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Mathematical and Linguistic Processing Differs Between Native and Second Languages: An fMRI Study

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Abstract This study investigates the neuro-mechanisms underlying mathematical processing in native (L1) and nonnative (L2) languages. Using functional magnetic resonance imaging (fMRI), Mandarin Chinese learners of English were imaged while performing calculations, parity judgments and linguistic tasks in their L1 (Chinese) and L2 (English). Results show that compared to L1, (1) calculation in L2 involves additional neural activation, especially in the left hemisphere, including the inferior frontal gyrus (Broca's area); (2) parity judgment engages similar regions for both languages, and (3) phonetic discrimination in L2 does not involve the perisylvian language (Broca's and Wernicke's) areas. These findings indicate that, calculation in L2, but not parity, can be processed through the L1 system, suggesting that the interaction between language and mathematics involves a specific neurocircuitry when associated with L2.

Keywords Brain processing · Mathematics · Linguistics · Native and nonnative languages · fMRI

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Introduction

Many people experience the confusion doing calculations in a second language (L2). Even proficient L2 learners resort to their native language (L1)[1] to perform mathematical operations (Dehaene 1997; Spelke and Tsivkin 2001). Since mathematical processing in an L1 is closely linked to language (Campbell 1994; Dehaene 1992; McCloskey 1992), involving an integrated neural network (Cohen et al. 2000; Dehaene et al. 1999, 2004; Simon et al. 2002, 2004), subsequent questions arise concerning the neuro-mechanisms underlying L2 mathematical operations. For example, do mathematical operations in L2 involve linguistic processing in the L2, and how do these processes interact with the L1? These questions address the fundamental issue of whether human cognitive capacities related to L1 and L2 employ a shared or independent neural system. Using functional magnetic resonance imaging (fMRI), this study explores these issues by examining Mandarin Chinese speakers' numerical and linguistic processing in Chinese (L1) and English (L2).

Mathematical processing and language

The extent to which numerical processing is language-dependent has been extensively debated in the literature (e.g., Ashcraft 1992; Campbell 1994; Dehaene 1992;

[1] For some early bilinguals, the most dominant language is not their L1. Their "preferred" language for arithmetic tasks is the dominant language in which they acquire mathematical knowledge (Bernardo 2001). For simplicity, in the present article "L1" is used more generally to refer to the most dominant language for both linguistic and mathematical knowledge.

Deloche and Seron 1987; Denes and Signorini 2000; Hurford 1987; McCloskey 1992; Spelke and Tsivkin 2001). Numerical tasks involve, among others, processes of understanding numerals, retrieving numerical facts, performing calculations or numerical operations, and producing results in spoken or written forms (Campbell and Epp 2004; Dehaene 1992; Hirsch et al. 2001). Since these processes require manipulating symbols or numerical words associated with transcoding and calculation rules, mathematical competence has traditionally been believed to be closely linked to language, enjoying a common "module of mind" with language as well as other cognitive capacities (Dehaene 1992; Hurford 1987).

Three recent models have been proposed to depict the nature of the number and language relationship. First, the abstract-code model (McCloskey 1992) hypothesizes a comprehension encoding system converting number input into an abstract calculation process independent of the surface language format. Second, the encoding-complex model (Bernardo 2001; Campbell 1994; Campbell and Epp 2004), on the other hand, proposes format-specific numerical representations, predicting more efficient processing for stimuli in a familiar format such as numerals presented in one's native language. Third, the triple-code model (Dehaene 1992, 1997; Dehaene et al. 1999, 2004) postulates both abstract and language dependent representations: analog magnitude and visual-Arabic codes mediating abstract quantity-based operations or digit recognition, and a language-dependent code supporting verbal fact retrieval. Whereas the abstract-code model postulates language-independent math operations, the encoding-complex and triple-code models, despite the different perspectives, both point to an integrated math and language processing system.

Evidence supporting the "integrated" view comes from developmental studies of children with good mastery of numerical competence simultaneously accompanied by the mastery of verbal skills (Gelman and Gallistel 1978; Wynn 1990), and from neuropsychological studies of patients with numerical disorders accompanied by language disorders (McCloskey 1992; Warrington 1982). Number fact retrieval has also been equated with the retrieval of words (Dehaene 1992), and the verbal representations of numbers is said to rely on the same structure as words in general (Cohen et al. 2000). On the other hand, some lesion studies have reported a disassociation between the ability to perform mathematical and verbal tasks (Dehaene and Cohen 1997; Goodglass et al. 1996). Furthermore, different modalities of numbers such as Arabic and verbal numerals have been isolated (McCloskey and Caramazza 1987), and different number and syntax lesions have been separated (Deloche and Seron 1982; McCloskey et al. 1986).

Cross-linguistic studies have also been inconsistent as to the extent to which numerical processing is language-specific. For example, some research claimed language independent numerical processing with Dutch and French speakers whose native languages differ in number–word syntax, as language-specific syntax related operand intrusion errors only occurred when problems were presented in written words but not Arabic digits (Brysbaert et al. 1998; Noël et al. 1997). On the other hand, although research with English and Chinese natives did find linguistically congruent intrusion errors (Campbell 1994, 1997; Campbell and Epp 2004; Campbell et al. 1999; LeFevre and Liu 1997), some of these differences have also been attributed to different cultural experiences or cognitive processes rather than linguistic difference per se (Campbell and Xue 2001). For example, Chinese children and young adults were found to outperform those from North America in simple arithmetic skills, presumably due to their educational experience emphasizing direct fact retrieval skills (Chen and Stevenson 1989, 1995; Geary 1996; Geary et al. 1996; LeFevre and Liu 1997). Thus, when performing simple addition and multiplication tasks, Chinese young adults tend to rely more on direct retrieval of numerical facts whereas North American young adults used more procedural strategies, but this difference disappears for older adults (Geary 1996; Geary et al. 1996), and for more complex arithmetic tasks where procedural strategy was dominant regardless of language background (Campbell and Xue 2001; LeFevre and Liu 1997). These results have shown that multiple factors determine arithmetic processing patterns across languages.

Similarly, recent neuro imaging research has revealed a complex language and math relationship. These studies have shown left perisylvian language activities in exact calculation (Dehaene et al. 1999; Delazer et al. 2003; Kong et al. 2005; Rickard et al. 2000) and intraparietal involvements in approximation and quantity comparisons (Dehaene et al. 2004; Delazer et al. 2003; Rickard et al. 2000). As the triple-code theory claims (Dehaene 1992), exact calculation involves the retrieval of information that is stored as verbal association and is thus language-dependent, whereas quantity-based operations which involve visual spatial processing are largely independent of language. Moreover, whereas simple exact calculation primarily engages language-related left frontal circuit, complex computation additionally involves visuospatial working memory and mental imagery areas in the left frontal and parietal areas (Zago et al. 2001). However, there have also been studies which show that fact retrieval associated with exact calculation activates the left precentral, superior and intraparietal regions rather than classical language areas, suggesting that arithmetical fact retrieval alone does not necessarily involve verbal processes, rather it is encoding mathematical tasks that becomes realized through language (Pesenti et al. 2000; Venkatraman et al. 2005; Zago et al. 2001). Functional imaging research with Chinese participants revealed similar patterns of activation in performing simple exact calculation in Chinese, involving intraparietal, precentral and middle frontal regions (Zhou et al. 2007).

These behavioral and neuro imaging findings do not offer a consensus regarding the respective roles of language systems in mathematical operations. One unique way to unfold the role of language neurocircuitry in math operation is to examine math processing in an L2 with unbalanced bilinguals who acquired math skills in their L1. Behavioral studies show that bilinguals, such as English–Spanish and English–Chinese, perform arithmetic problems slower and less accurately in their L2 than in their L1 (Marsh and Maki 1976; McClain and Huang 1982). Furthermore, there is a decreasing efficiency of numerical processing with the format of input being from Arabic to L1 to L2 (Bernardo 2001; Campbell et al. 1999; Frenck-Mestre and Vaid 1993). In particular, research with English–Chinese bilinguals (Campbell et al. 1999; Campbell and Epp 2004) showed that when naming numbers and responding to simple arithmetic questions (addition and multiplication) in an L1 (Chinese) and L2 (English) with stimuli presented either in Arabic or Chinese numerals, Arabic rather than Chinese numerals revealed strong associations with English number names and arithmetic. Furthermore, the retrieval of English arithmetic facts was claimed to involve an indirect route, via Chinese (Campbell and Epp 2004). These data have been interpreted in terms of the bilingual encoding complex model (BECM, Bernardo 2001; Campbell and Epp 2004), which assumes three associated format-dependent memory codes: digit, verbal in L1, verbal in L2. As the associative pathways for calculation are most readily activated by the L1 input but not well developed in the L2, calculation is mediated by the L1. With more experience in the L2, direct retrieval may become possible (Bernardo 2001). As shown by training studies, if bilinguals were trained to perform numerical tasks in one language, they showed a preference to this language with exact number tasks (Dehaene et al. 1999; Spelke and Tsivkin 2001). Consistently, one recent neuroimaging study (Venkatraman et al. 2006) showed similar results with early balanced Chinese–English bilinguals who were trained with unfamiliar arithmetic tasks in Chinese or English, and responded to these tasks in both languages. For the exact numerical task, greater activation was found in the untrained compared to the trained language in the language related areas including left inferior frontal and inferior parietal regions, whereas for estimation, the effect of switching the trained language was mainly found in the intraparietal areas bilaterally.

Linguistic processing in English–Chinese bilinguals

As mathematical operations are closely linked to language, research in English–Chinese bilingual linguistic processing is fundamental in the understanding of bilingual math processing. Findings in this arena are complex, depending on multiple factors such as linguistic domain (e.g., semantic, phonemic, etc.), format of input or task (e.g., visual/reading, or auditory/perception), and linguistic experience (e.g., age of acquisition, proficiency), etc. (Booth et al. 2002; Chee et al. 2001; Klein et al. 1999; Tan et al. 2003; Tham et al. 2005; Weekes et al. 2004; Xue et al. 2004). For example, English–Chinese bilinguals revealed different patterns reading English words and Chinese characters (Cheung et al. 2006; Tan et al. 2001), showing more left-hemisphere activation for English and bilateral processing for Chinese with additional right hemisphere involvement. The right hemisphere dominance for Chinese was possibly due to the logographic nature of Chinese characters which involves processing visual–spatial information (Tan et al. 2001). On the other hand, more general linguistic tasks which do not specifically pertain to Chinese or English, for example, verb generation (Pu et al. 2001) or semantic decision (Xue et al. 2004), engage similar processing for the two languages. Nevertheless, comparing the high and low proficiency English–Chinese bilinguals, it has been shown that additional cortical areas especially in the right hemisphere are recruited for late low proficiency bilinguals to process the L2 (e.g., Chee et al. 2001), just as what has generally been found for L2 learners of other languages (e.g., Callan et al. 2003, 2004; Wang et al. 2003; Zhang et al. 2005). Research with low proficiency, late English–Chinese bilinguals revealed that some similar processing patterns for the two languages may have been due to these bilinguals applying the L1 (Chinese) processing strategy to process L2 (English, e.g., Tan et al. 2003). Together, these studies suggest common as well as specialized neural substrate underlying L2 processing, which can then be affected by the nature of linguistic properties and linguistic experience.

The current study

The behavioral results with L2 numerical tasks suggest that mathematical processing in an L2 may be mediated by the L1 (e.g., Bernardo 2001; Campbell et al. 1999; Marsh and Maki 1976; McClain and Huang 1982). However, previous behavioral measurements only provide indirect evidence of such processing. The only existing imaging evidence showed that balanced bilinguals prefer the language in which they learned new arithmetic tasks (Venkatraman et al. 2006). Nevertheless, that these bilinguals were equally proficient in both languages cannot address how math is processed in an unfamiliar L2. To our knowledge, research has not examined numerical processing in an L2 at the cortical level. The current study extends these findings to cortical processing related to L2, to determine the extent to which math processing employs a specific neurocircuitry when associated with L2.

Cortical activation patterns associated with arithmetic processing (exact mental calculation) are compared with those associated with general number processing (parity judgment), as well as the processing of linguistic phonetic contrasts (L1 and L2 vowel discrimination) as control conditions. Based on the encoding complex and the triple-code mode models, we hypothesized that, during the numerical tasks in an L2, calculation which has been found to be language-dependent would be mediated by the L1, involving more extensive cortical activation (compared to doing calculation in an L1), especially in the language related areas. In addition, parity judgment which involves language-independent processing would lead to similar activation for L1 and L2. More generally, if mathematical operations occur within the L2-related systems, results would be consistent with neural correspondence between math and language functions. If the math and L2 systems remain separate, then evidence would support neural specialization for the two functions. Alternatively, interactions between mathematical operations performed in L1 and L2 may offer new insights into these fundamental neural circuits.

Chinese learners of English were chosen not only because Chinese and English are two of the most widely used languages in the world (Tan et al. 2003), but also because English–Chinese bilinguals have been included in many of the previous behavioral studies on mathematical processing (e.g., McClain and Huang 1982; Campbell et al. 1999; Campbell and Epp 2004), which found similar patterns by learners of English whose L1 was Chinese and those whose L1 was an alphabetic language (e.g. Spanish or French; Marsh and Maki 1976; Frenck-Mestre and Vaid 1993). These studies provided the basis for the current study to extend the behavioral findings to the cortical domain. Moreover, previous research has shown that mathematical processing in Chinese does not differ from that in any other languages tested, either strategically (e.g., Campbell and Xue 2001) or cortically (e.g., Venkatraman et al. 2006; Zhou et al. 2006, 2007). Furthermore, Arabic numerals are the standard format learned and used to perform numerical tasks and calculation in Chinese just as the usages of Arabic digits and number words in English and many other languages (Campbell and Epp 2004). These consistencies between the two languages offer the baseline to examine Chinese bilinguals' mathematical processing in their L2 (English) and L1 (Chinese), as well as that it makes it possible to generalize the current findings to the more general contexts for the L2 math processing.

Methods

Participants

Nineteen adult native speakers of Mandarin Chinese with no history of speech or hearing impairments participated in the current study (12 female, 7 male[2]; average age, 36; see Table 1). These participants were graduate students at Columbia University when the experiment was run in the spring of 2004. They started learning English as an L2 at an average age of 12, which involved formal class instruction of 5 hours/week. The participants all received a TOFEL score of higher than 550, the minimum score for admission to most graduate schools in the USA (Pu et al. 2001; Tan et al. 2003). They all came to the USA as adults (average age of arrival, 30), and had been residing in the USA for an average of five years. According to self-estimation, their average daily use of English was 56%, and their fluency in English was rated an average of 5 on a 7-point scale (with 7 being native-like fluency and 1 being elementary fluency). They were therefore considered moderately proficient late learners of English. Since these participants received elementary and secondary education in China, they learned mathematics in Chinese, and were assumed to have similar basic arithmetic skills (Campbell and Xue 2001; LeFevre and Liu 1997). None of the participants had majored in either English or mathematics related disciplines. All participants were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield 1971). They were recruited according to institutional informed consent procedures. All were compensated for their participation.

[2] An effort was made to maintain a balanced number of male and female participants, as previous research has discussed the effect of gender on linguistic (Baxter et al. 2003; Frost et al. 1999; Shaywitz et al. 1995; Weiss et al. 2003) and mathematical (e.g., Kucian et al. 2005) processing. However, due to participant availability and the need to control for their level of L2 proficiency, we were not able to recruit equal number of males and females. As our preliminary behavioral analysis did not show gender and language interactions, the male and female data were pooled for subsequent analyses. However, the gender difference should not affect the interpretation of the current results in terms of the differences in math processing in L2 versus L1. Since the present participants performed the tasks in both L1 and L2, they served as their own controls. That is, if gender difference existed in L1 processing, it would be so in L2 processing as well. In our data analysis, we used direct language comparisons for each task, the results of which were presumably the differences only due to language.

Table 1 Participants' (n=19) language background information

	Age	AOL	AOA	LOR	L2 use	L2 fluency
Average	36	12	30	5	56%	5
Standard deviation	7	2	7	3	22	1
Range	26–45	12–14	25–39	1–8	40–90%	3–6

AOL: Mean age of L2 (English) learning, *AOA*: mean age of arrival in the US, *LOR*: mean length of residence in the USA (years), *L2 use*: mean % daily use of L2, *L2 fluency*: self-rated level of L2 fluency on a 7-point scale (1, elementary; 7, native-like).

Stimuli

The stimuli (see Table 2) include three conditions presented auditorily in Mandarin Chinese (L1) and English (L2): exact calculation (addition, multiplication), general numerical concept processing (parity judgment), and basic linguistic phoneme condition (vowel contrast). Auditory (rather than visual) presentation was adopted as previous research has shown that it would induce bilinguals to encode and calculate in the presented language (Marsh and Maki 1976). The calculation and parity tasks were used based on the previous findings of native math processing, that calculation involves verbal associations whereas parity is processed in an abstract language-independent manner (Dehaene 1992). In addition, phonemic task has previously been used as a linguistic task to compare with native math processing (Simon et al. 2002, 2004).

The calculation condition included 14 two-digit number addition and two-by-one-digit multiplication equations, with the sum or product also being a two-digit number to control for the level of task difficulty (e.g., "24 times 2 is 68"—right or wrong). Two-digit numerals are used, given that some strategic differences were observed with single but not two-digit arithmetic for Asians and non-Asians (Campbell and Xue 2001; Geary 1996). The parity condition involved parity judgment questions of 14 pairs of two-digit odd or even numbers (e.g., "34 and 22 are even numbers"). The linguistic condition was phonetic discrimination of the native vowel contrast [*i*]–[*y*] in Chinese, and the nonnative contrast [*i*]–[*I*] in English. Whereas all these vowels are acoustically and perceptually similar, [I] does not exist in the Chinese phonetic inventory and [y] is not an English sound. These vowels appear in 14 minimal word pairs of each language, which are embedded in carrier sentences for a rhyming truth judgment task (i.e., "Heat and seat are in rhyme"). For each of the three conditions, the level of difficulty in Chinese (L1) and English (L2) was carefully controlled by choosing similar numerical size and/or similar first and second operands in the two languages. Similarly, the stimulus sentences in Chinese (L1) and English (L2) have the same syntactic structure, with the number of syllables being either the same or very close (e.g., "24 times 2 is 48" in English is the same as "*Ershi-si cheng er shi sishi-ba*" in Chinese; "34 and 22 are even numbers" in English equals "*Sanshi-si he ershi-er shi shuang shu*"; and "HEAT and SEAT are in rhyme" equals "*QI he XI shi ya yun-de*". In order to avoid practice effect, no items in Chinese and English were the same.

Image acquisition and tasks

A 1.5T GE MR scanner located in the fMRI Research Center at Columbia University was used to obtain T2* weighted images with a gradient echo pulse sequence (echo time, 52 ms; repetition time, 2,000 ms; flip angle, 60). The cubic

Table 2 Stimuli used during fMRI scanning for the calculation, parity and linguistic tasks

Stimulus type	Contrast	Language	Example (presented auditorily)	Correct response (button press)
Calculation	Addition/multiplication	English (L2)	24 plus 12 is 36	Right
			18 times 2 is 46	Wrong
		Chinese (L1)	27 jia 16 shi 43	Right
			18 cheng 4 shi 62	Wrong
Parity	Odd/even numbers	English (L2)	12 and 24 are even numbers	Right
			14 and 48 are odd numbers	Wrong
		Chinese (L1)	12 he 24 shi shuang shu	Right
			14 he 48 shi dan shu	Wrong
Linguistic	[*i*−*I*]	English (L2)	Heat and Seat are in rhyme	Right
			Hit and Seat are in rhyme	Wrong
	[*i*−*y*]	Chinese (L1)	Xi he Qi shi ya yun-de	Right
			Xu he Qi shi ya yun-de	Wrong

size of each voxel was 40 mm^3 (in-plane resolution, 3×3 mm; slice thickness, 4.5 mm). Twenty-one contiguous axial slices of the brain covering the entire cortex were taken parallel to the anterior-posterior commissure line.

Each participant was scanned for four runs (two in Chinese, two in English). The order of Chinese or English presentation was counter-balanced across subjects. An event-related design was performed where 188 images were acquired for each run: a rest period (10 images, 20 s), a stimulation-baseline period (168 images, 336 s) including 21 trials (8 s stimulation/response and 8 s baseline periods for each trial), and another rest period (10 images, 20 s). In each run, the 21 stimulus trials were from all the three tasks (calculation, parity, and linguistic, seven stimuli/task) presented in a randomized order. For each trial, participants heard the entire statement over headphones, and gave a right/wrong response by pressing a button. Half of the participants were asked to press the left button for "wrong", and the other half were asked to press the right button for "wrong" responses. The "right" and "wrong" prompts ("√" and "x" respectively) were shown on the screen during the response periods. The rest periods contained no tasks, but the participants were asked to press a button when they heard periodically presented pure tone beeps (200 Hz), while viewing a fixation mark on the screen (+). This was later used to control for primary motor, visual and auditory processing in the test conditions (Hirsch et al. 2001; Wang et al. 2003).

Behavioral responses were logged during the scans using IFIS/E-prime. T1-weighted images were acquired along the same plane locations as the T2*-weighted images for anatomical reference. After the behavioral and imaging session, all participants completed a post-experiment questionnaire on the strategies they used to perform calculation in the two languages as well as their perceived level of difficulty of each of the tasks.

Data analysis

Spatial pre-processing and statistical testing were carried out with SPM99 (Wellcome Department of Cognitive Neurology, University College London, UK). For each participant, functional T2* images were slice-timing corrected, spatially realigned to the first volume, and coregistered with the corresponding T1 image. These images were then spatially normalized to the Montreal Neurological Institute stereotactic coordinate system, and applied to all functional scans. Functional images were smoothed, spatially normalized, and analyzed according to a general linear model using regressors of stimulus events created for each task in each language relative to baseline and rest periods. Contrast maps from individual participants were entered into a random-effects group analysis.

The following contrasts were created at the group level: (1) six separate language contrasts: calculation, parity, and phonemic discrimination, each with L1 and L2 greater than rest and baseline. (2) As the current study focuses on between-language differences, significant activation was directly compared between in L1 and L2 for each task condition, by excluding activation in one condition relative to the other. Voxel by voxel signal changes were evaluated using an empirically determined false positive rate of $p<0.001$ (uncorrected). An active area was defined as a cluster of at least five contiguous voxels. In addition, significant activation at $p<0.05$ (corrected) at the cluster level was also reported. This variation in p values did not fundamentally change the findings, although the threshold of an uncorrected p value at $p<0.001$ may increase the possibility of false positive results (e.g., Brett 2007). The less conservative threshold was adopted in the current study since the activation for some subjects and in some conditions (especially the linguistic and parity tasks) was relatively weak, and particularly so with direct language contrasts. This level of stringency assured that all reported findings were observed on all individual subjects. Similar less stringent thresholds have been used previously in mathematical processing studies where the signal was weak (e.g., Kong et al. 2005; Venkatraman et al. 2005, 2006; Wang et al. 2007; Zhou et al. 2006). Furthermore, some studies focused on effects that were replicated over time as a way to control for type I error (e.g., Crinion et al. 2006), which we adopted in the current study. Since for each language the tasks were repeated in two runs, a conjunction analysis was performed prior the contrastive analyses for each task in each language (e.g. runs 1 and 2 for calculation in English) such that an area was considered "active" only if it was activated in both runs. Thus the requirement for replicability also served to enhance confidence in these findings.

Results

Behavioral results

Behavioral data were analyzed with error rate (ER) and response time (RT) as dependent variables in a two-way ANOVA with language (Chinese, English) and task (calculation, parity, linguistic) as repeated measures factors. Results (Fig. 1) show that ER is lower and RT is faster in Chinese (L1) than in English (L2, ER [$F(1,18)=28.4$, $p=0.000$]; RT [$F(1,18)=48$, $p=0.000$]), with post hoc analyses

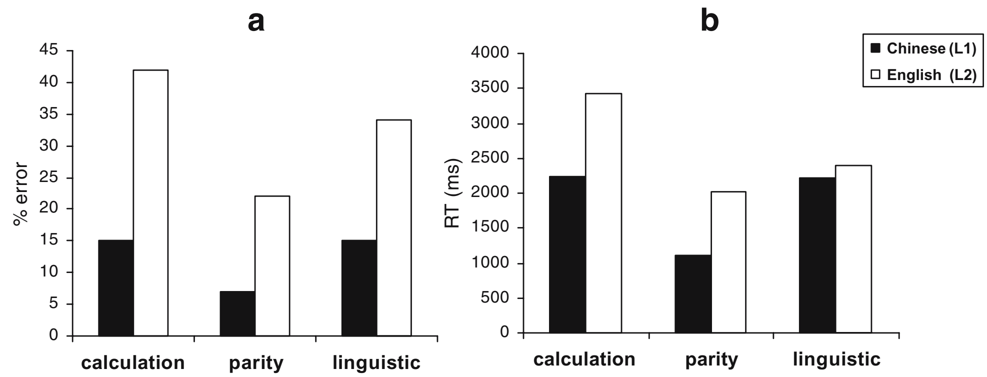

Fig. 1 Behavioral results: **a** error rate (%) and **b** response time (in millisecond) in the calculation, parity, and linguistic tasks in Chinese (L1) and English (L2)

revealing the same pattern for each of the three tasks ($p<0.006$). Furthermore, there was also a reliable task difference in ER [$F(2, 18)=13.4$, $p=0.000$] and RT [$F(2, 18)=25.3$, $p=0.000$]. Post hoc analyses show no task and language interaction. For both Chinese and English, subjects made more errors in performing the calculation and phonetic tasks than the parity judgment task. For both languages, the response time for calculation was longer than for the phonetic task which in turn was longer than parity judgment.

Imaging results

Figure 2 highlights the imaging results during calculation in L1 (top row) and L2 (bottom row), the major finding of this study. Table 3 compares the brain activation patterns for the three tasks from the group analysis, and Tables 4, 5, and 6 summarize the activated regions for each task (calculation, parity, and linguistic, respectively) in terms of anatomical and Brodmann's areas (BAs), as well as the [*x*, *y*, *z*] coordinates.

Calculation in L1 (Table 4) involves bilateral middle frontal gyri (GFm), anterior/posterior cingulate (GCa/GCp), left inferior parietal lobule (LPi), insula, and right cuneus. The L2 task additionally activated bilateral superior frontal gyrus (GFs), medial frontal gyrus (GFd), GCp, left inferior frontal gyrus (GFi), pre/post-central gyri (GPrC/GPoC), LPi, superior parietal lobule (LPs), and precuneus. Direct between-language comparisons show that whereas the left GCa and insula were more strongly activated for L1 calculation, additional activation for the L2 task most strongly focused on left GFd, GPrC/GPoC, LPs and precuneus.

Parity judgment (Table 5) in L1 involves activation in bilateral GCa and GPoC, left GFm and GPrC, and right LPi. In L2, activated areas include left GPrC/GPoC, LPi, GCp, and right GCa. Direct between-language comparisons show that the only distinctive difference is within left GCa, which is more extensively activated in the L1 task.

For the phoneme judgments (Table 6), activated areas for the L1 include left GFi, superior temporal gyrus (GTs), GPoC, LPi, and bilateral GCa. The L2 phoneme discrimination activated GPrC/GPoC and LPi bilaterally. Direct between-language comparisons show that the left GFi had significantly greater activation for the L1 but not L2, while the activation unique to L2 is noticeably in LPi.

The activation magnitude was analyzed with a three-way repeated measures ANOVA, with the number of activated voxels as a function of language, task and hemisphere (Fig. 3). The results revealed main effects of language [$F(1, 18)=31.4$, $p=0.000$] and task [$F(2, 18)=3.2$, $p=0.048$], but not hemisphere [$F(1, 18)=2.4$, $p=0.132$], showing that the L2 tasks involved greater activation than L1, and calculation involved greater activation than parity and linguistic tasks. In addition, significant interactions were observed for task × hemisphere [$F(2, 24)=3.8$, $p=0.030$], and task × hemisphere × language [$F(2, 24)=3.6$, $p=0.036$]. Post hoc analyses show a left-hemisphere dominance for all three tasks in L2, but only for the phonetic task in L1.

Discussion

Calculation

Consistent with the previous research (e.g., Frenck-Mestre and Vaid 1993; Marsh and Maki 1976), calculation in L2 resulted in more errors and longer RT than that in L1. They are also in line with the participants' post-experiment self-report claiming more difficult and slower processing in the L2.

Cortically[3], calculation in Chinese (L1) aligns well with the previous findings of a parieto-frontal-cingulate network (Chochon et al. 1999; Dehaene et al. 2004; Delazer et al.

[3] It should be noted that the discussion is based on the data at the threshold of $p<0.001$ (uncorrected). See also the discussion in the Method section.

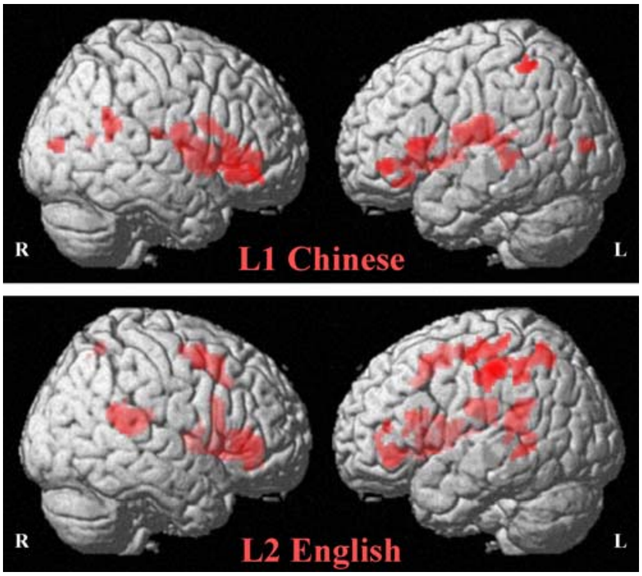

Fig. 2 Results from the random effect group analysis showing fMRI signal changes for the calculation task in Chinese (*L1*) and English (*L2*). These results show additional regions and greater magnitude of activation for the L2 than L1 task. The threshold was $p<0.001$ uncorrected with five contiguous voxels

2003; Hirsch et al. 2001; Zago et al. 2001), engaging the LPi supporting the semantic representation of numerical quantity (Chochon et al. 1999; Dehaene et al. 1999, 2004; Hirsch et al. 2001; Kong et al. 2005; Simon et al. 2002) and GFm and GC for arithmetic procedure complexity processing (Kong et al. 2005; Zago et al. 2001). Whereas there was little GFi and GTs activity, language involvement may have been modulated by the left GFm which have been reported to excite both language processing and mental calculation (e.g., Hirsch et al. 2001; Simon et al. 2002), and LPi which may be activated independently of the frontal regions for verbal fact retrieval (Pesenti et al. 2000).

In contrast to these native patterns, performing calculation in English (L2) engaged additional and more extensive neural activation, particularly in the language-dominant left hemisphere, including the GFi, GFm, GFd and GPrC/GPoC, which have previously been associated with language processing (Booth et al. 2002; Hirsch et al. 2001; Indefrey and Levelt 2004; Pulvermüller et al. 2006; Zatorre et al. 1992). Noticeably, the left GFi (Broca's area, the classic "language area") was activated only for the L2, consistent with the previous finding with balanced bilinguals that activation of this area may result from an effort to translate the problem from an unfamiliar language to a familiar language so as to retrieve the answer in the familiar language (Venkatraman et al. 2006). Together, these patterns demonstrate the reliance of L2 calculation on language systems, suggesting that the L2 input may have been translated into L1 to perform calculation. Indeed, on the basis of the bilingual encoding complex model, (Bernardo 2001; Campbell 1994, 2004), verbal codes in L1 would be activated in the retrieval of arithmetic information if the arithmetic memory system is not well developed in bilinguals' L2. As a consequence, L2 calculation is mediated by the L1. The post-experiment questionnaire consistently revealed that 79% (15 out of 19) of the participants claimed to have to do calculation in their L1 (Chinese) even when the questions were presented in English (L2), while the others could either calculate directly in their L2 (10%) or visualized the questions in Arabic numerals (10%).

Parity judgment

Compared to the massive cortical differences revealed in the calculation task, parity judgments in Chinese and English engaged relatively similar regions, mostly in the GPrC/GPoC and LPi areas. According to the triple-code model, parity information involves direct retrieval of information from a semantic store of simple arithmetical properties rather than a mental computing process, and thus proceeds from the Arabic representation independent of input format (Dehaene 1992; Dehaene et al. 1993). Behavioral research consistently shows that parity information may be easily extracted even in mathematically unsophisticated individuals (Dehaene et al. 1993), and that bilinguals access arithmetic but not parity information in their L1 system (Campbell 1994; Dehaene 1992; Gonzalez and Kolers 1987). The current results of similar L1 and L2 activation lend support to these findings. Since parity information retrieval is mediated in a language independent abstract manner, the processing patterns are conceivably less influenced by the input language.

The language independent nature of parity processing also is consistent with the lack of classical language area involvement in parity judgments for both Chinese and English revealed in the current study, which was in line with the previous findings for the processing of Arabic codes (Pesenti et al. 2000). Previous research has claimed that Arabic numerals may automatically evoke an internal quantity code, known as the SNARC effect (spatial-numerical association of response codes, see Dehaene 1992). Presumably, parity judgment which involves the retrieval of conceptual mathematical information could also excite a semantic route just as the processing of quantity-based information. Indeed, the present results of the pre/postcentral and parietal activation foci are consistent with the previous findings for quantity-based processing such as approximation (Dehaene et al., Chochon et al. 1999; Pesenti et al. 2000). Together, these patterns suggest the general involvement of the parietal lobe in sensory, attentional and semantic processing (Chochon et al. 1999; Simon et al. 2002; Dehaene et al. 2004).

Table 3 Summary of the activated regions across tasks and languages from the random-effect group analysis ($p<0.001$ uncorrected)

Anatomical areas	Calculation				Parity				Linguistic			
	L1 (C)		L2 (E)		L1 (C)		L2 (E)		L1 (C)		L2 (E)	
	L	R	L	R	L	R	L	R	L	R	L	R
Superior frontal gyrus (GFs)			■	■								
Inferior frontal gyrus (GFi)			■						▲			
Middle frontal gyrus (GFm)	▲	▲	■		▲							
Medial frontal gyrus (GFd)			■	■								
Anterior cingulate (Gca)	▲	▲		■	▲	▲		■	▲	▲		
Posterior cingulate (GCp)	▲	▲	■	■			■					
Precentral gyrus (GPrC)			■		▲		■					■
Postcentral gyrus (GpoC)			■		▲	▲	■		▲		■	■
Superior parietal lobule (LPs)			■									
Inferior parietal lobule (LPi)	▲		■			▲	■		▲		■	■
Superior temporal gyrus (GTs)									▲			
Precuneus			■									
Cuneus		▲										
Insula	▲											

The triangles indicate activation in the Chinese (L1) tasks and the square ones indicate English (L2).
L Left hemisphere, *R* right hemisphere, *C* Chinese, *E* English

Linguistic processing

The discrimination of the L2 English contrast [*i*−*I*] resulted in greater error rate and longer response latencies than that of the L1 Mandarin [*i*−*y*], consistent with previous findings with Chinese learners of English (Bohn 1995; Wang and Munro 2004), suggesting that the new L2 vowel [I] was likely assimilated with its similar counterpart [i] (Best 1995; Flege 1995).

Imaging results revealed consistent patterns with previous findings from similar rhyming task (e.g., Booth et al. 2002; McDermott et al. 2003). The results show that phonemic processing in the L1 system involves an integrated fronto-temporal language system, including the left GFi and GTs, the putative language areas previously found for linguistic phonetic processing in Chinese (Wang et al. 2003) as well as other languages (McDermott et al. 2003; Simon et al. 2002; Zatorre et al. 1992), and the GPoC, LPi, and GC regions claimed to be language-related areas (Cohen et al. 2000; McDermott et al. 2003; Pulvermüller et al. 2006; Simon et al. 2002; Stamatakis et al. 2005). In particular, the LPi region has also been observed to be involved in phonetic processing (Cohen et al. 2000; McDermott et al. 2003; Simon et al. 2002), since this area provides an auditory-motor interface, connecting the frontal areas for motor planning in speech articulation and the temporal areas for auditory speech analysis (Hickok and Poeppel 2000; Simon et al. 2002).

Phonetic processing in the L2, however, did not involve the left GFi and GTs language areas. Yet, the left hemisphere dominance in L2 suggests that listeners may still have processed the English vowels as language components. Comparing L2 and L1, the current results show significantly greater left LPi involvement in L2. This is in agreement with previous results involving English–Chinese bilinguals, showing more intensive activation in this region for L2 processing (e.g., Chee et al. 2001; Xue et al. 2004), possibly due to L2 processing requiring more attention (Xue et al. 2004). Different from a previously observed pattern for English–Chinese bilinguals, the current results did not reveal more right-hemisphere involvement associated with Chinese (L1) processing relative to more left-hemisphere processing for English (L2) (e.g., Cheung et al. 2006; Tan et al. 2001). Whereas those studies involved reading Chinese characters which likely engaged right-hemisphere processing of logographic information, the current study adopted auditory stimulus presentation which did not directly require processing of characters. Indeed, auditory phonetic processing of Chinese including Chinese tone processing has been found to be left-lateralized (e.g., Gandour et al. 2003; Klein et al. 1999; Wang et al. 2001, 2003, 2004).

Despite some of these spatial differences, what appears consistent across studies including the current one is that, for late adult L2 learners, L2 speech processing does not share the exact same regions with L1 processing, although for early and/or more proficient bilinguals neural processing of L1 and L2 may have shared patterns (Golestani and Zatorre 2004; Kim et al. 1997; Wang et al. 2003).

Table 4 Calculation: activated anatomical regions, Brodmann's areas (BAs), and activation centroids (in terms of peak voxel coordinates [*x*, *y*, *z*]) from the random-effect group analysis ($p<001$, uncorrected; italics indicates areas of significant activation with $p<0.05$ corrected at the cluster level), for Chinese (L1) and English (L2) separately, and significant differences in direct language comparison conditions

Language	Anatomical regions	Side	BA	Peak voxel [x, y, z]	Z score
Chinese (L1)	Middle frontal gyrus	L	11	[−28, 40, −2]	3.93
	Posterior cingulate	L	23, 29, 30	[−2, −60, 12]	3.68
	Inferior parietal lobule	L	40	[−38, −48, 54]	3.70
	Insula	L	13	[−26, 22, 8]	4.62
	Anterior cingulate	L	24, 25	[14, 24, −2]	5.19
	Middle frontal gyrus	R	11, 47	[14, 24, −2]	5.19
	Anterior cingulate	R	24, 25	[14, 24, −2]	5.19
	Posterior cingulate	R	23, 29	[−2, −60, 12]	3.68
	Cuneus	R	17, 18	[4, −84, 8]	3.82
English (L2)	*Inferior frontal gyrus*	L	47	[−22, 34, −4]	4.16
	Middle frontal gyrus	L	11	[−22, 34, −4]	4.16
	Superior frontal gyrus	L	8	[8, 4, 52]	4.13
	Medial frontal gyrus	L	6	[8, 4, 52]	4.13
	Posterior cingulate	L	24, 25	[8, 4, 52]	4.13
	Precentral gyrus	L	4,6	[−46, −30, 48]	4.38
	Postcentral gyrus	L	1,3	[−46, −30, 48]	4.38
	Inferior parietal lobule	L	40	[−46, −30, 48]	4.38
	Superior parietal lobule	L	7	[−24, −50, 52]	4.95
	Precuneus	L	7	[−24, −50, 52]	4.95
	Superior frontal gyrus	R	8	[8, 4, 52]	4.13
	Medial frontal gyrus	R	6, 32	[8, 4, 52]	4.13
	Posterior cingulate	R	24	[8, 4, 52]	4.13
	Anterior cingulate	R	24, 25	[18, 28, 2]	4.93
Chinese–English	Anterior cingulate	L	24	[−10, 56, −4]	4.19
	Insula	L	13	[−34, 0, 12]	3.70
English–Chinese	Precentral gyrus	L	4	[−38, −20, 54]	2.85
	Postcentral gyrus	L	3	[−44, −28, 50]	2.16
	Superior parietal gyrus	L		[−12, −58, 60]	2.83
	Precuneus	L	7	[−12, −58, 60]	2.83
	Medial frontal gyrus	R	6	[12, −18, 52]	2.58

L Left hemisphere, *R* right hemisphere

General discussion

The above comparisons of the calculation, parity and linguistic processing cumulatively suggest that numerical processing in L2 involves a specialized neurocircuitry. The findings indicate that calculation in the L2 was processed through L1, while parity processing was not. This is evident from results showing that compared to the Chinese condition, mental computation of the stimuli presented in English evoked more extensive activation mostly in the left hemisphere, including the classical language area such as GFi (Booth et al. 2002; Zatorre et al. 1992), as well as GFm also found to be specialized for language (Hirsch et al. 2001). Furthermore, that L1 but not L2 linguistic phonemic processing activated Broca's area provides supporting evidence that this area was most robustly activated when L1 was involved. In contrast, parity judgment resulted in similar activation for L1 and L2 without significant language area involvement. It is interesting to note that the behavioral results showed greater error rate and longer response time for all three tasks in English (L2) than in Chinese (L1), indicating that doing the tasks in the L2 was more difficult than in the L1. However, the imaging results of more extensive activation for the calculation task in L2 compared to that in L1, and similar activation patterns for the parity task in L1 and L2 cannot be attributed to the effect of task difficulty, as otherwise one would have expected more extensive activation for the parity task in L2 relative to L1. This suggests that the imaging results can reveal more about the nature of mathematical processing patterns than offered by the behavioral evidence.

Table 5 Parity judgment: activated anatomical regions, Brodmann's areas (BAs), and activation centroids (in terms of peak voxel coordinates [*x*, *y*, *z*]) from the random-effect group analysis ($p<0.001$, uncorrected; italics, areas of significant activation with $p<0.05$ corrected at the cluster level), for Chinese (L1) and English (L2) separately, and significant differences in direct language comparison conditions

Language	Anatomical regions	Side	BA	Coordinates [x, y, z]	Z score
Chinese (L1)	Middle frontal gyrus	L	11	[−40,24,40]	4.04
	Precentral gyrus	L	9	[−40,24,40]	4.04
	Postcentral gyrus	L	1, 2, 40	[−64,−20,26]	4.04
	Anterior cingulate	L	24, 25	[−22,22,18]	4.62
	Postcentral gyrus	R	2	[60,−26,28]	4.08
	Inferior parietal lobule	R	40	[60,−26,28]	4.08
	Anterior cingulate	R	24, 25	[18,34,−6]	3.93
English (L2)	Precentral gyrus	L	1, 2	[−62,−16,28]	4.54
	Postcentral gyrus	L	3, 4	[−62,−16,28]	4.54
	Postcentral gyrus	L	3, 4	[−56,−32,46]	4.88
	Inferior parietal lobule	L	40	[−56,−32,46]	4.88
	Posterior cingulate	L	31	[−36,−40,34]	4.05
	Anterior cingulate	R	25	[14,34,−6]	3.54
Chinese–English	Anterior cingulate	L	24	[2,42,−2]	4.11

L Left hemisphere, *R* right hemisphere

These results can be accounted for by incorporating the aforementioned triple-code, abstract, and (bilingual) encoding complex models (Bernardo 2001; Campbell 1994; Campbell and Epp 2004; Dehaene 1992; McCloskey 1992). That is, numerical processing is completed through both language-dependent and abstract modules: calculation involves addition and multiplication tables which are stored as verbal associations, and is thus format-dependent (Bernardo 2001; Campbell 1994; Dehaene 1992); whereas access to parity information depends on the language-independent Arabic numerical representation regardless of input formats (Dehaene 1992, Dehaene et al. 1993). Based on these accounts, the present participants may have translated or transcoded the incoming English (L2) calculation questions into Chinese (L1) to perform the computation tasks, as calculation involves verbal associations of

Table 6 Linguistic task: activated anatomical regions, Brodmann's areas (BAs), and activation centroids (in terms of peak voxel coordinates [*x*, *y*, *z*]) from the random-effect group analysis ($p<0.001$, uncorrected; italics, areas of significant activation with $p<0.05$ corrected at the cluster level), for Chinese (L1) and English (L2) separately, and significant differences in direct language comparison conditions

Language	Anatomical regions	Side	BA	Coordinates [x, y, z]	Z score
Chinese (L1)	Inferior frontal gyrus	L	47	[−56,14,−4]	5.75
	Superior temporal gyrus	L	22, 38	[−56,14,−4]	5.75
	Postcentral gyrus	L	1, 3	[−64,−18,30]	3.19
	Inferior parietal lobule	L	2	[−64,−18,30]	3.19
	Anterior cingulate	L	24, 25	[−4,22,0]	4.12
	Anterior cingulate	R	25, 32	[−4,22,0]	4.12
English (L2)	Postcentral gyrus	L	1, 43	[−60,−18,26]	3.65
	Postcentral gyrus	L	1	[−54,−38,48]	3.45
	Inferior parietal lobule	L	2, 40	[−54,−38,48]	3.45
	Precentral gyrus	R	4	[60,−16,28]	3.03
	Postcentral gyrus	R	3	[60,−16,28]	3.03
	Inferior parietal lobule	R	2, 40	[60,−16,28]	3.03
Chinese–English	Inferior frontal gyrus	L		[−34,18,12]	2.90
	Anterior cingulate	R	25	[12,10,−6]	3.03
English–Chinese	Inferior parietal lobule	L	40	[−32,−22,26]	3.44

L Left hemisphere, *R* right hemisphere

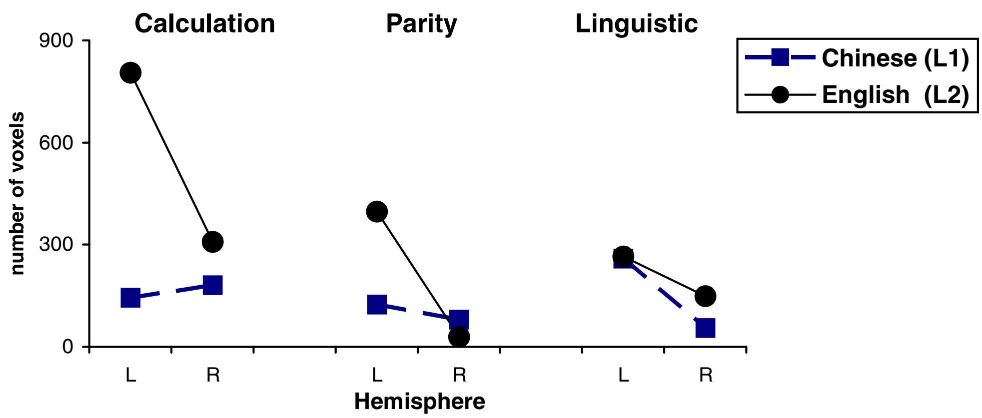

Fig. 3 Mean number of activated voxels in the *left* and *right* hemispheres for each task and language (based on group results)

the numerical lexicon and syntax which they acquired through the L1. These neuro-based findings are in line with the previous behavioral research reporting that bilinguals access addition and multiplication problems through the language that they first studied mathematics in (Dehaene 1992; Gonzalez and Kolers 1987; Marsh and Maki 1976), and that word-format costs for calculation were greater than for parity (Campbell 2004). For parity, the similar patterns for L1 and L2 are possibly due to that the input being transcoded directly into a common Arabic code (Bernardo 2001; Campbell 1994; Dehaene 1992). However, the associative link between L2 and the abstract code is still weaker than that between the L1 and the abstract code, as for unbalanced bilinguals the link has not been well developed (Bernardo 2001; Campbell and Epp 2004). This also accounts for the greater error rate and longer response time for parity in L2 than in L1. The current results thus provide the neural evidence extending the triple-code and encoding complex propositions to the bilingual contexts, suggesting a module- and format-specific numerical processing in L2.

While the L1 and L2 exhibited distinctive cortical patterns, common involvement was also observed. One noticeable area was LPi (especially left LPi) which was active in all three conditions in L1 and L2. Since its anatomical location determines that this region is linked with associative functions connecting the frontal and temporal lobes, it may be evoked for various cognitive operations, including math and language (Cohen et al. 2000; Simon et al. 2002, 2004), providing the interconnection of the quantity and linguistic representations (Pesenti et al. 2000).

In sum, the present study along with the previous research suggests a general pattern of functional connectivity and integration of cognitive processing (Hirsch et al. 2001; Stamatakis et al. 2005). The LPi is commonly activated across conditions and can be assumed to serve shared spatial, attentional, or response requirements of the tasks (Cohen et al. 2000; Xue et al. 2004). On the other hand, each task excites unique regions (e.g., the fronto–parietal–cingulate network for calculation, and the fronto–temporal foci for linguistic processing). These findings suggest that it is the integration of the shared and unique processing involving both central and supportive cortical regions that shapes the architecture for L1 and L2 characteristics.

Concluding remarks and future directions

The current study examined mathematical processing with late unbalanced bilinguals. Further studies will be required to include bilinguals varying in age of L2 acquisition (e.g., early vs late learners) and L2 proficiency levels, as L2 learning involves dynamic processes occurring under the effects of such factors (Flege 1995), and are also reflected as changes in the cortical organization in L1 and L2 (Kim et al. 1997; Perani et al. 1998; Wang et al. 2003; Callan et al. 2003; Golestani and Zatorre 2004). Consequently, these factors may affect mathematical processing in L2. Indeed, previous research claimed that the associative link between L1 and L2 can be developed with increased proficiency in the L2, such that direct retrieval of arithmetic information may become possible (Bernardo 2001; Campbell and Epp 2004). In addition, bilinguals process math differently depending on the language in which mathematical knowledge was acquired (Bernardo 2001; Spelke and Tsivkin 2001; Venkatraman et al. 2005). Our future research plans to examine the cortical changes in L2 math processing as late learners achieve greater L2 fluency, as well as the processing patterns for early bilinguals, for a more complete picture of the nature of mathematical processing in bilinguals and the relationship between linguistic and numerical processes.

Another line of extension is the generalizability of the current findings with Chinese learners of English. Previous cross-linguistic studies have shown that mathematical processing patterns for different languages are affected by language specific factors such as syntactic structures (e.g., Noël et al. 1997) or numerical formats (e.g., Brysbaert et al. 1998). Presumably these factors may affect how math is processed in an L2. A question thus arises as to whether the current findings can be applied to L2 math processing where these language-specific differences exist, e.g., Dutch learners of English whose L1 numerical syntax differs from that of English. Moreover, given that Chinese is a logographic language and English is alphabetic, visually presented stimuli in Chinese characters and English words to compare the Chinese patterns and those of learners whose L1 is also alphabetic.

Finally, the current results have clinical implications. Studies with brain damaged patients suffering from aphasia and acalculia showed dissociated impairment of verbal and non-verbal numerical abilities in bilinguals (Proios et al. 2002) as well as monolinguals (e.g., Cohen et al. 2000), and that bilingual patients' L1 or L2 may be differentially susceptible to the effects of damage (e.g., Marrero et al. 2002). Understanding the brain architecture of bilinguals' numerical and linguistic processing may help diagnosing and assessing the mechanisms underlying the spared or impaired performance in bilingual patients. It may also have impact for rehabilitation such that therapy could be conducted in the language that maximizes the patients' recovery and retrieval of various mathematical skills.

Research on mathematical processing in native and second languages enables us to unfold the neurocircuitry of numerical and linguistic operations. The significance reaches beyond language and mathematics per se to advance our understanding of how multisensory brain systems cooperate functionally in cognitive processing.

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