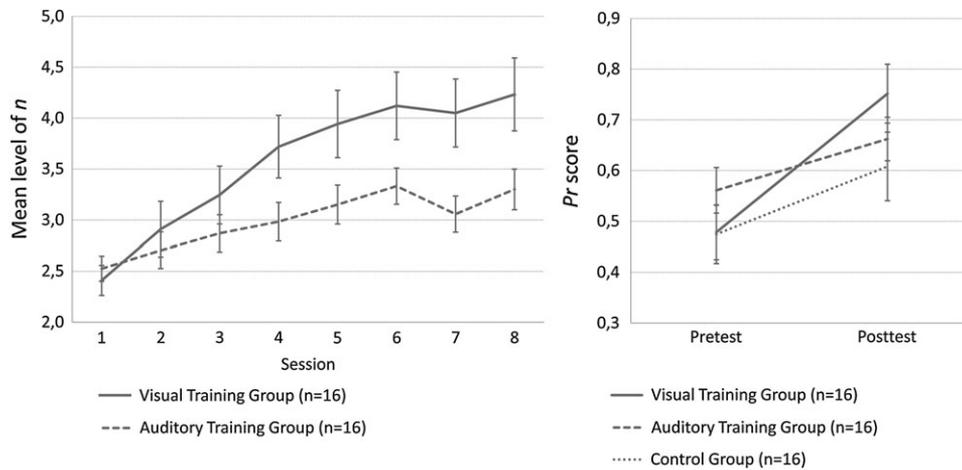
Figure 3. (*a*) Performance increases in the *n*-back task shown for the visual and the auditory training group. The mean level of *n* as an indicator of the participants' mean performance for each session and corresponding standard errors of mean are shown. (*b*) Mean *Pr* scores and corresponding standard errors of the mean of the visual 2-back task for both training groups and the control group during pretest and posttest.

training groups improved their performance as indicated by a significant main effect of Session, $F_{7,24} = 11.58$, $P < 0.001$, $\eta_P^2 = 0.77$, and significant Session effects for both groups separately, visual training group: $F_{7,9} = 5.64$, $P < 0.01$, $\eta_P^2 = 0.81$, auditory training group: $F_{7,9} = 6.37$, $P < 0.01$, $\eta_P^2 = 0.83$. Although the visual and the auditory training group showed comparable performance levels in the beginning (collapsed across Sessions 1 and 2), $M = 2.66$ versus $M = 2.61$, $P = 0.86$, the Group by Session interaction approached significance, $F_{7,24} = 2.25$, $P < 0.10$, $\eta_P^2 = 0.40$. Post hoc analysis showed significant differences between the training groups at the end of training (collapsed across Sessions 7 and 8), $M = 4.14$ versus $M = 3.18$, $t_{1,30} = 2.48$, $P < 0.05$, suggesting a greater training effect for the visual than for the auditory training group.

The most interesting analysis in the light of our predictions concerns the improvements (training gains) measured in the visual 2-back task from pretest to posttest after intra-modal (visual) and across-modal (auditory) training. The corresponding results are shown in Figure 3*b*. The 2-way MANOVA with factors Time (pretest vs. posttest) and Group (visual training vs. auditory training vs. control group) revealed a main effect of Time, $F_{1,45} = 36.25$, $P < 0.001$, $\eta_P^2 = 0.45$ and a significant Group by Time interaction, $F_{2,45} = 3.52$, $P < 0.05$, $\eta_P^2 = 0.14$, indicating group-specific performance improvements.

The improvement from pretest to posttest was reliable for the visual training group, $F_{1,15} = 36.01$, $P < 0.001$, $\eta_P^2 = 0.71$, the control group, $F_{1,15} = 7.75$, $P < 0.05$, $\eta_P^2 = 0.34$, and marginally significant for the auditory group, $F_{1,15} = 3.73$, $P < 0.10$, $\eta_P^2 = 0.20$. Importantly, in 2 separate MANOVAs, the Group by Time interaction was significant for the visual training versus control group, $F_{1,30} = 4.44$, $P < 0.05$, $\eta_P^2 = 0.13$, but not for the auditory training versus control group, $P = 0.65$. So the interaction of the initial 2-way MANOVA reflects a larger training gain after visual training which is also indicated by a considerably greater effect size compared with those of the auditory and control group.

Brain Imaging Results

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 left and right parietooccipital cortex and in the left and right dorsolateral

Table 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**	**59 940**	**−39**	**−46**	**40**
[1]	IPS anterior	40	L	12.557	13 255	−39	−46	40
[2]		40	R	12.154	13 465	39	−43	40
[3]	IPS posterior	7	L	11.777	14 082	−33	−58	37
[4]		7	R	10.152	11 644	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**	**44 878**	**24**	**−4**	**61**
[8]	MFG	6	R	11.257	6755	24	−4	61
[9]	MFG	9	R	9.696	12 241	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**	**44 208**	**−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**

Note: H, hemisphere; L, left; R, right; IPS, intraparietal sulcus; SOG, superior occipital gyrus; MFG, middle frontal gyrus; SFG, superior frontal gyrus; PrCG, precentral gyrus. Clusters are listed based on cluster peak coordinates (in bold) and are more than 15 contiguous voxels surviving a threshold of 0.01 (FDR corrected). Local maxima within these clusters on which VOIs were defined (see Materials and Methods) 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.

PFC and also in the left fusiform gyrus, left and right cerebellum, right thalamus, and left caudate nucleus (for a list of peak cluster coordinates and local maxima coordinates, see Table 1).

With respect to the second analyses (VOI analyses), the main interactions of interest were Group (visual vs. auditory) by Time (pretest vs. posttest) as these interactions reveal differential pre–posttest activity changes in the visual and auditory groups. Significant Group by Time interactions were found in the right middle frontal gyrus (Brodmann's area [BA] 9) [9] (Numbers in square brackets refer to numbers of the

VOIs as indexed in Table 1.), $F_{1,30} = 4.84$, $P < 0.05$, $\eta_P^2 = 0.14$ and marginally significant in the anterior part of the right middle frontal gyrus (BA 9/46) [10], $F_{1,30} = 2.89$, $P < 0.10$, $\eta_P^2 = 0.09$ (see Fig. 4, left panel). Post hoc analyses revealed that these interactions resulted from a significant reduction in activity from pretest to posttest for the visual training group, BA 9 [9]: $F_{1,15} = 16.04$, $P < 0.001$, $\eta_P^2 = 0.63$; BA 9/46 [10]: $F_{1,15} = 12.37$, $P < 0.01$, $\eta_P^2 = 0.45$, whereas this was not the case for the auditory training group, BA 9: $P = 0.27$, BA 9/46, $P = 0.18$.

Moreover, most of the VOIs in this analysis showed main effects of Time (pretest vs. posttest): banks of the right and left intraparietal sulcus (BA 40) [1 and 2], $F_{1,30} = 11.74$, $P < 0.01$, $\eta_P^2 = 0.28$, $F_{1,30} = 9.86$, $P < 0.01$, $\eta_P^2 = 0.25$, right superior medial frontal gyrus (BA 6) [8], $F_{1,30} = 11.86$, $P < 0.01$, $\eta_P^2 = 0.28$, right middle frontal gyrus (BA 9) [9], $F_{1,30} = 12.76$, $P < 0.001$, $\eta_P^2 = 0.30$, right middle frontal gyrus (BA 9/46) [10], $F_{1,30} = 16.02$, $P < 0.001$, $\eta_P^2 = 0.35$, left middle frontal gyrus (BA 6) [13], $F_{1,30} = 6.81$, $P < 0.05$, $\eta_P^2 = 0.19$, and left medial superior frontal gyrus (BA 6) [14], $F_{1,30} = 5.90$, $P < 0.05$, $\eta_P^2 = 0.16$. 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 we 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. We performed repeated measure MANOVAs with factors Group (collapsed across trained groups vs. control group) and Time (pretest vs. posttest). These analyses revealed interactions in the banks of the right intraparietal sulcus (BA 40) [2], $F_{1,46} = 4.83$, $P < 0.05$, $\eta_P^2 = 0.10$ and the right superior middle frontal gyrus (BA 6) [8], $F_{1,46} = 4.18$, $P < 0.05$, $\eta_P^2 = 0.08$, (see Fig. 4, right panel). The interactions resulted from reductions in activity for the 2 training groups, BA 40 [2]: $F_{1,31} = 12.04$, $P < 0.01$, $\eta_P^2 = 0.28$; BA 6 [8]: $F_{1,31} = 12.10$, $P < 0.01$, $\eta_P^2 = 0.28$, while activations for the control group remained stable over time, BA 40 [2]: $P = 0.90$; BA 6 [8]: $P = 0.76$.

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 parietooccipital cortex and in the left and right dorsolateral PFC and the left and right cerebellum (for a list of peak cluster coordinates and local maxima coordinates, see Table 2). 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.

Discussion

The first aim of this study was to investigate whether working memory for visual materials can be trained by means of a visual
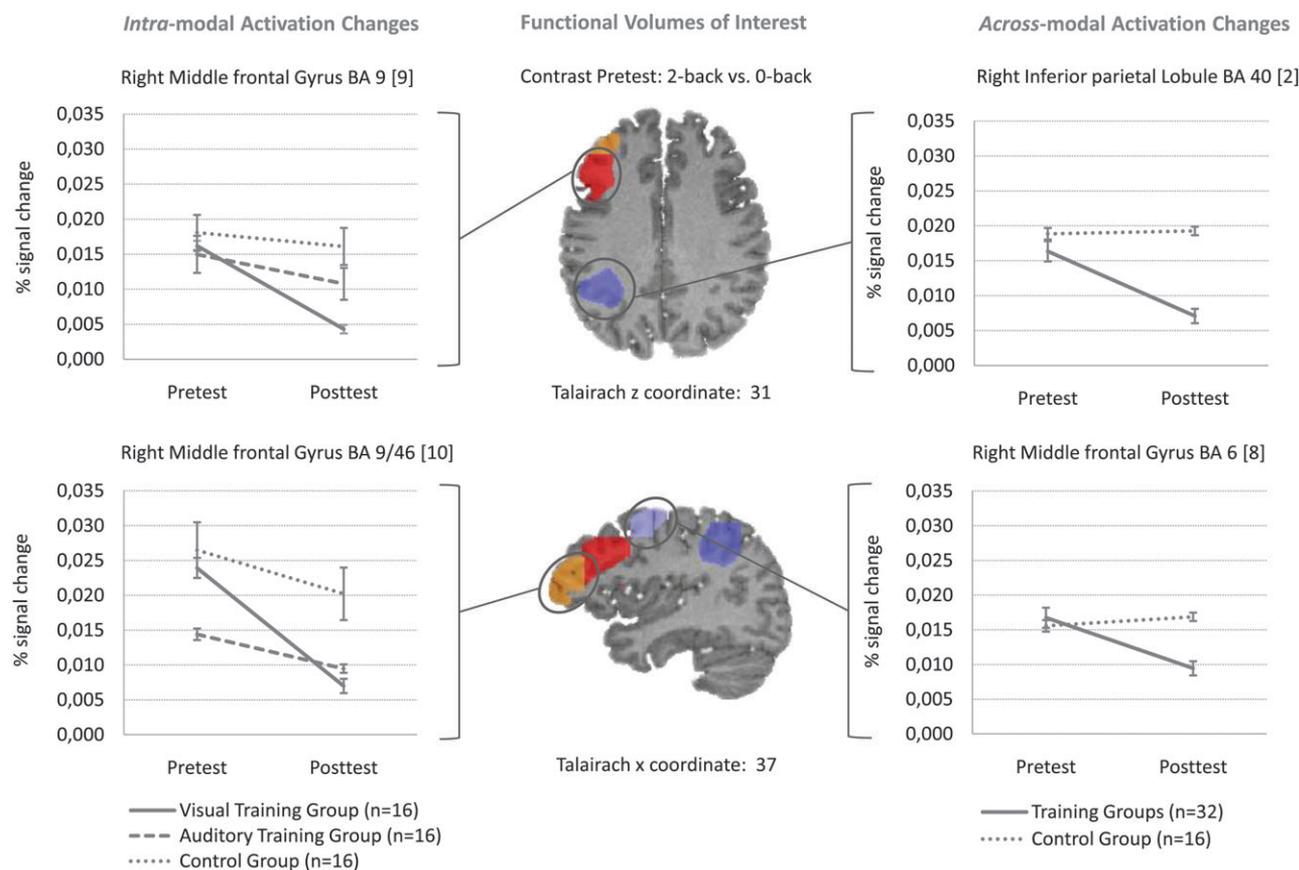

Figure 4. Intra-modal and across-modal training-related activation changes during performance of a visual 2-back task. Percentage signal change values of functional volumes of interests are shown for the visual versus auditory training groups (right middle frontal gyrus at BA 9 [9], right middle frontal gyrus at BA 9/46 [10]) in the left panel and for both training groups (collapsed) versus the control group (right inferior parietal sulcus at BA 40 [2], right middle frontal gyrus at BA 6 [8]) in the right panel. Numbers in square brackets refer to numbers of the VOIs as indexed in Table 1.

Table 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**	**44 828**	**−30**	**−64**	**43**
[1]	IPS anterior	40	L	5.464	5119	−42	−38	34
[2]		40	R	9.134	10 241	36	−46	43
[3]	Precuneus	19	L	10.382	11 001	−30	−64	43
[4]		7	R	8.140	10 130	18	−76	43
	MFG	**9**	**R**	**6.948**	**10 763**	**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**	**14 892**	**−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

Note: H, hemisphere; L, left; R, right; 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 0.01 (FDR corrected). Local maxima within these clusters on which VOIs were defined (see Materials and Methods) 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.

n-back task and whether this training results in activation changes of underlying brain networks. Second, we examined the extent to which those training effects in visual working memory are intra-modal or across-modal, that is, can also be obtained by means of cross-modal (auditory) working memory training.

We found training-induced performance increases in the trained tasks for both training groups which allowed us to compare the impact of the 2 training effects on performance in the visual 2-back task. Our results indicated that 1) training of the visual n-back task was accompanied by a greater training gain in the visual 2-back task compared with auditory training and no training, 2) Blood oxygen level–dependent activity within the right middle frontal gyrus (BA 9 and BA 9/46) decreased after the visual training only, whereas 3) both trainings lead to decreased activation in the superior right middle frontal gyrus (BA 6) and posterior parietal region (BA 40) as compared with the control group.

Several conclusions can be drawn from these results. 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 (Smith and Jonides 1997; Protzner and McIntosh 2007).

An objection against this interpretation could be that the greater training gain in the visual 2-back task from pretest to posttest after visual training 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, we selected 2 training groups of n = 10 participants each, which were matched according to their training effects, that is, 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 2 groups, $t_{1,18} = 1.13$, $P > 0.05$. Paired-sample t-tests revealed that the visual training group showed a performance increase from pretest to posttest, $t_{1,9} = 3.75$, $P < 0.01$, whereas this was not the case for the auditory training group, $t_{1,9} = 1.79$, $P > 0.05$. We performed equivalent post hoc analyses on activation changes in the right middle frontal gyrus for the subgroups equated for training gains to make sure that these activation decreases did not arise from differences in training gain. Paired-sample t-tests comparing pretest and posttest parameter estimates yielded significant activation decreases for the visual training group in both VOIs in the right middle frontal gyrus, BA 9: $t_{1,9} = 2.99$, $P < 0.05$, BA 9/46: $t_{1,9} = 3.55$, $P < 0.01$, while changes for the auditory training group did not reach significance, BA 9: $t_{1,9} = 1.66$, $P > 0.05$, BA 9/46: $t_{1,9} = 1.99$, $P > 0.05$. 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.

An explanation for the different training effects between the visual and auditory training group can be derived from the study by Jaeggi et al. (2010) that reports a greater dropdown of performance in the auditory n-back task compared with 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. If indeed so, 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 pretest 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 (Mahnke et al. 2006; Smith et al. 2009; Jolles et al. 2010; Owen et al. 2010) as well as in other training studies (Karbach and Kray 2009; Zeidan et al. 2010). In an attempt to specify how

repetition determines skill learning in mirror-reading, Ofen-Noy et al. (2003) 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.

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

The intra-modal activation decreases after visual training in the 2 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 with locations in high load conditions. Moreover, Protzner and McIntosh (2007) found that the right middle frontal gyrus showed greater activation for visual noise burst stimuli compared with 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 2 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 a general framework of functional plasticity as suggested by Kelly and Garavan (2005) (see also Poldrack 2000). In an effort to provide a taxonomy for training-related changes in neural activation patterns, they suggest a distinction between redistribution and true 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 frontoparietal working memory network mentioned above. 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. According to this 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 provide evidence for across-modal training effects at the neural level, that is, 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 and 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, that is, 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 our 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 nth 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 (for similar arguments, see Olesen et al. 2004; Sayala et al. 2006). 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.

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., Garavan et al. 2000; Landau et al. 2004; Olesen et al. 2004; 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.

In sum, behavioral as well as brain imaging results corroborate the hypothesis that intra-modal training of visual working memory is possible. To our 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 2 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.

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Notes

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