Research report

fMRI evidence for the automatic phonological activation of briefly presented words

Dan-ling Peng\textsuperscript{a}, Guo-sheng Ding\textsuperscript{a}, Conrad Perry\textsuperscript{b,*}, Duo Xu\textsuperscript{a}, Zhen Jin\textsuperscript{c}, Qian Luo\textsuperscript{a}, Lei Zhang\textsuperscript{c}, Yuan Deng\textsuperscript{a}

\textsuperscript{a} Beijing Normal University, Hong Kong, China
\textsuperscript{b} Joint Lab of Language and Neuroscience, The University of Hong Kong, Hong Kong, China
\textsuperscript{c} Beijing 306 Hospital, Beijing, China

Accepted 19 February 2004
Available online 14 April 2004

Abstract

Functional magnetic resonance imaging was used to investigate whether people generate the phonology of briefly presented words that they do not attend. This was done in Chinese by examining the effect of orthography–phonology regularity (i.e., how predictable the phonology of a word is from its components rather than whole-word form) with high- and low-frequency words, and by using a task that diverted participants’ attention to a mask, rather than the words. The results showed that there was a significant interaction between regularity and word frequency in blood oxygen level-dependent (BOLD) signal, which mirrored the pattern found in behavioral data. Specifically, for low-frequency characters, bilateral fusiform gyri, the posterior superior temporal gyrus, and inferior parietal regions were more active when using irregular compared to regular characters. There were no significant differences when high-frequency characters were used. These results support the possibility that at least for low-frequency words, phonology is automatically generated when reading, even when people do not attend to the words and even in a language where the orthography–phonology mapping is extremely irregular.

© 2004 Elsevier B.V. All rights reserved.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Chinese characters; Regularity; Word frequency; Unattended condition; Automatic activation

1. Introduction

When words have regular\textsuperscript{1} spelling–sound correspondences (e.g., cat, hit, lawn), they are read aloud faster than words that have irregular correspondences (e.g., have, pint, chef). This is known as the regularity effect. The regularity effect is often used to argue that phonology has been generated when reading. Interestingly, the effect is not stable across either task type or language. In French, for instance, the regularity effect occurs with both high- and low-frequency words [5,30]; in English, the effect sometimes occurs with high-frequency words [13], and sometimes it does not (e.g., Ref. [22]); and in Chinese\textsuperscript{2}, it occurs only with low-frequency words [12,21]. Similarly, in English lexical decision tasks, no regularity effect is typically found (e.g., Ref. [3]), and nor is a regularity effect typically found in English semantic classification tasks (e.g., Ref. [23]).

\textsuperscript{1} There is a distinction between regularity and consistency in the literature. Regularity refers to a metric derived from a set of rules (e.g., Coltheart et al. [4]), whereas consistency is a measure based on the number of occurrences of spelling–sound units (e.g., Treiman et al., 1995). For the purposes of this paper, the distinction is irrelevant.

\textsuperscript{2} The regularity of Chinese characters can be manipulated using the phonetic radical of Chinese characters. This is a subcomponent of the character, and it occurs in nearly 90% of all characters. It typically tells the reader something about the pronunciation of the character. The reliability of the phonetic component differs considerably, however. The phonetic component can go from being completely predictive of the character pronunciation (e.g., the “’huang’” in “’huang’/huang”) to completely unpredictable (e.g., the “’duo’/duo” in “’yi’/yi”). In general, however, the phonetic radical cannot be reliably used, because only 37.5% of Chinese characters use a phonetic radical that is able to determine the pronunciation of the character correctly (see Li and Kang [14], for a discussion).
These conflicting patterns of results have led some to suggest that the effect of phonology in reading is limited to tasks that require overt articulation of the stimuli [23]. The idea behind such a suggestion is that the regularity effect shows that phonology is used when reading, and when regularity effects are absent, it shows that people are not using phonology when reading. Based on this idea and a number of experiments showing purely orthographic effects occur in semantic classification tasks, Taft and van Graan [23] suggested that phonology might not be used in silent-reading tasks at all.

One problem with interpreting null effects of regularity to mean that phonology is absent in reading tasks is that it might be that phonology is used, but that the regularity effect is simply not a good marker of its use [1]. Thus, for instance, in a primed lexical decision task, Berent [1] showed that it was possible to prime the phonological representation of regular and irregular words. This was done by comparing the effect of pseudohomophone primes with the effect of graphemic controls (e.g., SONE priming swn vs. SNEP priming swn). The results showed that the pseudohomophones caused a priming effect compared to the graphemic controls, but no regularity effect was found. Berent [1] argued that because there was a pseudohomophone priming effect, it meant that phonology was used in the lexical decision task, even though the regularity effect failed to capture its use.

Further evidence that phonological effects occur in reading tasks comes from neuroimaging studies that have examined the regularity effect [11,10,20]. Those studies found that brain areas including the left inferior frontal gyrus (IFG), left superior temporal cortex, right inferior frontal areas and bilateral motor cortex were more activated when reading irregular words compared to regular words. This was despite the fact that in some of the studies, participants did not read aloud the words. In addition, it is unlikely that the differences found were due to stimuli confounds, as the stimuli in those studies were carefully controlled for potential confounds not related to regularity.

It is not only alphabetic languages where a regularity effect has been found. In an fMRI study, Tan et al. [27] investigated the brain mechanisms used for reading regular and irregular Chinese characters. The results of their study showed that irregular characters compared to regular characters produced larger MR signal intensity changes over extensive regions involving the left inferofrontal frontal cortex, left motor cortex, right inferofrontal gyrus, bilateral anterior superior temporal areas, and anterior cingulated cortex. Tan et al. [27] did not examine how the areas might interact with word frequency, however. These results were somewhat surprising because the probability of extracting the correct phonological information from a character is much less than extracting the correct phonological information from words in alphabetic languages, even in languages considered to have large amounts of spelling–sound irregularity, such as English. (In English, approximately 21% of all grapheme–phone correspondences used in words are irregular [29], whereas in Chinese, only 37.5% of characters can be predicted completely from their phonetic radical—i.e., the part of the character that contains the phonological information, including initial consonant, vowel and tone, which around 90% of characters have [14]).

We should note that the regularity effect in Chinese is somewhat different from that of English, because the phonetic radical (which is only part of the character) maps onto whole-character phonology (a syllable in Chinese), whereas in English, the regularity effect is due to part of a word (a grapheme) mapping onto part of its pronunciation (a phoneme). Thus, for example, all words that use “m” (e.g., “m”) are pronounced with the same syllable, although the phonetic radical constitutes only the right-hand part of the character.

In addition to the regularity effect, effects of word frequency have also been shown to exist in a number of studies examining brain activation [2,8]. These studies have found that low- and high-frequency words cause differences in activation in several brain regions such as the left inferior frontal gyrus (IFG). We [16] have further found that word frequency effects occur in a procedure where the attention of subjects is directed away from the words via the use of a mask (with a word exposure duration of 51 and 151 ms). The paradigm followed that of Dehaene et al. [6], in which people were exposed to words masked such that they could not be recalled. Instead of using a mask to completely obscure the stimuli, subjects in our task made a decision about the mask instead, and hence attended to it and not a word presented before the mask. The results showed that even at a relatively long exposure duration (151 ms), subjects could not recall what words they had seen. However, effects of being exposed to the words were still found. Presenting masked words to subjects in such a paradigm provides a very strong test of whether people use phonology when reading, because logically, participants do not need to process the words at all. Thus, any activation that is found should be related to automatic processing, rather than deliberately controlled processing.

In the current study, we examined the extent that participants use phonology when reading words of different frequency. In particular, we were interested in the interaction between the frequency and regularity effect that has been demonstrated in behavioral studies, but in conditions that are not necessarily conducive for its use (i.e., with an exposure duration of 151 ms and an attention diverting task that causes words to be unrecallable). Furthermore, we examined the effect in a language that should not be conducive to the use of phonology when reading (i.e., Chinese). The idea was to examine whether automatic phonological activation could be observed, even under silent unattended reading conditions that potentially
discourage its use and in a language where the orthography–phonology mapping is very irregular.

2. Methods

2.1. Subjects

Eight right-handed college students, four males and four females, aged from 18 to 28, participated in the study. Informed consent was obtained in accordance to the guidelines set by the Laboratory for Cognitive Science and Learning of the China’s Ministry of Education. They were familiarized with the procedure of the experiment before scanning. A further 20 subjects, who were from same subject pool but did not participate in the fMRI study, participated in a behavioral experiment identical to the fMRI experiment (i.e., luminance, screen size, font size, etc.), apart from being in the scanner.

2.2. Design and stimuli validation

One hundred twenty Chinese characters were used in a 2 × 2 (word frequency: high, low) × 2 (regularity: regular, irregular) design. There were an identical number of items in each of the four cells. Across each cell, characters were matched on stroke number, concreteness of meaning, character structure, and a number of other variables that are potentially important in Chinese reading (all t’s < 1). The stimuli were validated in a pilot experiment conducted in standard naming conditions (i.e., no masking). This was done with 15 subjects. The results showed that there was a significant interaction between frequency and regularity in both reaction times (RTs) and error rates (ERs) (p < 0.001 for RTs and p < 0.05 for ERs). Further analysis showed that the regularity effect was significant in RTs for low-frequency words only (low: p < 0.001; high: p > 0.1). For ERs, there was a significant regularity effect with both high- and low-frequency words, but the significance level was different (p < 0.001 for low-frequency words and p < 0.01 for high-frequency words). Mean stimuli information is presented in Table 1.

The fMRI experiment consisted of two runs (scanning sessions). The high- and low-frequency words were included in each run. The regular and irregular characters were presented in two different runs. The order of runs was counterbalanced across subjects. In each experimental trial, a character was presented for a duration of 151 ms followed by one of two figures (see Fig. 1) serving as a

![Fig. 1. Examples and arrangement of material. The tasks were arranged into six blocks. Three used high-frequency characters and three used low-frequency characters. Each block consisted of 20 trials. In each trial, a Chinese regular or irregular character was presented for 151 ms and was then replaced by a target drawing. This drawing remained on the screen until 1 s had elapsed from the initial presentation of the character. The control condition (baseline) also consisted of six blocks, with the control stimuli (character-like pictures), presented for the same duration as the test stimuli.](image)
mask. If the mask was “区块” (see Refs. [17,18]), the participant responded to it by pressing a button; otherwise, no response was made. In the baseline trials, the procedure was the same as the experimental trials, but the character was replaced by a noncharacter stimulus (“区块” or “区块”) that was very character-like.

Each run had 12 (30-s) blocks including six experimental blocks and six baseline blocks (see Fig. 1). In each run, within the experimental blocks, three blocks used high-frequency characters and the other three used low-frequency characters. Each block consisted of 20 (1.5-s) trials. In total, it took 6 min to finish a run.

**Behavioral experiment:** Response times and accuracy data were collected from the experiment. In addition, to see if the subjects attended to the masks instead of words in the different conditions, subjects were required to perform a recognition task after the experiment, in which they were asked to judge if the words in a list (only half of them were previously shown) had been previously displayed.

### 2.3. Apparatus and procedure

This study was performed on a 2T GE/Elscint Prestige whole-body MRI scanner (Elscint, Haifa, Israel). Functional scans were obtained by using a single-shot T2*-weighted gradient-echo echo planar imaging EPI sequence (20 contiguous axial slices, slice thickness=6 mm, in-plane resolution=2.9×2.9 mm, TR/TE/θ=3000 ms/65 ms/90°, FOV=373×210 mm²; matrix, 128×72). For each slice, 120 images were acquired with a total scan time of 360 s. The High-resolution anatomical image was acquired using a T1-weighted, three-dimensional, Spoiled GRASS imaging (SPGR) sequence resample (slice thickness=2 mm; FOV, 220×220 mm²; matrix, 220×220).

### 2.4. Data analysis

We used the AFNI 2.2 software (NIHM) for image processing. The images of the first four time points that were collected before the scanner reached equilibrium magnetization were discarded. Images were preprocessed using the iterated linearized weighted least-squares algorithm to correct small head motions. The impulse response functions were estimated for each voxel. General linear tests were used to test the significance of each condition at multiple time lags and then approximate the area under the curve by summing the impulse response function parameters over all time lags. The output represented by activation maps was used as input data for further group analyses.

After spatial normalization to the Talairach and Tournoux [25] brain atlas, resampled as 1 mm³ and smoothed with FWHM=3 mm, the activation maps of individual subjects were analyzed with the applied linear statistical model using a two-factor analysis of variance and post hoc t-tests. For the contrast between words and the baseline, the voxelwise threshold was set at \( p<0.05 \). We corrected statistical maps to a \( p<0.05 \) significance level estimated by Monte Carlo simulation for multiple comparisons based on the results of a Monte Carlo simulation at the cluster level. The Talairach coordinates of the max-of-mass and volume \( (\text{mm}^3) \) of the activation clusters were determined based on the averaged activation maps.

### 2.5. ROI analysis

#### 2.5.1. Selection of ROI

Based on previous studies of language processing, several regions of interest (ROIs) involved in word reading were identified to examine the regularity effect: bilateral inferior frontal gyri [around Broca’s area (BA44/45/46), posterior superior temporal gyri (Wernicke’s area, BA22), inferior parietal lobules (BA 40), and fusiform gyri (BA37/21)]. The ROIs were demarcated on the high-resolution SPGR images slice-by-slice according to the boundary of Brodmann Areas in the atlas of Talairach and Tournoux [25]. For each ROI, regional activation intensity under each condition for each subject was computed by averaging the intensity value in each voxel based on the individual activation maps. These values were then submitted to standard statistical analysis.

### 3. Results

#### 3.1. Behavioral

In terms of responses to the masks, no significant RT or accuracy difference under the four different conditions was found, all \( F<1 \). The average RT was 445 ms for high-frequency characters and 442 ms for low-frequency characters in the regular word condition; and 455 ms for high-frequency characters and 439 ms for low-frequency characters in the irregular word condition. The accuracy rate was at ceiling (above 95%) across all conditions.

In terms of the accuracy rate of word recognition, all groups were at the chance level. In the regular word condition, the Hit rate/Miss rate/False alarm rate/Correct rejection rates were 37.9%/62.1%/37.6%/62.4% for high-frequency trials and 34.9%/65.1%/33.5%/66.5% for low-frequency trials. In the irregular word condition, the Hit rate/Miss rate/False alarm rate/Correct rejection rates were 36.9%/61.3%/32.2%/67.8% for high-frequency words and 36.2%/63.8%/35.2%/64.8% for low-frequency words, all \( t<1 \). Besides the Hit/Miss rates, we also calculated the sensitivity \( (d') \) and the subjective bias \( (\beta) \) in each condition. In the regular word condition, the \( d' \) and \( \beta \) values were 0 and 1, respectively, for both high-frequency trials and low-frequency trials. In the irregular word condition, the \( d' \) and \( \beta \) values were 0.14 and 1.06, respectively, for high-frequency words and 0.03 and 1.01, respectively, for low-frequency words.

Overall, because neither spelling–sound regularity nor character frequency caused significant differences in Hit/
Miss, False alarm/Correct rejection rates, it suggests that subjects attended to the masks and not the characters during the experiment.

3.2. Brain imaging

The results of the brain imaging studies are shown in Fig. 2 and Table 2.

Results found showed that significant areas were recruited by high-frequency irregular words in the bilateral fusiform gyri (BA37) and the right superior temporal gyrus (BA38) (corrected $p<0.05$); by low-frequency irregular words in bilateral middle temporal gyri (BA21), bilateral fusiform gyri (BA37), bilateral cerebellum, the left middle frontal gyrus (BA6), the right inferior frontal gyrus (BA47) and the right superior temporal gyrus (BA38) (corrected $p<0.05$). A common area was the right fusiform gyrus (BA37). A comparison between low- and high-frequency irregular words showed a significant difference between activation produced in the right middle temporal gyrus (BA21) (corrected $p<0.05$).

Significant areas recruited by high-frequency regular words were bilateral fusiform gyri (BA37) and cerebellum, left medial occipital gyrus (BA18), superior occipital gyrus (BA19), occipitotemporal junction (BA21/37) ($p<0.05$); by low-frequency regular words were bilateral fusiform gyri (BA37), bilateral cerebellum, left medius occipital gyrus.

Table 2

Peak activation loci and $t$ scores in each condition

<table>
<thead>
<tr>
<th>Regions activated</th>
<th>BA</th>
<th>Regular characters</th>
<th>Irregular characters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High frequency</td>
<td>Low frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x$ $y$ $z$ $t$</td>
<td>$x$ $y$ $z$ $t$</td>
</tr>
<tr>
<td>Frontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R medial frontal gyri</td>
<td>6</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>R inferior frontal gyri</td>
<td>47</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>Temporal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R superior temporal gyri</td>
<td>38</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>R superior temporal gyri</td>
<td>22</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>L medial temporal gyri</td>
<td>21</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>R medial temporal gyri</td>
<td>21</td>
<td>– – – –</td>
<td>– – – –</td>
</tr>
<tr>
<td>Occipital</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L fusiform gyri</td>
<td>19</td>
<td>31 –65 –16 2.75 37</td>
<td>–66 –10 3.03</td>
</tr>
<tr>
<td>L superior occipital gyri</td>
<td>19</td>
<td>19 –84 16 3.08</td>
<td>– – – –</td>
</tr>
<tr>
<td>L medial occipital gyri</td>
<td>18</td>
<td>28 –84 7 3.01 36</td>
<td>–81 –20 3.45</td>
</tr>
<tr>
<td>L Cerebellum</td>
<td>–</td>
<td>31 –63 –19 2.68 37</td>
<td>–73 –22 2.79</td>
</tr>
<tr>
<td>R Cerebellum</td>
<td>–</td>
<td>–34 –52 –18 3.16 37</td>
<td>–43 –39 2.48</td>
</tr>
</tbody>
</table>

*Cluster threshold: 4000 mm$^3$.

*Cluster threshold: 2000 mm$^3$. 

Fig. 2. Brain activation for different stimuli vs. the baseline (corrected $p<0.05$).
(BA18), superior occipital gyrus (BA19), and right superior temporal gyrus (BA22).

Comparing the irregular and regular words, we found that low-frequency irregular words caused significantly stronger activation than regular words, with a significant difference in the right inferior frontal gyrus (BA47) and bilateral medial temporal gyri (BA21) ($p<0.05$). There was no significant difference between high-frequency irregular and high-frequency regular words (all $p's>0.05$).

### 3.3. ROI analysis

Further ROI analysis (see Fig. 3) was performed using a general linear model (GLM) using the SPSS 10.0 software package in the fusiform gyrus, the inferior prefrontal gyrus, and the inferior parietal gyrus. The results showed that there was a significant main effect of frequency at all ROIs (all $p's<0.05$) except for the left inferior parietal gyrus which only approached significance ($p=0.08$). There was also a significant main effect of regularity in the left fusiform gyrus ($p<0.05$). The interaction between frequency and regularity was significant at all ROIs (all $p's<0.05$) except for the left inferior parietal gyrus ($p>0.1$). In a further analysis, a nonparametric Wilcoxon signed-rank test showed that there was a significant regularity effect in bilateral fusiform gyri (left: $z=2.52$, $p<0.05$; right: $z=2.1$, $p<0.05$); the posterior superior temporal gyrus (left: $z=2.24$, $p<0.05$; right: $z=1.96$, $p<0.05$), and the left inferior parietal ($z=1.96$, $p<0.05$), where stronger activation was evoked in the low-frequency condition by irregular vs. regular words. A significant frequency effect was also found in all selected ROIs (low>high, all $p's<0.05$) when only irregular words were examined.

### 4. Discussion

#### 4.1. Basis of the lexicality effect

Compared to noncharacter masks (baseline), several brain areas were activated by characters including bilateral fusiform gyri/tempooccipital junction (BA37/21), the right superior temporal gyrus (BA22), the left inferior frontal gyrus (BA47), SMA (BA6) and bilateral cerebella. None of the areas found in this study is unique, and the results are consistent with many other studies examining alphabetic languages (see Ref. [9], for a review and discussion). Because our task did not require deliberate controlled processing, our results extend these findings by showing that these areas are automatically activated even in character-based languages in conditions where people do not attend to the words.

A potentially surprising pattern in the overall results is that the amount of activation in the medial cortex compared...
to the inferior frontal gyri was greater than many language tasks that have been reported. Although we can only speculate as to why this is, there are at least two potential reasons. One is that Chinese reading tasks tend to display more activation in the medial cortex than English reading tasks. This is not only true of reading individual words [26] but also of syntactic processing [15]. The second is that the mask may have had an affect on various aspects of processing that we did not specifically examine that typically occur in unmasked conditions in the inferior frontal gyri, such as the processing of individual word semantics (e.g., Ref. [7]).

4.2. Orthography–phonology regularity

The results of our ROI analysis showed that the BOLD signal displayed a significant interaction between regularity and word frequency, with the regularity effect only occurring with low-frequency characters. Compared to low-frequency regular characters, low-frequency irregular characters caused more activation in the right inferior frontal gyrus (BA47) and bilateral medial temporal gyrus (BA21). Alternatively, with high-frequency characters, there was no significant difference in any ROIs. These results confirm the possibility that, at least for low-frequency words, phonology is generated automatically when reading, even in what might be considered circumstances particularly unfavorable for its generation, a language where orthography–phonology relationships are weak, and in a task where people do not attend to the words. These results are consistent with those reported in a number of behavioral experiments (e.g., Refs. [12,22,28]).

One particularly important aspect of the data was that our results also showed that bilateral middle-temporal areas (BA21) were involved in reading Chinese characters. However, the results differed depending on the type of character used. When low-frequency irregular characters were used, bilateral activation was found in the middle-temporal area (BA21), unlike when regular or when high-frequency characters were used. At least for left BA21, these results are consistent with those of Tagamets et al. [24], who reported that activation of BA 21 was reduced with words of increasing familiarity. This suggests that character familiarity in Chinese is modulated by the interaction between the frequency and regularity of the character, rather than either one of those forms separately.

An important cross-linguistic difference exists between this pattern and that found in alphabetic languages. In particular, although a regularity by frequency interaction is also found in the BOLD signal of people reading alphabetic languages, the specific areas activated by irregular Chinese characters compared to irregular words in alphabetic languages is different. In general, in alphabetic languages, it is the left frontal opercular (the borders of BA44/BA45) that is activated more by low-frequency irregular words than low-frequency regular words [9]. That result, combined with others that have shown that working memory tasks also use that area, have lead some to suggest that part of the regularity effect in reading arises in the context of a phonologically based rehearsal strategy [10]. Alternatively, left BA21 was more activated by low-frequency irregular words in this study, as were areas in the right superior temporal gyrus (BA 38).

One potential reason for the activation in right BA38 is that the resolution of irregular phonology in Chinese needs to be done at a level that does not exist in English: a tone level. In this case, since all syllables used in Chinese may be pronounced in up to four different tones (i.e., the same syllable can be pronounced either falling, rising, high, or falling then rising—this gives the syllable a different lexical status), both the correct syllable and the correct tone for that syllable needs to be retrieved. This idea is supported by the fact that previous research [27] has suggested that mediation of tonal information in Chinese reading occurs in the right superior temporal gyrus.

4.3. Word frequency

The other main result of interest was the fact that we found no frequency effect with regular words. This differs from a number of other studies that have found frequency effects with regular words (e.g., Ref. [8], but see Ref. [2] who found the effect in a semantic by not silent reading task). The most likely reason for this is that it is because of the word exposure duration we used and the fact that our participants did not attend to the words in our task. This is consistent with our previous results where we examined regular words [16]. In that study, identical conditions were used, except that we used an exposure duration of 51 and 151 ms, rather than just 151 ms. At 151 ms, we did not find a frequency effect. However, at the 51-ms exposure duration, we found differences between low- and high-frequency words in the bilateral fusiform gyri, cerebella, posterosuperior temporal lobe, and inferior prefrontal lobe.

The combination of these results is important because they isolate three different components of character recognition. In particular, very early in processing (i.e., when 51-ms exposure durations are used), there is a short-lived frequency effect. That effect is not found at longer exposure durations (i.e., when a 151-ms exposure duration is used). However, even when there is no frequency effect with regular words, there is still an effect of regularity for low-frequency words. Finally, when reading tasks are used that require attention, in some but not necessarily all conditions, frequency effects are again found.

This combination of results points to a multicomponent system where different types of information are being processed at different levels. In particular, the fact that very early frequency and late attention-based frequency effects occur suggests that there are two quite different sources of frequency effects. As for the latter attention-based frequency effects, some authors [10] have suggested that these are related to rehearsal strategies that are phonologically based.
Our paradigm would have minimized these by directing participants’ attention to a mask, and hence we did not find such an effect. This is also consistent with the fact that Chee et al. [2] failed to find a frequency effect in a silent-reading task. In this case, due to the nature of the task, participants task may not have been using phonologically based rehearsal strategies. In addition, because most major models of reading suggest that frequency effects arise at an orthographic level, whether they be of lexical [4] or semantic [19] form, the very early frequency effect may be arising from processing at that level. Alternatively, the later occurring regularity effect is most likely to be caused by some form of conflict resolution processes, whereby different conflicting phonology generated lexically and sublexically is resolved.

5. Conclusion

By examining reading processes using words that subjects do not attend, it was possible to examine the automatic activation of brain areas when reading. This was done using high- and low-frequency regular and irregular Chinese words. A significant interaction between regularity and frequency was found in the neuroimaging data, which is consistent with behavioral results. The results of an ROI analysis showed that bilateral fusiform gyri, the posterior superior temporal gyrus, and the left inferior parietal gyrus were more active for words with regular compared to regular orthography–phonology correspondences, but only for low-frequency words. These results suggest that phonology is activated automatically, even in conditions where words are not attended and in a language far less conducive to phonology processing than alphabetic languages. In addition, because the areas specifically activated by the irregular words differ somewhat to similar studies using alphabetic languages, they suggest that important cross-linguistic differences exist.

Acknowledgements

This work was supported by the National PANDENG Project (95-Special-09), the National Basic Research Program (G1999054000) of China granted to the first author and a UDF grant from the University of Hong Kong to the corresponding author.

References