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Combined ERP/fMRI Evidence For Early Word Recognition Effects In The Posterior Inferior Temporal Gyrus

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Abstract

Two brain regions with established roles in reading are the posterior middle temporal gyrus and the posterior fusiform gyrus. Lesion studies have also suggested that the region located between them, the posterior inferior temporal gyrus (pITG), plays a central role in word recognition. However, these lesion results could reflect disconnection effects since neuroimaging studies have not reported consistent lexicality effects in pITG. Here we tested whether these reported pITG lesion effects are due to disconnection effects or not using parallel ERP/fMRI studies. We predicted that the Recognition Potential (RP), a left-lateralized ERP negativity that peaks at about 200–250 ms, might be the electrophysiological correlate of pITG activity and that conditions that evoke the RP (perceptual degradation) might therefore also evoke pITG activity. In Experiment 1, twenty-three participants performed a lexical decision task (temporally flanked by supraliminal masks) while having high-density 129-channel ERP data collected. In Experiment 2, a separate group of fifteen participants underwent the same task while having fMRI data collected in a 3T scanner. Examination of the ERP data suggested that a canonical Recognition Potential effect was produced. The strongest corresponding effect in the fMRI data was in the vicinity of the pITG. In addition, results indicated stimulus-dependent functional connectivity between pITG and a region of the posterior fusiform gyrus near the visual word form area (VWFA) during word compared to nonword processing. These results provide convergent spatiotemporal evidence that the pITG contributes to early lexical access through interaction with the VWFA.

Keywords

ERP; fMRI; Language; Lexical Decision; Recognition Potential

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1. General Introduction

The remarkable human ability to decode written language into meaning relies on multiple cognitive subsystems. It is generally agreed is that the reading comprehension system involves a division between a phonological decoding subsystem and an orthographic decoding subsystem (Coltheart et al., 2001; Plaut et al., 1996). While reading comprehension models differ on how these two domains of information relate to each other, they all agree that they must be coordinated in some fashion. The Dual Route Cascaded or DRC model (Coltheart et al., 2001) terms it "indexed phonology", wherein an entry in the orthographic lexicon enables accessing of an entry in the phonological lexicon. Likewise, a version of the Triangle Model cites a general process of resonance between subsymbolic representational domains (Stone and Van Orden, 1989; Van Orden and Goldinger, 1994).

The functional neuroanatomy linking orthographic and phonological decoding systems is not well understood, although there is a general agreement that the reading pathways can be distinguished (Jobard et al., 2003; Price, 2012; Vigneau et al., 2006). It is well-agreed that orthographic decoding relies importantly on the inferior temporal surface, sometimes termed the basal temporal language area (Burnstine et al., 1990; Büchel et al., 1998; Lüders et al., 1986, 1991; Mani et al., 2008; Schäffler et al., 1994). According to the local combination detector (LCD) model (Dehaene et al., 2005), the inferior temporal region consists of a gradient of posterior-to-anterior areas that associate increasingly larger chunks of information, starting with letter features, then letters, then bigrams, and eventually entire words. This model is supported both spatially by fMRI data (Levy et al., 2008; Vinckier et al., 2007) and temporally by ERP data (Dien, 2009b).

Furthermore, neurological data suggests that this gradient of increasingly higher levels of word features continues into the anterior temporal regions, mediating increasingly finer gradations of semantic representations (Patterson et al., 2007). In general, this pathway is centered on the fusiform gyrus (FG). Within the broad expanse of the FG, a region labeled the Visual Word Form Area (VWFA), located at roughly y=−50, is thought to mediate pairwise letter associations, or bigrams (Binder et al., 2006; Dehaene and Cohen, 2011; Dehaene et al., 2005; Dien, 2009a; McCandliss et al., 2003; Polk and Farah, 1997). Such a system could be instantiated as a series of modules (not necessarily encapsulated), each consisting of connectionist networks. It has also been suggested (Dien and O'Hare, 2008) that a more anterior portion of this pathway between about y=−30 to −40, the Fusiform Semantic Area or FSA, might mediate word-level associations due to its responsiveness to semantic manipulations (Binder et al., 2009; Dien and O'Hare, 2008; Moore and Price, 1999), which may occur in a relatively automatic manner (see Gold et al., 2006).

Another key neural hub in the reading system centers on a posterior portion of the left middle temporal gyrus (pMTG). Results from functional neuroimaging studies have suggested that this region is involved in post-lexical processing downstream of the VWFA, either semantic (Binder et al., 2009; Demonet et al., 1992; Gold and Buckner, 2002; Hickok and Poeppel, 2004; Jobard et al., 2003, 2003; Lau et al., 2008; Shannon and Buckner, 2004) or phonological (Blumstein, 2009; Dronkers et al., 2004; Indefrey and Levelt, 2004). It may be that the pMTG, centered on [−49 −54 13] by one review (Jobard et al., 2003), is the phonological equivalent of the FSA of the orthographic pathway (whatever their roles may be). Such a view would be consistent with the report (Cohen et al., 2004) of a possible phonological counterpart to the VWFA located in the left anterior superior temporal sulcus.

Given the prominent role of the lateral temporal lobe (notably pMTG) and the ventral temporal lobe (notably FG) in the neuroanatomy of reading, the question arises as to whether the area in-between might participate in reading processing as well. Some initial

evidence for such a role arises from observations of lesion effects to the so-called Language Formulation Area or LFA (Nielsen, 1946). Nielsen described the LFA as being "area 37 of Brodmann in association with the posterior part of areas 21 and 22" (p. 32). This region includes posterior portions of the fusiform gyrus, the inferior temporal gyrus, and the middle temporal gyrus. He observed that anomias (where the patient displays full semantic knowledge of objects but is unable to name them, although they are able to recognize the word if presented with it) are particularly characteristic of damage to this region (p. 127). In modern terms, this might be called a convergence zone and indeed it is part of a broader region described as such (see Damasio et al., 2004).

The central portion of this broad LFA region is the posterior inferior temporal gyrus (pITG). The pITG, situated as it is midway between the orthography and phonology regions (Figure 1), would appear to be ideally situated to bridge orthographic and phonological reading subsystems (Dien et al., 2008; Tagamets et al., 2000). Thus, one might expect that lesions would prevent the ability to directly link orthography with phonology (by analogy to visual object anomias), or indexed phonology, while having less effect on assembled phonology. Especially pertinent data has been provided by Japanese lesion cases. The Japanese language has both a logographic script (kanji) that should require indexed phonology and a syllabic script (kana) that can be sounded out. A double dissociation has been found in that lesions of the temporal lobe which include the pITG impair reading of kanji whereas parietal lesions centered on the angular gyrus impair reading of kana (Iwata, 1984; Sakurai et al., 1994; Sakurai, 2004; Yamadori, 2000; Yamawaki et al., 2005), although for a dissenting view see Sugishita, Otomo, Kabe, and Yunoki (1992).

While lesion studies are compelling because they provide direct tests of brain function (i.e., the brain loses a function when a specific part of it is damaged), as with all neuroscience methods, lesion evidence has limitations. A prime concern is what is termed "disconnection" syndromes (Geschwind, 1965). The problem is that the effects of a lesion may not in fact be due to the damage to the neuronal cell bodies in the gray matter but rather due to interruption of white matter tracts from other parts of the brain that just happen to pass through the lesioned area. For example, it has been suggested that some of the more severe aphasic symptoms attributed to lesions of Broca's Area are actually due to damage to the underlying superior longitudinal fasciculus (Dronkers et al., 2007).

Thus, lesion evidence alone cannot be relied upon to determine functional neuranatomy. Convergent evidence is required to rule out disconnection syndromes as an explanation of lesion effects. Some supporting data comes from a report (Schwartz et al., 1999) that intracranial stimulation of posterior temporal cortex at or near the pITG resulted in disruption of both reading and naming. Nonetheless, intracranial stimulation can also be somewhat unspecific because it may have effects across large portions of cortex. Ideally, one would want converging evidence from neuroimaging studies since BOLD effects are attributable solely to the local gray matter and are not caused by signals being transmitted along white matter tracts.

To date, however, neuroimaging studies have been inconclusive as to the role of pITG in word recognition. Indeed, a meta-analysis of reading aloud studies (Turkeltaub et al., 2002) did not identify it as an area of interest. There have been both reports where no lexicality (i.e., word vs. non-word) effect was found in the vicinity of the pITG (Carreiras et al., 2007; Fiebach et al., 2002; Fiez et al., 1999; Herbster et al., 1997; Mechelli et al., 2005; Woollams et al., 2011) and others where there were lexicality effects in pITG (Binder et al., 2003, 2005; Hagoort et al., 1999; Ischebeck et al., 2004; Price et al., 1996). Even fMRI studies of kana versus kanji have been inconclusive with respect to the pITG (Nakamura et al., 2000, 2002, 2005).

Some reason for optimism is provided by the especially strong contrast provided by comparing across languages. A prominent PET study (Paulesu et al., 2000) reported that Italian readers (who have a phonologically transparent language) activate the superior temporal gyrus to a greater extent than English readers (who have a phonologically dense language), and who in turn activate the pITG to a greater extent. Likewise a similar pattern is seen when comparing Hindi (phonologically transparent) to English for simultaneous bilingual learners, wherein Hindi produces more inferior parietal activation and English produces more pITG activation (Das et al., 2011). Such observations are consistent with fMRI evidence that there are at least two posterior reading pathways starting in visual cortex, an orthographic one that follows along the inferior temporal surface and a phonological one anchored in the inferior parietal (Levy et al., 2008, 2009; Richardson et al., 2011); however, these studies did not implicate the pITG. It may be that what is needed to reliably reveal involvement of the pITG in reading in a pure sample of English readers is just a stronger manipulation.

One such strong manipulation is suggested by the ERP literature. The Recognition Potential or RP has repeatedly demonstrated robust lexicality effects that are reliably visible only when the stimuli are degraded by temporally flanking them with supraliminal masks, even though behavioral performance is largely unaffected. Similarly, it may be that the pITG can indeed display a lexicality effect but only under conditions of perceptual degradation. An immediate motivator for the present study was the observation of a pITG effect in a prior study (Dien et al., 2008) paralleled by a borderline significant ERP effect (Dien et al., 2004) displaying the same condition effects and resembling an RP in its scalp topography and latency.

We therefore set out to determine whether the conditions that elicit a lexicality (i.e., word vs. non-word) effect in the RP component of the ERP also elicit an fMRI lexicality effect in the pITG by first supporting that we could replicate the classical RP effect using ERP methods and then using the same task with fMRI methods. Such fMRI data would provide crucial evidence that the pITG is indeed sensitive to word recognition and therefore would support the proposed functional neuroanatomical account in which the pITG serves to link associations between the lateral and inferior temporal lobe reading regions. Furthermore, if it were confirmed that the RP is generated in part from the pITG, it would help clarify the latency of the pITG activity and help provide a further test of its proposed function.

2. ERP Experiment Introduction

The ERP experiment was primarily concerned with replicating the standard Recognition Potential effect, a left-lateralized negativity that peaks at about 200–250 ms. Although it was given the evocative name of "Recognition Potential" by its discoverer (Rudell, 1991), it is not yet clear what kind of process it reflects, other than that it seems to reflect an early stage of word recognition processing (for reviews, see Dien, 2009b; Martín-Loeches, 2007). It has been suggested that RP source analyses have been consistent with both the Visual Word Form Area (Martín-Loeches et al., 2001) and the pITG (Dien, 2009b). Furthermore, the RP lexicality effect is normally difficult to detect unless the stimuli are visually degraded via temporally flanked by masks at an SOA of about 250 ms (Iglesias et al., 2004).

Since optimizing the experimental parameters for fMRI purposes meant modifying the conventional ERP paradigm, the primary purpose of the ERP study was to check whether that the modified task would still elicit an RP effect. The usual rapid stream stimulation procedure (in which there is a continuous stream of stimuli alternating with masks) was modified to involve discrete trials of stimuli flanked by masks, with intertrial intervals long enough to be optimal for detecting hemodynamic responses even for the ERP experiment to

ensure a common experimental design across the two imaging modalities. On each trial, the participants performed a lexical decision judgment (deciding whether the stimulus was a word) on bisyllabic letter strings that are either temporally flanked by masks at 250 ms SOA or not. For reasons that are irrelevant to the present report and will not be further discussed due to lack of significant results, the stimuli themselves were divided into two colors with a boundary that is either congruent with the syllable boundary or not. If the RP could be reliably evoked, then the task would be repeated with a new set of participants (to avoid practice effects) in an fMRI scanner.

2.1 ERP Experiment Material and Methods

Participants—Twenty-six volunteers participated in the ERP portion of the experiment in exchange for honoraria, following a protocol approved by the University of Louisville Institutional Review Board. Two were dropped due to poor behavioral performance (less than 60% correct where the chance level was 50%) and one was dropped due to excessive artifact, leaving twenty-three retained for the final analyses (7 male, 16 female; mean 27.7 and standard deviation 13.1 years old). All had normal or corrected-to-normal vision, were right-handed, and were native English speakers. The mean handedness score on the 10-item Edinburgh Handedness Inventory (Oldfield, 1971) was +90.0 (12.9 standard deviation). None reported any history of brain injury, attention deficit disorder, or dyslexia.

Stimuli—The stimuli consisted of 160 words (nouns, verbs, and adjectives) with a length of 4–6 letters (mean 5.36; standard deviation 0.61), log HAL frequency of 7 or less (mean 5.65; standard deviation 1.01) by the English Lexicon Project (Balota et al., 2007), and a CVCV phonetic pattern by the MRC Psycholinguistic Database (Coltheart, 1981). By the English Lexicon Project, these words had a mean phonographic neighbors of 2.02 (standard deviation 2.27), mean mean-token bigram frequency of 1565.14 (881.96 standard deviation), mean lexical decision time of 753.57 (standard deviation 79.85), and a mean naming reaction time of 670.26 standard deviation 66.07). There were also 160 pronounceable non-words exactly matched in length, with a length of 4–6 letters (mean 5.36; standard deviation 0.61), derived from the ARC Nonword Database (Rastle et al., 2002). These nonwords were specified to have four phonemes, consist of legal bigrams, to have orthographically existing bodies, and to have orthographically existing onsets.

The stimuli were presented in 60 point Cambria font (half green and half red on a black background). Visual noise was distributed throughout a rectangular area around the stimuli (5% random dots sprinkled in the stimulus area) per standard practice for Recognition Potential experiments (e.g., Rudell and Hua, 1997). The visual noise was also colored red or green depending on the side of the stimulus. A thin boundary devoid of visual noise separated the two halves (see Figure 2).

Masks were generated by taking the same set of stimuli, dividing them into portions equaling the number of letters minus one, and then transposing the corresponding portions (first and last, second and second-to-last, etc.), following the methodology for creating "control stimuli" in a previous Recognition Potential experiments (Martín-Loeches et al., 1999). This procedure results in garbled stimuli that have the same general visual characteristics as the original words and nonwords but where most of the letters are no longer recognizable.

Procedure—The task was lexical decision. Experiment sessions were run using E-Prime 1.2 (Psychology Software Tools Inc., Pittsburgh PA). The session started with two practice sections with ten trials each (using stimuli not used in the experiment itself). The first practice section just presented the target stimuli and provided feedback after each one as to

whether the response was correct or not. The second practice section added the masks and removed the feedback. The participants were told to ignore the masks. The second section was repeated until the participant achieved 80% correct. Two runs of 160 trials each then followed, each lasting 7.5 minutes. Whether stimuli were presented in the first or second half of the experiment was counterbalanced across participants.

During each trial, first there was an intertrial interval randomly ranging from 1300 to 1600 ms. Then, a mask was presented for 250 ms, then the target stimulus for 250 ms, then a mask for another 250 ms, and finally a 1500 ms response period. A white fixation plus was visible throughout. The participant's task was to make a lexical decision as quickly and accurately as possible. They were also instructed to ignore the colors of the stimuli. The responses were registered with the left and right forefingers (word/nonword button counterbalanced across participants). The participant rested his/her chin on a chinrest 57cm from the LED computer monitor. The visual angle of the stimuli is not available, as the laboratory no longer exists. The stimuli were presented in a random order.

Data Collection—ERPs were recorded at a 250 Hz sampling rate using a 129-channel GSN200 geodesic net system (Tucker, 1993) manufactured by Electrical Geodesics, Incorporated and NetStation 4.2 software. The data were referenced to Cz (the recording reference is irrelevant as data can be mathematically referenced, see Dien, 1998). The impedance criterion was 50k ohms, which according to the vendor is appropriate for the system, which has been designed to accommodate high impedances (via the use of high amplifier input impedances).

Data Analysis—The data were low-pass filtered at 30 Hz. Artifacts were removed by using the EP Toolkit (Dien, 2010), available for download at http://homepage.mac.com/jdien07/), to remove independent components analysis factors (Delorme and Makeig, 2004) that correlated .9 with an automatically generated eyeblink template (Frank and Frishkoff, 2007). In addition, global bad channels were defined as having an R-squared of less than .4 when predicted by the neighboring six channels and trialwise bad channels were defined as either differing from neighboring channels by at least 30 μv or having a range of over 100 μv. Bad channels were replaced by interpolating the scalp voltage map at each time point. Finally, movement artifacts were removed by computing a temporal PCA on each trial and then removing factors with a maximum voltage range of over 200 μv. Finally, data were baseline corrected and average referenced (Bertrand et al., 1985; Dien, 1998). Only correct trials were included in the averaged waveforms. The average number of trials per condition per participant ranged from 33 to 36 (range of 22 to 40 within participants).

Conventional windowed measures were obtained by taking the mean of the voltage within the time points of interest and the channels of interest. For the Recognition Potential measure, the time points were 152–252 ms (based on visual inspection) and the channels were grouped around PO7 (e59, e60, e65, e66, e67, e71, and e72) and PO8 (e77, e78, e84, e85, e86, e91, and e92). The PO7 channel was chosen based on the existing literature (Martín-Loeches, 2007) and the PO8 channel was chosen as the corresponding right-sided electrode site.

ANOVAs were carried out with three factors: Lexical (word vs. nonword), Mask (masked vs. unmasked), and Syllable (division congruent vs. incongruent), resulting in a maximum of 40 trials per cell. For the Recognition Potential analyses, there was an additional factor of Hemisphere (left vs. right). Only correct trials were used for the ERP waveforms and the reaction time analyses.

Statistical Tests—Following standard procedure, robust ANOVAs (denoted by "TWJt/c") were used to test effects (Keselman et al., 2003), as implemented in the EP Toolkit (Dien, 2010). The purpose of the robust ANOVA is to achieve a Type I error rate that more closely complies to the nominal alpha rate than the conventional ANOVA by: 1) using bootstrapping to estimate the population distribution rather than assuming a normal distribution, 2) using trimmed means to be more resistant to outliers, and 3) using a Welch-James statistic to not assume a homogenous variance-covariance structure. Further discussion of the limitations of conventional ANOVAs, as they apply to ERPs, is available elsewhere (Dien and Santuzzi, 2005). The experience of the authors is that the robust statistic is generally more conservative than conventional F-tests (for side-by-side comparisons, see Dien et al., 2006). Aside from being more robust to violations of assumptions, the statistic is otherwise comparable to a conventional t-statistic and p-values are interpreted in the usual manner. Note that robust statistics (specifically the use of non-pooled error variance estimates) is endorsed by the journal Psychophysiology in their Guidance to Authors (as of December, 2009). A 5% symmetric trim rule was used. The seed for the number generation was set at 1000. The number of iterations used for the bootstrapping function was 50000. P-values are rounded to the second significant digit (where available). Condition means where given are the trimmed means.

Source Analysis—Source analyses were conducted on the grand average waveforms with LORETA-KEY (Pascual-Marqui et al., 1994) with a regularization parameter of zero. Based on inspection of the waveforms, fits were performed at 200, 250, and 300 ms.

2.2 ERP Experiment Results

Behavioral Data—For the median reaction time measures (in milliseconds), the reaction time was faster for words versus non-words: Lexical, TWJt/c(1.0,20.0)=30.53, p=0.00012 (Nonword 840, Word 729). Additionally, the reaction time was faster when there were no masks than when there were masks: Mask, TWJt/c(1.0,20.0)=6.04, p=0.027 (Masked 798, Unmasked 772). The interaction was not significant.

For the accuracy measures, the accuracy was higher when there were no masks than when there were masks: Mask, TWJt/c(1.0,20.0)=11.72, p=0.0023 (Masked .84, Unmasked .87). There was also an interaction between Lexical and Mask such that non-words were judged more accurately when not masked: Lexical by Mask, TWJt/c(1.0,20.0)=9.69, p=0.0076 (Nonword Masked 0.83, Nonword Unmasked .90, Word Masked .84, Word Unmasked .85).

ERP Data—For the Recognition Potential windowed measure (Figure 3), the RP amplitude was higher for words than for nonwords: Lexical, TWJt/c(1.0,20.0)=5.92, p=0.020 (Nonword −2.88, Word −3.31). It was also higher when there was no mask than when there were masks: Mask, TWJt/c(1.0,20.0)=4.88, p=0.036 (Masked −2.74, Unmasked −3.46). There was also an interaction such that the lexical effect was almost entirely for the masked condition only: Lexical by Mask, TWJt/c(1.0,20.0)=8.15, p=0.017 (Nonword Masked −2.30, Nonword Unmasked −3.45, Word Masked −3.17, Word Unmasked −3.46). There was a borderline significant tendency for the RP amplitude to be higher on the left: Hemisphere, TWJt/c(1.0,20.0)=3.93, p=0.057 (Left −3.33, Right −2.87). This hemispheric effect was significantly larger for congruent than incongruent words: Hemisphere by Syllable, TWJt/c(1.0,20.0)=5.42, p=0.026 (Left Congruent −3.40, Right Congruent −2.82, Left Incongruent −3.25, Right Incongruent −2.91). This hemispheric effect of congruent syllables was greatest for words: Hemisphere by Lexical by Syllable, TWJt/c(1.0,20.0)=7.17, p=0.032 (Left Nonword Congruent −3.04, Right Nonword Congruent −2.62, Left Nonword Incongruent −3.16, Right Nonword Incongruent −2.69, Left Word Congruent −3.76, Right Word Congruent −3.03, Left Word Incongruent −3.34, Right Word Incongruent −3.12).

The source analyses (Figure 4) yielded left-lateralized temporal generator locations in the vicinity of both VWFA and pITG at all three latencies of 200, 250, and 300, ms. At 200 ms., the three chief peaks were at BA17 [−17 −102 −13], BA18 [−3 −81 1], and the fusiform gyrus [−45 −53 −20]. At 250 ms., the three chief peaks were at BA17 [−17 −102 −13], the fusiform gyrus [−45 −53 −20], and BA18 [11 −81 13]. At 300 ms., the three chief peaks were at BA18 [11 −88 13], BA18 [32 −95 −13], and the fusiform gyrus [−45 −53 −20].

2.3. ERP Experiment Discussion

The ERP data supported that our paradigm elicited the canonical Recognition Potential. Furthermore, the source analyses indicate that the left fusiform gyrus in the vicinity of the VWFA is a plausible generator for this effect. Given the limited spatial resolution of EEG source analyses, on the order of 1cm under even ideal conditions (Leahy et al., 1998), the pITG cannot be ruled out as a possible generator site as well. Furthermore, existing evidence is that multiple ERP components contribute to the RP effect (Iglesias et al., 2004). Source analyses, while helpful for evaluating the plausibility of potential generator sources, are not appropriate for fine-grained spatial localization. It is also important to keep in mind that source analyses must be considered suggestive rather than conclusive due to their inherent imprecision. Thus the fMRI data, in addition to testing whether the pITG can respond to lexicality, may shed some light on potential contributors to the RP.

The event-related fMRI experiment was next conducted in order to test the prediction that the RP supraliminal masking procedure would produce a word recognition effect in the pITG. While the syllable manipulation did not produce the intended effect in the present experiment (and thus will not be further discussed), it was noted that the RP effect was stronger for the syllable congruent division line. Consequently, for the fMRI experiment, all the stimuli were presented with syllable congruent division lines. Otherwise, experiment parameters were largely unchanged.

3.1 fMRI Experiment Material and Methods

Participants—Fifteen volunteers participated in the fMRI portion of the experiment in exchange for honoraria (7 male, 8 female; mean 24.2 years old and 3.9 standard deviation years old), following a protocol approved by the University of Kentucky Institutional Review Board. All had normal or corrected-to-normal vision, were right-handed, and were native English speakers. The mean handedness score on the 10-item Edinburgh Handedness Inventory (Oldfield, 1971) was +91.7 (6.1 standard deviation). None reported any history of brain injury, attention deficit disorder, or dyslexia.

Stimuli—The stimuli were the same as for the ERP sessions except that the trials with incongruent dividing lines were omitted.

Procedure—Participants first completed two runs of a different (unrelated) experiment. Then they engaged in two runs of 80 trials each, each lasting about 7 minutes. There were half the number of trials as the ERP study since the syllable manipulation was dropped and the runs took about twice as long since the ITIs were extended to accommodate the hemodynamic response. The procedure for the fMRI sessions were the same as for the ERP sessions except that ITI ranged from a minimum of 750 ms up to several seconds in that trial types of interest were pseudorandomly intermixed with fixation cross-hairs to provide jitter (Dale, 1999). A total of eight pseudorandom orders were used (four pairs, one for each run, counterbalanced across participants) ordered for optimal experimental efficiency using optseq2 (http://surfer.nmr.mgh.harvard.edu/optseq/). One other change was that the fixation point was made larger during the response period as a cue to the participant.

Stimulus presentation and recording of responses was implemented with E-Prime software, using an MRI compatible projection system (SilentVision SV-6011 LCD, Avotec Inc., Stuart, FL). Visual stimuli were projected onto a screen at the back of the magnet bore, viewed by participants through a mirror mounted on the MR head coil. Responses were made via button-presses, using a fiber-optic button-box that registers latencies to the nearest ms. Reaction times were measured from the onset of target display.

Data Collection—The fMRI data were collected in a 3T Siemens Magnetom Trio scanner. Functional image runs were acquired in the transverse plane using a gradient-echo, echoplanar imaging (EPI) sequence (TE = 30 ms, TR = 2000 ms, flip angle = 77°). Thirty-three interleaved slices were acquired (64 × 64 image matrix, 224 × 224 FOV, with isotropic 3.5 mm voxels), covering the entire cerebrum and the upper cerebellum. A high-resolution, 3D anatomic image was acquired using a T-1 weighted (MP-RAGE) sequence (TR = 2100ms, TE = 2.93ms, TI = 1100ms, flip angle = 12°, 1 mm isotrop ic voxels, sagittal partitions) for the localization of functional activity in the stereotactic space of the Montreal Neurological Institute (MNI).

Data Analysis—The initial five volumes (a ten second countdown to the start of the trials) were dropped to minimize T1 stabilization artifact, leaving 207 volumes. Using SPM8 (Wellcome Department of Imaging Neuroscience, http://www.fil.ion.ucl.ac.uk) under OS X, the data were realigned and unwarped, time-corrected to the middle slice, normalized by matching a mean echoplanar imaging (EPI) image from each participant to the SPM canonical EPI template, resliced into a 2×2×2 mm resolution, and smoothed with an 8 mm full-width half-maximum kernel. The analysis utilized an event-related random effects approach with hrf and temporal derivative, AR(1) correction for temporal autocorrelation (see Smith et al., 2007), default high-pass filter, no global proportional scaling to avoid scaling artifacts (see Desjardins et al., 2001). In addition, head movement parameters in six dimensions, estimated during motion correction, were included in the model as nuisance covariates.

Voxelwise height thresholds were set at p < .05, using FWE correction for multiple comparisons. Coordinates presented in this report are in MNI-space. However, for the purpose of determining Brodmann Area of activation peaks, conversion to the Talairach and Tournoux atlas coordinates (Talairach and Tournoux, 1988) were performed using Matthew Brett's MNI2tal function (http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml). Determination of anatomical features corresponding to activation peaks was performed using BrainVoyager Brain Tutor. MRIcron was utilized to present the activation patterns, superimposed on the Colin brain.

The above voxelwise analyses identified a lexicality (word vs. non-word) effect in pITG. Psychophysiological interaction (PPI) analysis (Friston et al., 1997) was performed to examine connectivity patterns between the pITG cluster and other brain regions, to determine whether there was evidence for its postulated role as a bridge between the fusiform and MTG language areas. A 3mm spherical volume of interest was defined at the peak pITG voxel and the first eigenvariate extracted to summarize the major source of variance within this sphere. The condition effect of interest (Word Masked minus Nonword Masked), the VOI, and their interaction was entered into an analysis, using SPM8's PPI function to derive the neuronal time course of activity from the hemodynamic time course (Gitelman et al., 2003).

3.2 fMRI Experiment Results

Behavior—For the median reaction time measures (in milliseconds), the reaction time was faster for words versus non-words: Lexical, TWJt/c(1.0,14.0)=24.29, p=0.00068 (Nonword 824, Word 725). Additionally, the reaction time was faster when there were no masks than when there were masks: Mask, TWJt/c(1.0,14.0)=9.56, p=0.0097 (Masked 793, Unmasked 755). There was also an interaction such that the reaction time advantage of unmasked trials was greater for non-words and the reaction time advantage of words compared to nonwords was much greater for masked trials: Lexical by Mask, TWJt/c(1.0,20.0)=9.69, p=0.0076 (Nonword Masked 851, Nonword Unmasked 797, Word Masked 736, Word Unmasked 714).

For the accuracy measures, the accuracy was higher when there were no masks than when there were masks: Mask, TWJt/c(1.0,14.0)=6.56, p=0.026 (Masked .88, Unmasked .90). There was also an interaction such that the effect of masks was greatest for non-words: Lexical by Mask, TWJt/c(1.0,14.0)=11.73, p=0.0040 (Nonword Masked 0.87, Nonword Unmasked .92, Word Masked .88, Word Unmasked .88).

fMRI—For the voxelwise fMRI analyses (Figure 5), the result of the conservative voxelwise FWE correction for the critical masked word vs. masked non-word contrast was a single activation on the pMTG side of the pITG/pMTG boundary: cluster $p_{FWE} < 0.001$, $k_E=28$, peak-level $p_{FWE} = 0.011$, T = 9.87 at [−56 −48 −8].

In order to identify other larger regions that may contribute to the RP effect, we also report results of the masked word vs. masked non-word contrast at P < 0.001, FWE corrected at the cluster level to reach a corrected significance level of P < 0.05. Results of the clusterwise multiple comparison analysis indicated activation of several other regions, including a larger portion of left temporal cortex surrounding pITG proper (Table 1 and Figure 5).

In contrast, results from the reverse contrast indicated that there were no regions showing greater activation for the masked non-words compared to the masked words. There were also no significantly activated regions for either the non-masked word vs. non-word or the non-masked non-word vs. word contrasts. There was no syllable manipulation in the fMRI experiment.

Results from the PPI analysis showed that a large portion of left posterior fusiform gyrus (Figure 6), with a peak at [−38 −62 −16], displayed a positive interaction with the pITG region centered at [−56 −48 −8]. No significant effects in any other part of the brain volume were observed.

3.3. fMRI Experiment Discussion

Results from the conservative voxelwise-correction method revealed a single effect in the vicinity of the pITG and therefore this effect can be characterized as being the strongest effect, as previously predicted (Dien, 2009b). Although the most significant voxel was at the pITG/pMTG boundary, the majority of the cluster lay within the pITG. This finding thus suggests that the vicinity of the pITG is one of the generator sites for the Recognition Potential. Although this finding supported our prediction that a relatively small region focused on pITG is a key hub of the RP, it is unlikely that a single region alone gives rise to the RP. Indeed, the cluster-wise analysis that searched for larger patches of cortex demonstrated the involvement of a network of regions that contribute to the RP. The activity in the left supramarginal gyrus is consistent with the involvement of this region in phonological processing (although activation of the right fusiform, right precuneus, and

bilateral nucleus accumbens were unexpected). In addition, the PPI provided evidence of connectivity between the pITG and the fusiform region that is modulated by lexicality.

4. General Discussion

Results from the present ERP and fMRI experiments provide convergent evidence that the left pITG makes an important contribution to word recognition, evincing a robust lexicality effect when tested under masked conditions derived from observations in the ERP literature. The ERP data suggested that our paradigm elicited the canonical Recognition Potential and the source analysis indicated that the VWFA and the adjacent pITG as plausible generator sites. Furthermore, the source analysis did not indicate substantial activity at the locations of the other cortical clusters (the subcortical nucleus accumbens is not part of the LORETA head model) during the 100–300 ms Recognition Potential period (Figure 7). The fMRI experiment repeated the ERP experimental task and found that the masked lexicality effect was associated with activation in the vicinity of the pITG, as previously predicted (Dien, 2009b). The pITG is therefore a strong candidate for a primary generator for the RP. This in turn suggests that the pITG activation occurs at an appropriate latency for operating at an early word recognition level (Dien, 2009b; Sereno and Rayner, 2003; Sereno et al., 1998), helping bridge neural processing in the inferior temporal (orthographic) and lateral temporal (phonological/semantic) regions during reading.

While the results suggest that the pITG contributes to the RP effect, it cannot be concluded that it is the only source of the RP effect. There is already evidence in the literature that there may be two portions to the RP effect, a left-lateralized negativity and a bilateral negativity, that respond differentially to parameters like SOA of the temporal flanking masks (Iglesias et al., 2004). The more liberal clusterwise analysis presented in Table 1 and illustrated in Figure 5 suggests an additional contribution by the right fusiform gyrus region, although not specifically supported by the source analysis. Furthermore, not all neural activity will be detectable in either EEG or fMRI data even without the unavoidable possibility of Type II errors. For this reason, the observation of convergent pITG findings in both the EEG and fMRI data is suggestive whereas the absence of such convergence elsewhere is not conclusive as null effects cannot be interpreted. What can be said, therefore, is that the pITG is likely a key hub of the RP and that the supraliminal temporal flanking procedure appears to be a method for inducing a robust lexical effect in the pITG.

To provide context for our interest in this cortical region, it was suggested (Dien et al., 2008; Dien, 2009b) that the pITG serves as a convergence zone between the object recognition functions of the ventral temporal lobe, which include orthographic analysis (with special roles for the Visual Word Form Area and the Fusiform Semantic Area), and the phonological and semantic functions of the lateral temporoparietal surface (with a special role for the pMTG). Such a role would be consistent with the Dual Route Cascaded model's indexed phonology mechanism (Coltheart et al., 2001) but could also be consistent with the Triangle Model's resonance process (Stone and Van Orden, 1989; Van Orden and Goldinger, 1994). By this view, the orthographic representation formed in the inferior temporal region could then lead to activation of the phonological codes in the lateral temporoparietal region.

Conversely, eye tracking and ERP data suggests that both orthographic and phonological codes are activated at an early latency and it has been proposed that there is an activation-verification process in which an initial phonological code is accessed and then confirmed against the orthographic representation (Ashby et al., 2009; Lee et al., 1999; Pollatsek et al., 1992; Slattery et al., 2006). By this account, the phonological code could be activated in the lateral temporoparietal region and then the pITG could allow for its verification against the

orthographic representation formed in the inferior temporal region (with the RP reflecting the verification process). Other accounts could easily be postulated as well.

The PPI finding of an interaction between lexicality and the connectivity between the pITG and the VWFA for words vs. non-words provided support for this contention. As its name suggests, the VWFA shows sensitivity to orthographically legal letter strings, regardless of lexical status. Thus, the observation that VWFA interacts preferentially with pITG during word compared to nonword processing is consistent with a view that pITG contributes to early word recognition analysis. While the lexical effects reported in this study are not a direct test of the suggestions made elsewhere regarding the role of the pITG (for example, lexicality effects can be due to word recognition processes at both lexical and semantic levels), they do provide strong support that the effects on reading and naming by pITG lesions are not due to simple disconnection effects but really are informative about the role of this neural area. Furthermore, the timing information added by the ERPs provides further support for the view that the pITG does indeed operate in the window between lexical access and phonological/semantic access.

In either case, the latency of the effects was quite early and therefore consistent with early word recognition. Indeed, it has been proposed that the RP reflects some aspect of lexical access (Martín-Loeches et al., 1999), lexical selection (Hinojosa et al., 2001), or lexical-semantic access (Martín-Loeches, 2007). Any of these possibilities would be consistent with the time course of word recognition suggested by eye tracking studies (Sereno et al., 1998) and with the lexical effects observed in the present study.

It should also be noted that the Recognition Potential is not the sole ERP component that has been associated with word recognition. For example, a number of ERP components such as an N250 have been detected using repetition priming under subliminal conditions (Holcomb and Grainger, 2006). It is unclear how they relate to the Recognition Potential but are likely to be different as their scalp topographies tend to differ from the Recognition Potential. For a review of early latency ERP components related to reading, see Dien, (Dien, 2009b). Likewise, fMRI studies using this combination of subliminal conditions and repetition priming do not yield pITG activations (Dehaene et al., 2001; Nakamura et al., 2005). At any rate, it bears repeating that the Recognition Potential paradigm was adopted for the present experiment because there was reason to think it would reveal word recognition in the pITG and not because it was the only known word recognition ERP component.

A necessary caution is that the possibility that the ERP and the fMRI sessions elicited subtly different cognitive processing cannot be ruled out. Given that the technology for obtaining useable ERP data simultaneously with fMRI data remains as yet a challenge due to a number of artifacts (the ballistocardiogram in particular remains recalcitrant), we obtained them separately. This means that the data were collected from two different groups of participants and the session conditions did differ in some regards, such as the presence of auditory noise during the MRI recording sessions. However, examination of the behavioral data suggests that performance in the two sessions were largely comparable. The behavioral data from the MRI sessions displayed a significant interaction not seen in the ERP data, but the ERP data did show the same general pattern: (Nonword Masked 855 ms, Nonword Unmasked 825 ms, Word Masked 740 ms, Word Unmasked 719 ms), with the main difference being that the nonword unmasked condition was slower for the ERP data. Given the robustness of the neural effects for both recording modalities and the general similarity of the behavioral data, it is suggested that they are likely to be reflecting very similar cognitive processes.

A question for future study is whether the effects found are happening via automatic or controlled mechanisms. Since the masking was supraliminal, it is possible that the lexicality

effects were due to controlled strategies for coping with the visually degraded stimuli, particularly expectancy priming. Since the paradigm was not designed to produce priming effects, such expectancy priming effects are unlikely but cannot be ruled out. Future studies could address this issue by utilizing subliminal presentations or manipulating cognitive load.

5. Conclusion

Previous lesion evidence has suggested a role for the posterior inferior temporal gyrus (pITG) in word recognition. However, reading impairment in these studies could have been due to the severing of underlying white matter fiber tracts as neuroimaging evidence for gray matter involvement has been weak. Here we tested whether pITG contributes to word recognition using a lexical decision paradigm developed in the ERP literature. Results indicated a robust lexical effect in both ERP and fMRI data, demonstrating involvement of the pITG in word recognition peaking at about 200 ms. In addition, we found that functional connectivity between the pITG and a fusiform region near the VWFA was modulated by lexicality, further indicating that the pITG is a critical hub in the word recognition network. Our results may have basic science and clinical implications in that visual word recognition contributes to reading ability and comprehension of written language (Perfetti, 1994) and its impairment forms a central component of developmental reading disorders (Sigmundsson, 2005). It would be of great interest to determine whether reading disabilities are associated with abnormalities of these two neural signatures (ERP-RP and fMRI-pITG) of word recognition.

Acknowledgments

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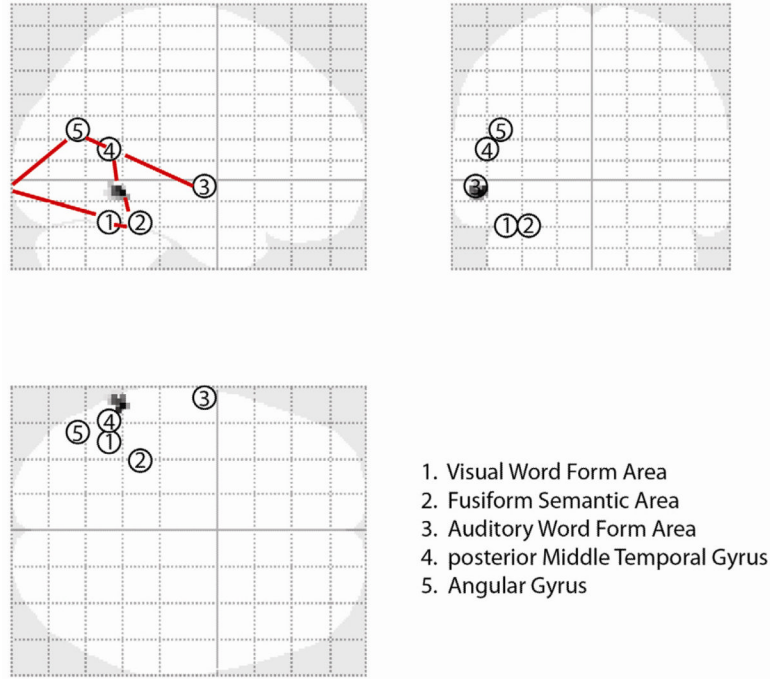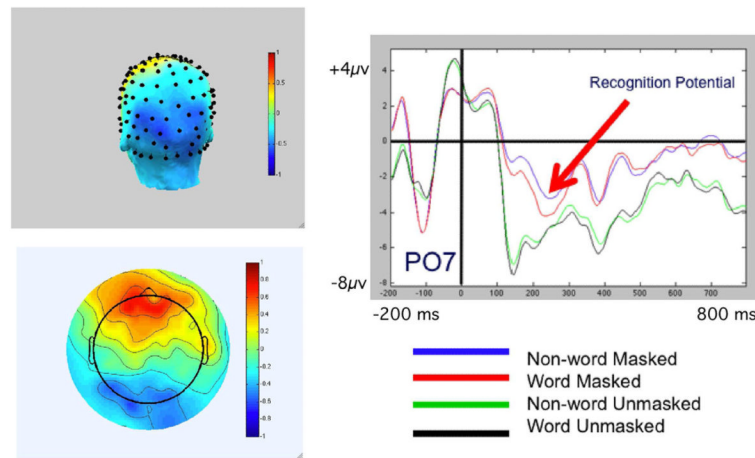
Figure 1.
Reading Areas Discussed in Text. In addition to the areas marked by numbers, the posterior Interior Temporal Gyrus (pITG) area identified in the current study is represented by the voxels found to be significant by FWE voxelwise significance testing. The red lines in the saggital view indicate suggested pathways of major information flow.
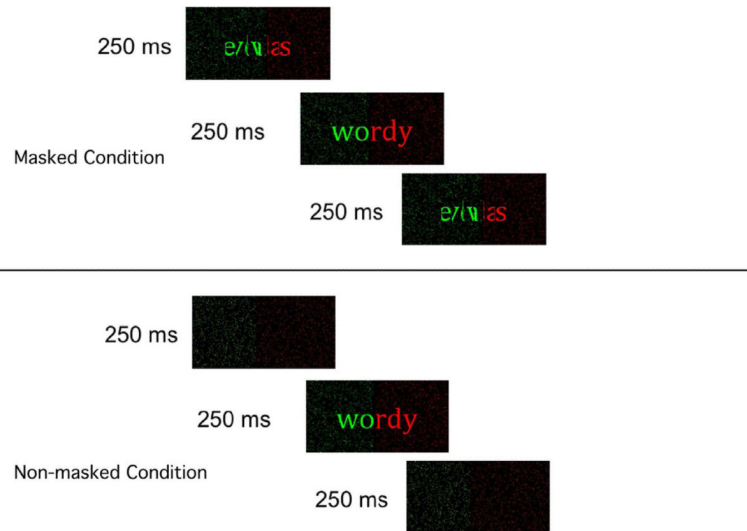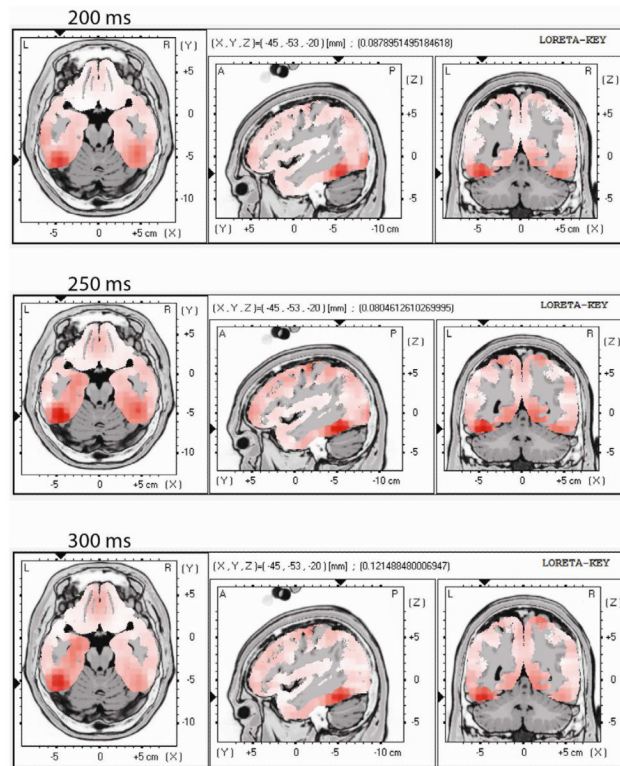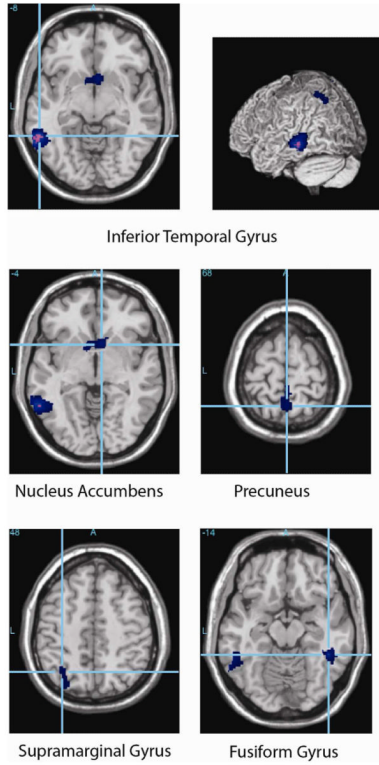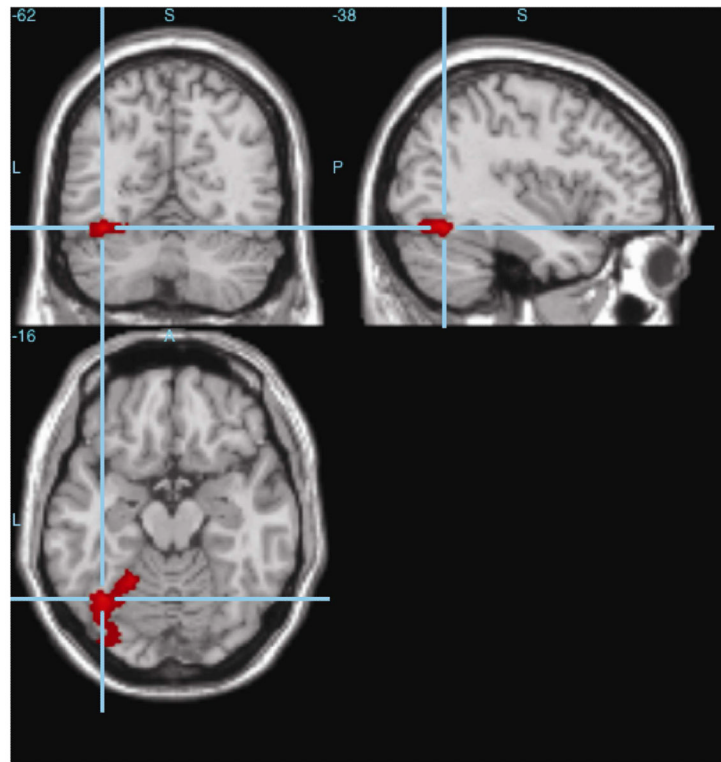
Figure 2.
Timeline of stimulus presentation.

Figure 3.
Recognition Potential effect. Topographical maps of the voltage difference (Masked word – masked non-word) at 250 ms displayed on a 3D head and on a 2D flat map, both with voltage scales running from +1 to −1 μv. The waveform plot shows the recordings from PO7 (the traditional peak channel for the Recognition Potential).
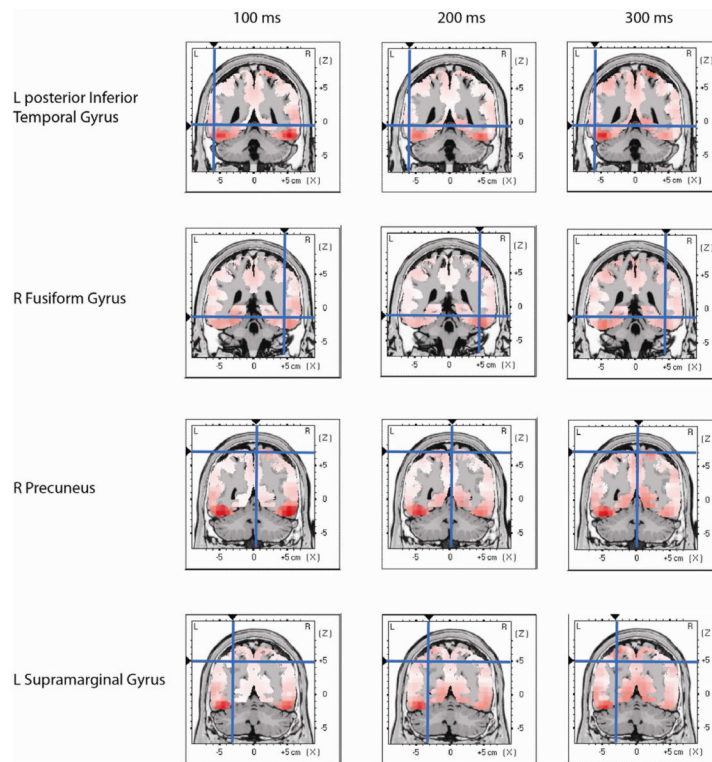
Figure 4.
Source Analysis Result for the Recognition Potential. The images are centered on the theoretically interesting fusiform gyrus activation at 200, 250, and 300 ms. Darkest red indicates strongest activation.

Figure 5.
Masked Word vs. Masked Non-Word Contrast. The five clusterwise effects are shown in blue. The more stringent voxelwise effect (in the posterior inferior temporal gyrus) is shown in pink. Voxelwise effects differ from clusterwise effects in that each individual voxel has passed stringent significance thresholding. In contrast, clusterwise effects reach significance as a whole, but carry uncertainty about which part of the cluster is noise and which part is signal. The effects are plotted on a typical (Colin27 brain) T1 image. Since activation within the pITG (top panel; pink) is significant according to a voxelwise test, its spatial extent can be interpreted with greater confidence.

Figure 6.
Stimulus-dependent pITG connectivity. A large portion of left posterior fusiform gyrus showed greater functional connectivity with the pITG in the masked word vs. non-word condition.

Figure 7.
Co-Registration Results for the Recognition Potential. The ERP source analysis images are centered on the coordinates for the peak voxel of each of the four cortical significant fMRI clusters. The blue crosshairs indicate the locations of the peak voxels. The nucleus accumbens cluster is not depicted as LORETA only includes cortical voxels in its model. The time points correspond to the beginning, peak, and end of the Recognition Potential: 100, 200, and 300 ms. Darkest red indicates strongest activation.

Table 1

Results of Main Effects Analyses. Cluster p-values are corrected. BA is Brodmann Area. Voxel p-values are FWE-corrected. Coordinates are MNI coordinates.

Cluster p	k_E	Voxel p	Voxel T	Coords	BA	Anatomical Landmark
Masked Word vs. Masked Nonword						
0.000	729	0.011	9.87	−56 −48 −8	21	L. Inferior Temporal Gyrus
0.011	212	0.099	7.89	46 −42 −14	37	R. Fusiform Gyrus
0.004	252	0.437	6.41	8 12 −4	-	Nucleus Accumbens
0.011	212	0.909	5.26	2 −54 68	7	R. Precuneus
0.014	202	0.954	5.07	−32 −60 48	40	L. Supramarginal Gyrus
Masked Nonword vs. Masked Word						

No Significance.