Effect of Language Switching on Arithmetic: A Bilingual fMRI Study

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Abstract

■ The role of language in performing numerical computations has been a topic of special interest in cognition. The "Triple Code Model" proposes the existence of a language-dependent verbal code involved in retrieving arithmetic facts related to addition and multiplication, and a language-independent analog magnitude code subserving tasks such as number comparison and estimation. Neuroimaging studies have shown dissociation between dependence of arithmetic computations involving exact and approximate processing on language-related circuits. However, a direct manipulation of language using different arithmetic tasks is necessary to assess the role of language in forming arithmetic representations and in solving problems in different languages. In the present study, 20 English–Chinese bilinguals were trained in two unfamiliar arithmetic tasks in one language and scanned using fMRI on the same problems in both languages (English and Chinese). For the exact "base-7 addition" task, language switching effects were found in the left inferior frontal gyrus (LIFG) and left inferior parietal lobule extending to the angular gyrus. In the approximate "percentage estimation" task, language switching effects were found predominantly in the bilateral posterior intraparietal sulcus and LIFG, slightly dorsal to the LIFG activation seen for the base-7 addition task. These results considerably strengthen the notion that exact processing relies on verbal and language-related networks, whereas approximate processing engages parietal circuits typically involved in magnitude-related processing. ■

INTRODUCTION

The extent to which numerical cognition is dependent on language has been a topic of considerable debate in cognitive science and linguistics (Gelman & Gallistel, 2004; Wiese, 2003). According to the "Triple Code Model" (Dehaene & Cohen, 1995, 1997), the verbal code facilitates the encoding and retrieval of stored arithmetic facts especially involving addition and multiplication and is thought to reside in the language-related left inferior frontal regions of the brain. In contrast, the analog magnitude code provides access to semantic knowledge about numerical quantities and is thought to reside in the inferior parietal lobes bilaterally. This distinction between the analog magnitude and the verbal code has led to the suggestion that adult numerical cognition is subserved by two representational systems: an exact language-dependent system and an approximate nonverbal system of number representation (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999).

Several lesion and imaging studies support a distinction between a language-dependent verbal code for exact arithmetic processing and a language-independent analog magnitude code for the approximate processing (see Dehaene, Piazza, Pinel, & Cohen, 2003, for a complete review). Patients with cortical and subcortical lesions in left frontal areas were unable to perform exact calculations such as multiplication, but did not exhibit significant difficulties in magnitude comparison, estimation, and subitizing (Lemer, Dehaene, Spelke, & Cohen, 2003; Dehaene & Cohen, 1997). In contrast, two separate studies found that patients with damage to areas within the inferior parietal lobe were proficient at performing exact numerical computations involving rote retrieval but had striking deficits in their ability to perform tasks requiring a representation of numerical quantity (Dehaene & Cohen, 1997; Delazer & Benke, 1997).

Several behavioral studies on normal adults have also sought to characterize the effect of language on exact and approximate processing of numbers (Gordon, 2004; Pica, Lemer, Izard, & Dehaene, 2004; Spelke & Tsivkin, 2001; Dehaene, Spelke, et al., 1999). Two recent, independently conducted studies of indigenous people in the Brazilian Amazon investigated the relationship between language and numerical processing by evaluating arithmetic competence in languages with only a limited vocabulary for numbers (Gordon, 2004; Pica et al., 2004). One study involved members of the Piraha tribe who use an impoverished counting system that consists

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of only words for numbers 1 and 2, and a second study involved speakers of Munduruku, a language that lacks words for numerosities greater than 5. Members of the Piraha community were limited in their ability to enumerate exact quantities when set sizes exceed 2 but were able to perform approximate number processing. This supports the notion that the analog magnitude representation is independent of language (Gordon, 2004). Similarly, Munduruku subjects were able to compare and approximately add large numbers that are outside of their verbal count sequence, but failed in exact arithmetic with numbers larger than 4 (Pica et al., 2004). Thus, individuals from both Amazonian groups were unable to perform exact calculation, but exhibited normal approximate number processing. These data suggest that the lack of a linguistically encoded count sequence prevents the acquisition of exact number processing competencies.

In another study looking at the relationship between arithmetic function and working memory using a dual-task paradigm, a phonological dual task had a suppressive effect on the performance of multiplication, but not on subtraction, whereas a visuospatial dual task had a negative influence on subtraction, but not on multiplication (Lee & Kang, 2002). These results indicate that multiplication is closely linked to the phonological loop and subtraction to the visuospatial sketchpad, providing further support for the differential routes for arithmetic processing.

The role of language in the formation of arithmetic representations has also been assessed by training bilingual subjects in one language and testing them on the trained problems using a different language. Studies with Russian–English bilinguals showed that subjects solved exact arithmetic problems faster in the language used during training independent of whether that language was English or Russian (Spelke & Tsivkin, 2001; Dehaene, Spelke, et al., 1999). This finding suggests that facts acquired during training were stored in a language-specific format and that the arithmetical skill did not transfer readily to a different language. In contrast, subjects performed approximate calculations with equal efficiency in both the trained and untrained languages, and their training on approximate problems generalized to new problems of the same type. In other words, the time taken for performing approximate problems in both trained and untrained languages as well as novel problems of the same kind in the trained language was similar, suggesting that switching languages neither impairs nor facilitates the ability to approximate.

The evidence reviewed suggests that language plays a crucial role in certain aspects of calculation but not others. Functional neuroimaging studies have also provided important insights into the role language may play in numerical cognition. In a study examining the neural correlates of exact and approximate calculation using functional magnetic resonance imaging (fMRI), participants performed both exact and approximate simple addition (Dehaene, Spelke, et al., 1999). Although exact addition elicited greater activation in left frontal areas and the angular gyrus (AG), approximate addition resulted in greater activation in the inferior parietal lobules, bilaterally. The greater activation of the left AG and left inferior frontal areas for exact calculations led the authors to hypothesize that exact calculation is dependent on language processing, as these cortical areas are typically implicated in the processing of linguistic information. Another study using fMRI has also implicated the involvement of the left AG and supramarginal gyrus in solving well-learned arithmetic tasks such as multiplication relative to subtraction (Lee, 2000). Notwithstanding, the dissociation between exact and approximate addition for simple mental arithmetic has not always been replicated (Venkatraman, Ansari, & Chee, 2005; Pesenti, Thioux, Seron, De Volder, 2000).

Several other functional imaging studies have suggested that cortical areas commonly associated with language functions are activated during mental arithmetic involving rote retrieval of well-learned facts (Gruber, Indefrey, Steinmetz, & Kleinschmidt, 2001; Stanescu-Cosson et al., 2000). In the only imaging study looking at the neural correlates underlying arithmetic learning (Delazer et al., 2003), participants were trained extensively in a set of multiplication problems. A subsequent fMRI session, involving both trained and untrained problems, revealed greater activation in the left intraparietal sulcus (IPS) and the left inferior frontal gyrus (LIFG) for untrained compared to trained problems. The left IPS activation suggested that calculation was more quantity-based and less automatic in the untrained condition, whereas the activation in the LIFG may have been due to the greater working memory demands of untrained problems. Trained problems elicited greater activation in the left AG. This could be a result of a shift of activation from quantity-based representations in the IPS to more automatic retrieval supported by the left AG. Alternatively, this could have resulted from the use of a verbal strategy that recruited the AG as a result of phonological processing. In either case, the findings support the notion that the AG is involved in the processing of well-rehearsed arithmetic facts (Dehaene, Spelke, et al., 1999).

The observation that language-related neural circuits are activated during exact calculation, although important, represents an indirect proof of a dependence of exact calculation on language processing. Only through the direct experimental manipulation of language can this inferred relationship and its neural correlates be ratified. With this in mind, the present study directly manipulated language in order to study its effects on exact and approximate arithmetic processing. To reduce the likelihood of prior mathematical instruction biasing our findings, we identified two tasks that are neither commonly taught in school nor used in everyday life:

base-7 addition task involving exact arithmetic and a percentage value estimation task involving approximations. Our subjects were English–Chinese bilinguals and we used English and Chinese as the two languages in this study. A Language-by-Problem type crossover design was used. In this design, each participant was trained in both tasks and the language of training differed between tasks, such that half of the participants were trained on the approximate task in English and the exact task in Chinese and the other half were trained in the approximate task in Chinese and the exact task in English. All subjects were tested in both tasks and in both languages during the scanning session so as to provide a counterbalanced mix of test problems involving switching from the language of training to untrained language across both languages.

For the base-7 exact addition task, we predicted that participants would acquire new rules for performing exact calculation, leading to the engagement of verbal processing. Against this background, two possible scenarios for the involvement of cortical areas typically involved in language processing, such as the LIFG and the left AG, are possible. If language-related cortical circuits are important in the encoding of exact addition facts into a verbal language-specific format, we would expect that these cortical areas would exhibit greater activation in the untrained compared with the trained language condition. If, however, language-related cortical areas function primarily as the final repository of exact arithmetic facts, then we would anticipate their involvement to be greatest during direct retrieval, and thus, to exhibit the greatest activation for the trained language.

For the approximate estimation problems, we predicted that the representations underlying the processing of these problems would be largely language-independent, and thus, would not recruit cortical areas typically involved in language processing. We further predicted that subjects would rely on nonverbal strategies using magnitude representation of numbers and therefore recruit areas in and around the bilateral intraparietal sulci. Finally, we expected that language switching in the course of solving the approximate problems would recruit neural circuits involved in visuospatial attention, because participants need to map the novel surface characteristics (problems presented in the untrained language) onto the semantic representations of numerical magnitude to solve the problems.

RESULTS

Behavioral Results (Training)

As the format of training and timing constraints varied for every session, it was not possible to perform a systematic analysis on the reaction time training data. Nevertheless, some trends in the accuracy data bear mention. For both tasks, accuracy improved with training except on Day 3 when a drop in accuracy can be attributed to the timing constraints imposed on the problems for the first time. By Day 5, all subjects had reached a high level of accuracy.

Behavioral Results (Scanning Session)

Reaction time and accuracy data collected during the scanning session were analyzed in order to probe main effects of language switching (untrained vs. trained language) and type of calculation (exact and approximate) as well as their interaction across both language groups combined. A two-way repeated-measures ANOVA was computed. Analysis of the reaction time data revealed a significant main effect of training [$F(1,19) = 5.5$, $p < .05$], as well as a main effect of the type of calculation [$F(1,19) = 15.3$, $p < .001$]. There was no significant interaction of training and type of calculation. Analysis of the accuracy data acquired during the scanning session revealed only a main effect of calculation [$F(1,19) = 5.38$, $p < .032$] with no significant main effect of training or Calculation × Training interaction. Therefore, for both calculation conditions, reaction times were faster for trained relative to untrained languages but there was no significant difference in accuracy. However, the approximate task was significantly slower and less accurate compared to the exact task (Table 1).

Functional Imaging

The main objective of this study was to evaluate regions underlying language-switching in the base-7 and percentage calculation tasks. Prior to evaluating language switching effects, we identified regions that were activated in both the trained and untrained conditions using a two-way conjunction of the conditions versus baseline for each of the tasks.

Table 1. Mean and Standard Deviation of Accuracy and Response Times for Each of the Experimental Tasks during the fMRI Session

	Reaction Time Data		*Accuracy Data*	
Experimental Task	*Reaction Time (msec)*	*Standard Error*	*Accuracy (% correct)*	*Standard Error*
Exact trained	796	34	92.85	1.1
Exact untrained	835	37	91.80	1.6
Approximate trained	888	38	91.20	1.0
Approximate untrained	938	38	89.30	1.5

For the base-7 addition task, conjunction analysis revealed activation in the bilateral IFG, the bilateral horizontal segment of the IPS, the posterior segment of the IPS, the fusiform gyrus, the lingual gyrus, the thalamus, the left inferior parietal lobule, the medial aspect of the superior frontal gyrus, and right insular regions (Table 2). Deactivation was observed in the bilateral AG, the medial prefrontal cortex, and posterior cingulate regions.

The conjunction of trained and untrained conditions for the percentage estimation task revealed activation in the bilateral horizontal segment of the IPS, the inferior frontal gyrus, the posterior segment of IPS, the fusiform gyrus, the lingual gyrus, the thalamus, the left inferior parietal lobule, and right insular regions (Table 2). Deactivation was observed in the bilateral AG, the anterior medial prefrontal cortex, and posterior cingulate regions.

A language switching effect for base-7 addition task was observed in the bilateral inferior frontal lobules, the left inferior parietal lobule extending to the AG, and bilateral fusiform gyrus (Figure 1, Table 3). We also observed significantly greater deactivation for the trained problems compared to untrained problems in the bilateral AG. None of these regions showed a significant Group × Training interaction when analyzed using a two-way ANOVA.

A language switching effect for the percentage calculation task was observed bilaterally in the parietal lobules along the posterior banks of the IPS, the LIFG, the right fusiform gyrus, as well as the left posterior fusiform gyrus (Figure 2, Table 3). As can be seen from Figure 2, the left inferior frontal activation for approximate language switching effect was more dorsal and nonoverlapping with the LIFG activation for exact language switching effect. All regions observed in these contrasts did not show a significant Group × Training effect when analyzed using a two-way ANOVA, indicating that these activations were consistent across both groups and not driven by any one group in particular.

DISCUSSION

Several studies of arithmetic processing have inferred the involvement of language in exact number processing

Table 2. Talairach Coordinates of Activation Peaks Obtained from the Conjunction of Trained and Untrained Problems for the Base-7 Addition Task and Percentage Estimation Task Using Random-Effect Analysis at $p < .005$, Corrected

	Base-7 Addition Task								*Percentage Estimation Task*							
	Left Hemisphere				*Right Hemisphere*				*Left Hemisphere*				*Right Hemisphere*			
	x	*y*	*z*	*t(19)*	*x*	*y*	*z*	*t(19)*	*x*	*y*	*z*	*t(19)*	*x*	*y*	*z*	*t(19)*
Activations																
Inferior Frontal Gyrus	−42	5	34	15.06	48	8	28	9.07	−38	5	31	17.73	48	8	31	8.44
Superior Frontal Gyrus	−6	8	49	13.14	–	–	–		−6	11	49	14.85				
Middle Frontal Gyrus	−30	−4	58	10.48	–	–	–		–	–	–		–	–	–	
Intraparietal Sulcus (IPS)	−27	−58	46	11.12	24	−64	43	11.92	−27	−58	40	13.01	24	−64	40	12.44
Posterior IPS	−27	−64	31	15.02	27	−67	31	9.07	−24	−64	31	14.68	27	−67	31	9.86
Inferior Parietal Lobule	−45	−37	46	9.27	–	–	–		−45	−34	43	11.66	–	–	–	
Anterior Insula	–	–	–		31	7	10	10.49	–	–	–		30	17	10	10.17
Thalamus	−18	−16	19	12.22	18	−16	22	10.99	−21	−22	1	11.38	21	−25	1	10.98
Mid Fusiform Gyrus	−45	−58	−12	13.73	39	−52	−14	13.84	−42	−58	−11	17.84	42	−55	−11	11.05
Posterior Fusiform Gyrus	−39	−70	−12	14.42	34	−73	−11	11.98	−36	−67	−12	17.33	33	−73	−12	14.93
Lingual Gyrus	−21	−88	1	17.32	17	−86	−2	11.54	−15	−88	−2	18.92	18	−82	−5	15.43
Deactivations																
Angular Gyrus	−48	−52	25	−11.31	48	−52	22	−13.42	−55	−52	25	−15.54	55	−52	29	−13.28
Posterior Cingulate	−9	−43	37	−15.87	–	–	–		−9	−44	37	−11.95	9	−43	49	−14.25
Medial Prefrontal	−6	35	−6	−11.91	–	–	–		−6	20	0	−14.95	–	–	–	
Superior Temporal Gyrus	−53	−10	−2	−10.29	–	–	–		–	–	–		–	–	–	
Middle Temporal Gyrus	−45	9	−14	−11.30	48	−6	−14	−11.05	−42	−1	−8	−9.62	51	−5	−8	−12.15

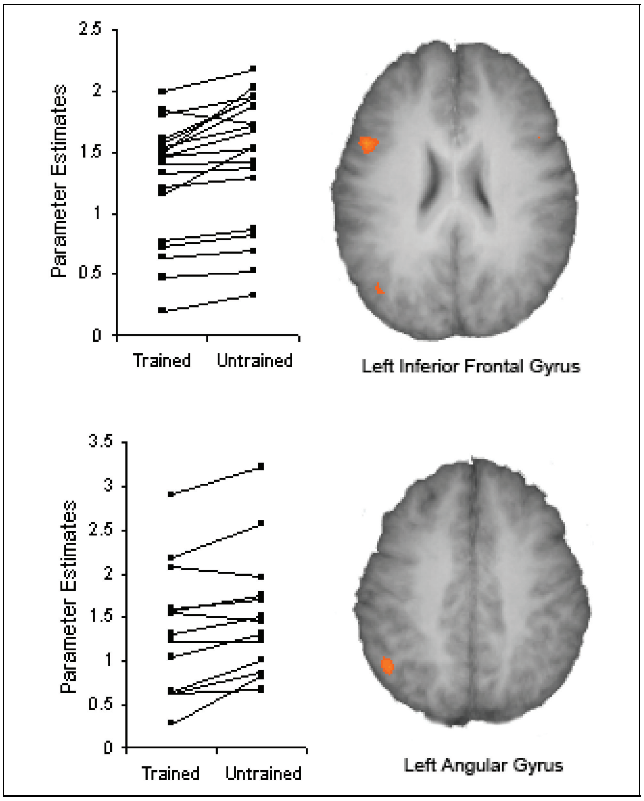

Figure 1. Axial slices of regions showing language switching effect for the base-7 addition task. The line plots show individual BOLD signal change for the trained and untrained problems.

from the activation of language-related circuits. The present study is the first to directly manipulate language to study its effects on two different arithmetic tasks: a base-7 addition task that requires exact processing and a percentage estimation task that engages approximate number processing. Although we did not find an interaction between the language switching effects on the two tasks behaviorally, dissociable frontal and parietal neural circuits were revealed for language switching from trained to untrained condition in each of the tasks, respectively. For the base-7 addition task, greater activation was found in the language-related areas of the brain for switching from trained to untrained language. In the percentage estimation task, greater activation was observed in the bilateral posterior parietal cortex, a region typically involved in visuospatial attention and nonverbal processing.

Behavioral Findings

Reaction time data showed a significant main effect of training with subjects being faster in trained problems compared to untrained problems as expected. We also found a significant main effect of task with subjects taking less time to solve the base-7 addition problems compared to percentage estimation, suggesting that the latter probably required slightly greater processing demands. The shorter time taken for base-7 addition task could be due to the fact that the subjects had the answer

Table 3. Talairach Coordinates of the Activation Peaks Showing Language Switching Effects for Both the Base-7 Addition as well as Percentage Estimation Task Using Random-Effect Analysis at $p < .005$, Uncorrected

	Talairach Coordinates							
	Left Hemisphere				*Right Hemisphere*			
Brain Region	*x*	*y*	*z*	*t(19)*	*x*	*y*	*z*	*t(19)*
Exact Training Effect								
Inferior Frontal Gyrus (BA 44)	−46	10	24	5.16	44	10	27	4.14
Inferior Parietal Lobule (BA 40)	−43	−56	39	4.65	–	–	–	
Precuneus (BA 7)	−21	−73	43	3.60	–	–	–	
Fusiform Gyrus (BA 37)	−43	−56	−13	3.87	32	−41	−18	5.18
Angular Gyrus (BA 7) [Deactivations]	−40	−68	24	3.93	38	−64	24	3.62
Approximate Training Effect								
Posterior Intraparietal Sulcus	−28	−74	30	4.85	29	−68	30	4.49
Precuneus (BA 7)	−26	−65	39	3.52	20	−74	33	3.68
Inferior Frontal Gyrus (BA 44)	−56	16	24	4.55	–	–	–	
Posterior Fusiform Gyrus	−46	−71	−6	3.93	–	–	–	
Mid Fusiform Gyrus	–	–	–		53	−44	−6	3.88

retrieved and ready by the time the choices were presented and they had just to choose the appropriate answer from the two choices provided. For the percentage estimation task, we hypothesize that there is a need to decide between the two choices after they are presented and this could account for the longer reaction times. More interestingly, we did not find an interaction between the two tasks. Unlike previous behavioral data studies, we found a training effect even for the percentage calculation task involving approximate processing. The lack of similar training effect in approximate problems in previous studies (Spelke & Tsivkin, 2001) could be due to the inherent differences in the tasks: their approximate tasks involved only an unary operation (cube-root of a number), hence, could have been easier to process even when presented in an unfamiliar language unlike their exact processing tasks and our tasks which involve binary operations. This is also reflected in the fact that the subjects took considerably longer for solving the exact problems compared to approximate problems during training in their study. Our findings suggest that there was a benefit of training over five sessions in both the tasks and subjects found it easier in general to solve problems in the language of training compared to the unfamiliar language.

Regions Activated during Arithmetic Processing Independent of Task and Training

The base-7 addition as well as the percentage calculation task involved reading the problem presented in either language, performing numerical processing related to the task, and then choosing an appropriate answer among two given alternatives. Therefore, there were a number of regions that were activated consistently across both tasks for both trained and untrained problems. The activation in the IFG is consistent with a number of studies involving language processing (Binder, Frost, Hammeke, Cox, et al., 1997) as well as verbal and phonological working memory (Poldrack et al., 1999; Smith & Jonides, 1998). Within the parietal lobe, consistent activation was found in the bilateral anterior IPS as well as another more posterior region along the IPS. The activation in the anterior IPS was similar to the activation seen along the horizontal segment of the intraparietal sulcus (HIPS) in a number of other studies involving number processing (Dehaene, Piazza, et al., 2003). The activation in the posterior IPS has been associated with tasks involving saccades and eye movement (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). Given that both tasks required participants to read long sentences, it is likely that eye movements may have contributed to the observed posterior IPS activation.

The left occipital lobe and the posterior fusiform play a role in identifying the alphabetical strings and transmitting them to areas involved in number processing as well as retrieval of arithmetic facts, such as the IPS and the LIFG. The activation in the right fusiform region has been previously found in numerical tasks involving Arabic numerals (Pinel, Dehaene, Riviere, & LeBihan, 2001). Similar networks of posterior regions have been observed in numerous studies, particularly in tasks that involve reading and semantic processing (McCandliss, Cohen, & Dehaene, 2003). Because the stimuli in this study were presented as words, these regions might be involved in the conversion of visual orthographic codes into the appropriate semantic numerical codes for appropriate processing.

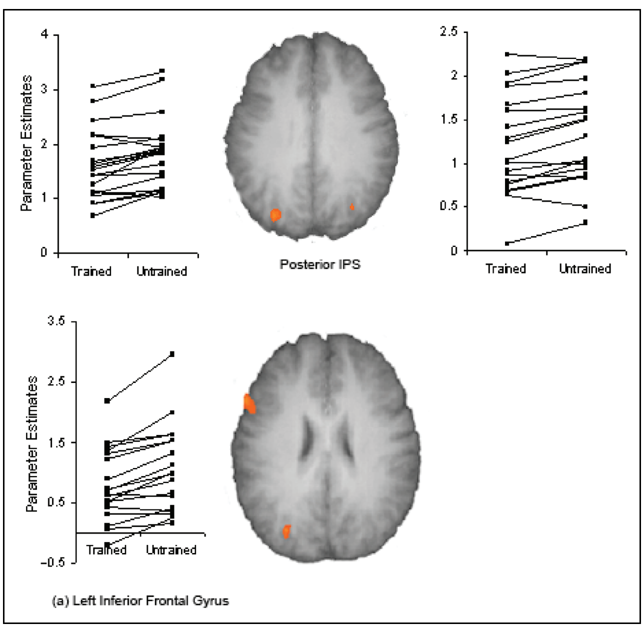

Figure 2. Axial slices of regions showing language switching effect for the percentage estimation task. The line plots show individual BOLD signal change for the trained and untrained problems.

Deactivation

Deactivation refers to a reduction in BOLD signal change during task performance relative to baseline. Several task-induced deactivations have been observed in functional imaging studies, although these are generally not discussed in detail due to complexities in interpretation (see Gusnard & Raichle, 2001, for a complete review). They can be attributed to specific physiological mechanisms that are incompletely understood at present. Although a number of studies have revealed consistent deactivations in a specific set of regions across a wide variety of tasks referred to as task-independent deactivations, some are task-induced and vary in location depending on the demands of the task. These task-induced deactivations can be particularly important in making significant inferences about the task at hand.

In this study, we also observed a number of deactivations across both tasks in both the trained and untrained conditions. However, the only region to show a task-related behavior was the left AG, which showed less deactivation for untrained compared to trained exact problems. Deactivation in the superior and middle temporal regions have also been observed in earlier studies involving arithmetic processing relative to rest, although their exact cause is still unclear (Zago et al., 2001). The deactivations in the rest of the areas, including the posterior cingulate, precuneus, and anterior prefrontal cortex, were task-independent. These regions have previously been shown to be attenuated during the performance of various goal-directed tasks relative to rest. The posterior cingulate and precuneus regions are involved in gathering information about the world around as well as within, whereas the medial prefrontal cortex is associated with spontaneous and task-related self-referential or introspectively originated mental activity (Gusnard & Raichle, 2001).

Language Switching Effect in Exact Arithmetic

The language switching effect for exact arithmetic was most prominent in the bilateral frontal regions and the left inferior parietal lobule. The greater frontal activity for untrained compared to trained problems is consistent with earlier findings which have linked similar activations to automaticity of arithmetic tasks, whereby less automatic tasks engage the region to a greater extent than more automatic ones (Pauli et al., 1994). The frontal activation was localized in the bilateral IFG (BA 44) whereas the activation in the left inferior parietal lobule extended to the AG. In a recent study, a similar frontal–parietal network was revealed in a phonological working memory experiment involving auditory words in an unfamiliar language (Chee, Soon, Lee, & Pallier, 2004). The present results suggest a greater involvement of language-related neural circuits during exact number processing. Particularly, the LIFG activation may be associated with the greater subvocal phonological rehearsal of the problem presented in the untrained language, which may result from an effort to translate the problem to the trained language so as to retrieve the answer by rote. The posterior parietal activations have been associated with the retrieval of phonologically coded verbal material in other studies (Jonides et al., 1998). This suggests that facts acquired during training of exact arithmetic are stored in the language of training and that this representation is accessed when participants are presented with the same problems in a different language. This hypothesis is further corroborated by the observation that about two-thirds of the participants indicated in the postscanning debriefing session that they tend to think in the language of training when solving the base-7 addition problems. Another way of interpreting these findings is that participants were storing the facts during training in a verbal format and needed to reorganize the verbal storage according to the new input during retrieval in the untrained conditions.

Among the several deactivations observed in this study, the only region to show a significant difference between conditions of interest was the bilateral AG which showed a greater decrease in BOLD signal when solving trained compared to untrained base-7 addition problems, suggesting that a greater inhibition of internal processes is necessary when solving trained problems. Deactivation in a similar region has been reported previously in paradigms involving semantic and language processing and has been attributed to disruption of tasks that are active during rest like internal speech (Binder, Frost, Hammeke, Bellgowan, et al., 1999). Even within numerical processing, similar deactivations in a region around the AG have been reported by earlier studies involving multiplication (Fulbright et al., 2000; Rickard et al., 2000; Dehaene, Tzourio, et al., 1996). Our results therefore suggest that there is a greater inhibition of the resting state verbal processes when performing the trained problems compared to untrained problems. This interpretation would also be consistent with previous training studies that have implicated a similar region in the AG for solving trained compared to untrained multiplication problems (Delazer et al., 2003).

Language Switching Effects in Approximate Arithmetic

Language switching effects for approximate percentage calculation task were predominantly seen in the bilateral posterior parietal areas and also in the left prefrontal cortex. The frontal activation was slightly dorsal and dissociable from the LIFG activation seen for exact arithmetic and a similar region has previously been associated with working memory tasks in a number of studies, specifically when manipulation of information held in working memory is required (D'Esposito, Postle, Ballard, & Lease, 1999). The parietal activation, extending along the IPS bilaterally, has been associated with solving problems involving approximate processing and subtraction, tasks that involve greater emphasis on quantity manipulation (Simon et al., 2002; Dehaene, Spelke, et al., 1999). Tasks which place higher demands on spatial attention and working memory have also been associated with activation along the IPS (Wojciulik & Kanwisher, 1999; Coull & Frith, 1998). Similar network of frontal–parietal regions was also found in another study involving complex mental calculations, providing evidence for the involvement of visuospatial representations in different levels of mental calculation (Zago et al., 2001). Therefore, the activation of these areas for language switching effect in the percentage estimation task suggests a greater emphasis on visuospatial and quantity manipulations when solving the problems in the untrained language.

The results in this study suggest a greater processing demand on visuospatial circuits during estimation and lesser activation of language-related neural circuits. This is convergent with existing behavioral findings that approximate representations are stored in a language-independent manner (Spelke & Tsivkin, 2001; Dehaene, Spelke, et al., 1999). However, contrary to earlier behavioral findings, our findings indicate that solving approximate problems in an untrained language still requires a greater effort. Although the solutions to problems in the trained language can be readily solved due to familiarity with the problem, some additional processing might still be required when the same problem is presented in a different language. We speculate that this additional processing involves converting the problems into an abstract language-independent code.

In our earlier study involving simple addition, we failed to find a dissociation between problems involving exact and approximate problems (Venkatraman et al., 2005). Although the present results appear on the surface to contradict those findings, there are several differences between the two studies which could explain the divergence in results. The previous study involved only simple addition problems and the same problems were solved both in an exact as well as approximate manner. We proposed that with simple problems, it is hard to inhibit retrieval of exact answer even for approximate problems. In the present study, however, the two tasks were substantially different and more complex than the simple addition task in our earlier study. Moreover, in this study, one task encouraged participants to learn novel calculation procedures by rote, whereas the other required magnitude processing. These differences, related to both task difficulty and nature of processing required by the tasks, might account for the differences between the findings reported here and those observed in the earlier study.

In summary, this study manipulated language in the context of numerical cognition. Consistent with the Triple Code Model, the results suggest that language switching has differential effects on exact and approximate number processing. Although language switching for exact calculation leads to greater engagement of fronto-parietal circuits typically involved in verbal processing, language switching for approximate processing invokes greater activation of posterior parietal areas typically associated with visuospatial processing. Future studies are required to further specify and characterize the nature of these differential effects by manipulating other stimulus variables such as numerical distance, carry operations, strategy choice, and the comparison of trained versus untrained problems.

METHODS

Participants

Twenty neurologically normal, right-handed English–Chinese bilinguals gave written consent to participate in this study and were selected provided they fulfilled criteria assessed through a questionnaire. All volunteers had been exposed to both English and Chinese before the age of 5 years and underwent at least 10 years of formal training in English and in Chinese, following a common syllabus. In general, English is the more dominant language in Singapore, hence, it is reasonable to expect our bilingual participants to be English-dominant. All participants scored excellent grades for English, Chinese, and mathematics in standardized high school examinations.

Training Procedure

Subjects were required to undergo five training sessions across 5 days for both the tasks—a base-7 exact addition task and an approximate percentage calculation task. The 20 subjects were randomly divided into two groups with one group performing the exact task in Chinese and the approximate task in English and the second group performing the exact task in English and the approximate task in Chinese. Instructions for a task were given in the language used to perform the task. For example, if the task was to be performed in Chinese, these were given in Chinese. The order of two tasks was alternated across the five training sessions.

For the base-7 addition task, the first lesson consisted of introduction to the base-7 representation as well as solving simple single-digit problems, whereas the second session consisted of single- and double-digit addition with no time constraint. From the third session, subjects were trained in problems used for the fMRI session. Subjects had to key in the exact answer to the problems provided for the first three sessions. They chose the correct answer from the two alternatives provided during the last two training sessions. Problems in all sessions were presented on a computer screen using Presentation 0.60 (Neurobehavioral Systems, Albany, CA, USA).

For the percentage calculation task, the emphasis for the first three sessions was to get subjects to estimate percentage value of a number and orient the result along an imaginary number line. To achieve this, participants were instructed to decide if the result of percentage calculation was greater or smaller than a given number. For the last two sessions, subjects chose the nearest answer from the two choices provided, similar to the fMRI session. The first two lessons consisted of simple calculations involving only the decades (e.g., 30% of 60). From the third lesson, subjects were trained in problems that were used in the final fMRI session.

For both tasks, the first, second, and fourth sessions had no time constraints for solving the problems. For the third session, subjects were given 4 sec to respond but they could control the pace of presentation of the problems. The timing for the final session was similar to the actual fMRI session.

Experimental Procedure (Scanning Session)

The fMRI experiment consisted of eight runs, four successive runs of the exact task and four successive runs of the approximate task. These were ordered in a counterbalanced manner. Each run started with a 24-sec rest period when the volunteer viewed a cross-hair, followed by four experimental blocks of 30 sec duration each alternating with rest period of 21 sec (Figure 3). The four experimental blocks consisted of two English and two Chinese blocks in an alternating manner, with the starting block counterbalanced across runs and subjects. The first four scans from the total of 74 acquisitions in each run were discarded to allow for steady-state magnetization.

Each experimental block consisted of six events of 5 sec each (Figure 3). In each event, a problem was presented for 2.5 sec followed by two choices for 2 sec. Participants then responded by pressing a button on a response box corresponding to the selected answer during the 2-sec interval. Finally, another 500 msec of fixation ensued before the presentation of the next problem. A total of 96 unique problems were used in the scanning session and the participants had an equal exposure to each of these problems across the 5 days of training.

Stimuli

The problems for the English tasks were presented as words in Times New Roman font. The Chinese problems were presented in Simhei font. All problems were presented in sentence format for both tasks in both English and Chinese. In general, the length of sentences was longer in English compared to Chinese. For the exact base-7 addition task, the operands ranged from one–one (smallest two-digit base-7 number) to four–six, with the result of addition also being a valid two-digit base-7 number. Operands with units digit zero (two–zero) were excluded as they are easier to add than the rest of the numbers. The two alternatives provided were the correct result and a number that was off by at least one and at most one–zero.

For the percentage estimation task, the value on which the percentage was calculated was always a multiple of 10 between 30 and 90. In contrast to the exact tasks, participants were instructed to perform the percentage estimations in the decimal (base-10) system. The percentage value itself was a two-digit integer greater than 20 and a nonmultiple of 5 or 10 as these are relatively easier to calculate. The alternatives were rounded to the nearest integer, and the mean distance of the correct

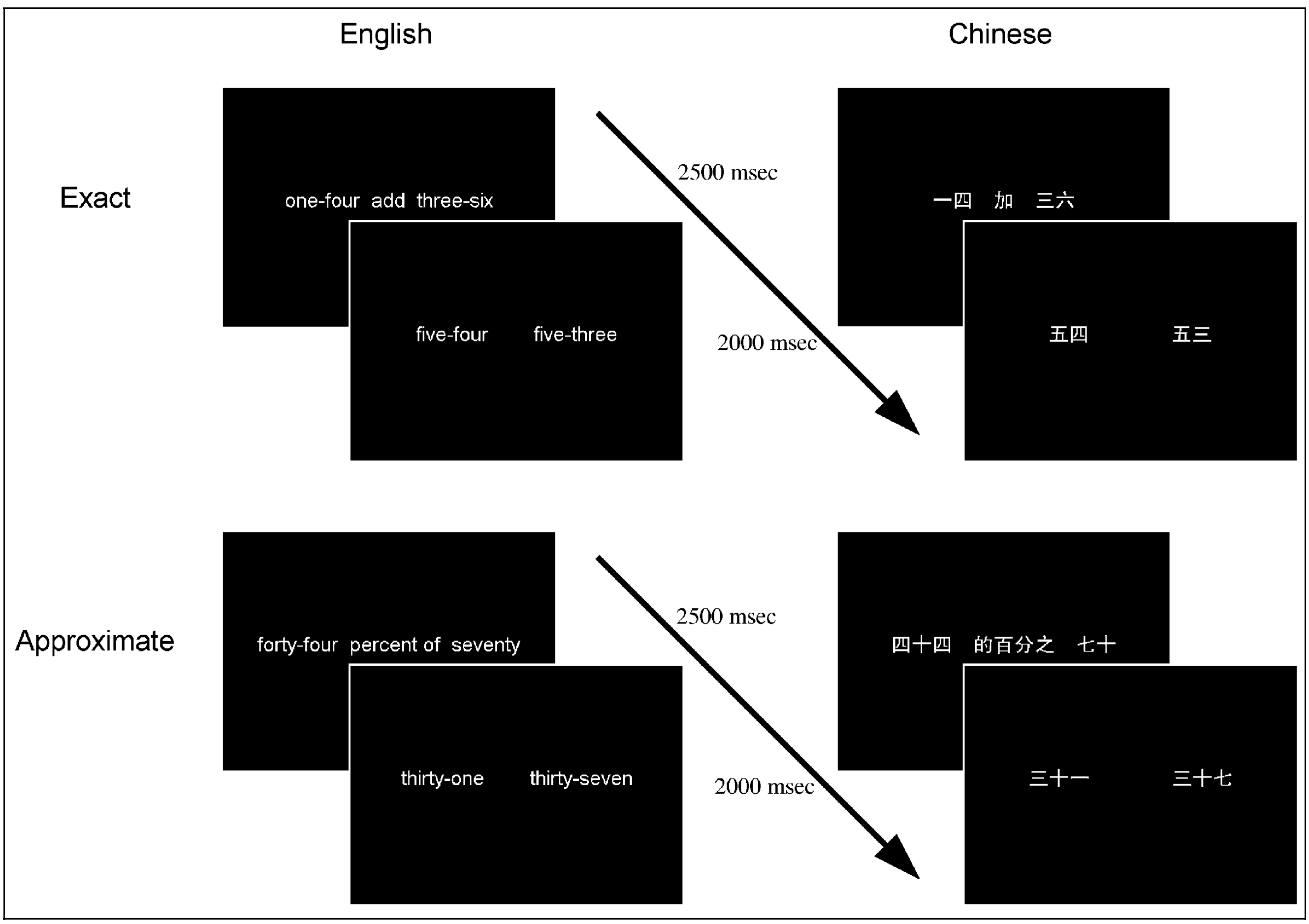

Figure 3. Schematic showing exemplars of the stimulus display and the timings used in different trial types.

choices from the exact answer was 0.78 (min = 0.1, max = 2.8, *SD* = 0.66), and the mean difference between the two alternatives was 5.25 (min = 3, max = 8, *SD* = 1.03). The location of the correct response (left or right) was randomly varied and balanced.

Imaging and Image Analysis

Imaging was performed in a Siemens 3-T Allegra system (Siemens Allegra, Erlangen, Germany). All problems were rear-projected (Epson EMP 7250) onto a silk screen placed at the rear of the magnet bore. Participants viewed the problems via a mirror. A bite-bar was used to reduce head motion. Thirty-two oblique axial slices were acquired parallel to the AC–PC line using a T2*-weighted gradient-echo EPI sequence (TR = 3000 msec, effective TE = 30 msec, matrix = 64 × 64, FOV = 192 × 192 mm, 3.0 mm thickness, 0.3 mm gap). A set of T2-weighted images was acquired in an identical orientation to the functional MR data. High-resolution anatomical reference images were obtained using a three-dimensional MP-RAGE sequence.

The functional images from each subject were preprocessed and analyzed using BrainVoyager 2000 software version 4.9 (Brain Innovation, Maastricht, Holland). Global mean intensity normalization was performed for each subject. In the spatial domain, data were smoothed with a Gaussian smoothing kernel of 8 mm FWHM. A temporal high-pass filter of period 110 sec was applied following linear trend removal. The functional images were aligned to co-planar high-resolution images and the image stack was then aligned to a high-resolution 3-D image of the brain. The resulting realigned dataset was transformed into Talairach space (Talairach & Tournoux, 1988).

The expected BOLD signal change was modeled using a gamma function (tau of 2.5 sec and a delta of 1.5) convolved with the blocks of cognitive tasks (Boynton, Engel, Glover, & Heeger, 1996). Random-effect analysis at the group level was performed using a general linear model. The threshold for considering a voxel significantly activated for a condition against baseline was $p < .005$, corrected, whereas for a contrast it was $p < .005$, uncorrected. To identify regions that are jointly activated in more than one condition, we performed conjunction analysis and picked only those regions that satisfied the minimum threshold ($p < .005$, corrected for task vs. baseline) in each of the conditions (Venkatraman et al., 2005; Goh et al., 2004).

For estimating the effect of language switching on each of the tasks, we used counterbalanced data combined across both groups of subjects. In other words, to test the effect of language switching in base-7 addition, we combined subjects who were trained in English and tested in Chinese, as well as subjects who were trained in Chinese and tested in English, into the same pool and analyzed the results. This was because we are interested in language switching effects independent of the language of training. To ensure that the results obtained were not purely due to one of the groups, we obtained parameter estimates from all resulting regions of interest and subjected them to further analysis. For each task, we performed ANOVA with training as within-subject factor and group as between-subject factor to explore any Group × Training interactions.

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The data reported in this experiment have been deposited in the fMRI Data Center (www.fmridc.org). The accession number is 2-2005-1198T.

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