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Research Report

fMRI characterization of the language formulation area

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ABSTRACT

Participants read sentences presented one word at a time, half of which ended with a semantically incongruent ending. 1.5T functional magnetic resonance imaging data were collected from 11 participants, showing that the left posterior inferior temporal region, which has previously been termed the Language Formulation Area (LFA), responded to cloze probability. It is suggested, based on anatomical positioning and a literature review, that the responsiveness of the LFA to cloze probabilities may reflect a role in coordinating the lexical and non-lexical reading pathways. Finally, it is noted that previous studies have implicated this region in dyslexia and some speculations are made in this regard.

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1. Introduction

While the mechanisms of word recognition have been intensively studied, the role of sentence context is much well understood. While some studies indicate that message-level sentence context can influence word recognition (Camblin et al., 2007; Ehrlich and Rayner, 1981; Eisenberg and Becker, 1982; Jordan and Thomas, 2002; Kleiman, 1980; Morris, 1994; Paul et al., 1992; Schwanenflugel and LaCount, 1988; Simpson et al., 1989), other studies suggest otherwise (Duffy, Henderson, and Morris, 1989; Fischler and Bloom, 1985; Forster, 1981; Stanovich and West, 1983; Zwitserlood, 1989). Thus, while some models suggest that lexical access is influenced by the sentence context (Becker, 1980; Becker,

1985; Federmeier, 2007; Marslen-Wilson and Tyler, 1980; Tabossi and Zardon, 1993) many assert that sentence context only affects the choice of the lexical alternatives generated by an encapsulated word processing module (Altmann and Steedman, 1988; Forster, 1979; Zwitserlood, 1989); many current models do not even explicitly address sentence context (Coltheart et al., 2001; Grainger and Jacobs, 1996; Van Orden and Goldinger, 1994).

Neuroimaging studies thus far have not clarified the situation. A common approach for examining the effects of sentence context on semantic processing is to contrast normal sentences with sentences containing an unexpected or anomalous word, such as "They called the police to stop the SOUP." The present authors were able to identify seven such

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functional magnetic resonance imaging (fMRI) studies wherein exact Talairach coordinates were provided; even when one focuses on the left temporal lobe, the active regions were surprisingly variable (Table 1). One possibility is that the differences represent Type II errors due to insufficient statistical power. However, at least one region (posterior middle temporal gyrus or pMTG) sometimes was more active for the unexpected/anomalous endings (Baumgaertner et al., 2002; Stringaris et al., 2007) and sometimes more active for the expected/congruent endings (Kuperberg et al., 2000).

It is possible that subtle differences between the studies were responsible for these varying results. For example, four used visual stimuli (Baumgaertner et al., 2002; Kiehl et al., 2002; Newman et al., 2001; Stringaris et al., 2007) and three used auditory stimuli (Cardillo et al., 2004; Friederici et al., 2003; Kuperberg et al., 2000). This distinction may be responsible for the opposite pMTG effects, being more active for the unexpected/anomalous visual stimuli and less active for the unexpected/anomalous auditory stimuli. Nonetheless, the pattern of results is not clear. For example, increased fusiform activity (expected to be more responsive to visual processing) for anomalous endings was seen both with visual stimuli (Kiehl et al., 2002) and auditory stimuli (Kuperberg et al., 2000). Indeed, it has been argued that there is no evidence for separate visual word form and auditory word form regions (Price et al., 2003).

One problem with the existing neuroimaging studies is that the comparison of expected/congruent words with unexpected/anomalous words may confound semantic effects with more strategic effects. For example, six studies

used a meaningfulness judgment and one (Cardillo et al., 2004) used a lexical decision task on the final word, so effects could reflect the decision-making processes rather than semantics per se. Furthermore, it is possible that unexpected/anomalous endings might not be processed in the same manner as the expected/congruent endings. For example, the participant might not make the effort to fully integrate a stimulus word into the sentence once it is recognized as being anomalous, resulting in qualitatively different patterns of activations. Another problem is that neuroimaging studies provide little or no temporal information so it is unclear whether activations reflect influences on the initial word recognition or subsequent processes.

One strategy that has proven successful in event-related potential (ERP) studies is manipulation of cloze probabilities. Cloze probabilities are generated by presenting a norming group with a sentence stem and having them generate endings for it; the cloze probability for a particular sentence is the proportion of the norming group that generated that particular sentence ending for the sentence stem (Bloom and Fischler, 1980; Taylor, 1953). A semantically sensitive ERP component termed the N400 (Kutas and Hillyard, 1980b; Kutas and Schmitt, 2003) has been shown to be larger for smaller cloze probabilities (Kutas and Hillyard, 1984). For isolating semantic context effects, the cloze probability effect has the advantage that it is comparing within a range of congruent stimuli that are more likely to be processed in a qualitatively similar and more ecologically valid fashion.

Support for the reasoning behind this approach of examining parametric cloze effects is the observation in a prior study from this lab (Dien et al., 2003) that the scalp topography of the region most responsive to cloze probability in the N400 window was more frontally distributed than the scalp topography of the overall scalp region responsive to congruity. This observation suggested that at least two different ERP components were involved (if one defines ERP components as those aspects of the ERP that are differentially responsive to experimental manipulations in ways that are conceptually qualitatively different, as opposed to which finger being moved or frequency of auditory stimulation). Inspection of the data suggests the presence of an ERP component anterior to that of the classic N400 and it is this component that was most responsive to the cloze rating. While this observation does raise some questions about to what extent the N400 itself responds to cloze probabilities (Kutas and Hillyard, 1984), it too did seem to respond to cloze, albeit to a lesser extent. This frontal effect (appearing to be a P400 of some sort) is anterior to that usually reported for semantic studies so it may be atypical, responding to some aspect of that particular experiment, such as the presence of syntactic anomalies (although it was seen even when only the semantic anomaly trials were included in the analysis). In any case, this observation suggests that some neural processes may respond to congruity in a dichotomous fashion while others may respond to cloze probabilities in a more parametric fashion.

The present experiment utilizes the cloze probability effect in an event-related design, marking the first time it has been applied to fMRI data, to isolate the effects of sentential semantic context on word recognition. Sentences were visually presented one word at a time. Within the conventional design of having

Table 1 – Sentence fMRI studies and list of activations

Articles	Left temporal lobe activations
(Baumgaertner et al., 2002) (visual)	Unexpected vs. normal MTG [−54 −54 6]
(Cardillo et al., 2004) (auditory)	None
(Friederici et al., 2003) (auditory)	Normal vs. anomaly STG [−54 −19 13] Anomaly vs. normal STG [−60 −42 20]
(Kiehl et al., 2002) (visual)	Anomaly vs. normal Anterior temporal [−48 32 4] Fusiform [−48 −52 −16][−48 −60 −20] [−48 −44 −24]
(Kuperberg et al., 2000) (auditory)	Anomaly vs. normal STG [−49 −31 9] Fusiform [−29 −36 −13] Normal vs. anomaly Temporal pole [−38 8 −13] ITG [−40 −33 −7] ITG [−35 −53 −2] MTG [−40 −56 9] Lingual gyrus [0 −78 −2]
(Newman et al., 2001) (visual)	Anomaly vs. normal Hippocampus [−39 −16 −20] Parahippocampus [−20 −6 −36]
(Stringaris et al., 2007) (visual)	Normal vs. anomaly MTG [−51 −7 −7] Anomaly vs. normal MTG [−47 −52 4]

half incongruent sentences, a novel feature was to include a full range of cloze probabilities amongst the congruent sentences and to perform a parametric analysis of these congruent endings. Furthermore, instead of using a meaningfulness judgment that could contaminate the effects with decision-making processes, the task was to read for comprehension, with a recognition memory task during the breaks to verify compliance. Finally, the discussion will provide a theoretical framework based on the results with which to organize the relevant literature and provide for a basis for generating hypotheses for future experiments.

1.1. Regions of Interest (ROI)

According to current models of reading comprehension (Berent and Perfetti, 1995; Coltheart et al., 2001; Grainger and Jacobs, 1996; Reichle et al., 2003; Shelton and Caramazza, 1999; Van Orden and Goldinger, 1994), there are two methods by which words can be understood. The non-lexical or phonological route is a system by which graphemes are mapped onto sounds and accounts for the ability to readily assign a pronunciation even to novel non-words such as "yark." Conversely, the lexical route is based on rote memorization of the pronunciation of words, including irregular words that do not follow standard rules such as "pint." The lexical route is thought to be the more efficient process since it can allow meaning to be mapped directly onto word forms, bypassing phonological representations entirely (for a contrary view see Frost, 1998). It has been suggested that during language development reading is initially dependent on the non-lexical route, which then entrains the lexical route (Pugh et al., 2001). However, behavioral evidence suggests that even practiced adult readers continue to utilize both methods (Baron and Strawson, 1976) and some argue that phonological encoding continues to be a primary route even in adults (Berent and Perfetti, 1995; Frost, 1998).

The two reading routes appear to correspond to a division in the neural architecture of cortical areas implicated in language comprehension. The temporal lobes are roughly divided into a dorsal portion devoted to auditory processing and a ventral portion devoted to visual object recognition. Much of the left temporal lobe has been shown to be responsive to language processing (Binder et al., 1997). It therefore seems reasonable to suggest that the lexical (more visually based) route might be centered in the visual regions and the non-lexical route might be centered in the auditory regions, although there is a lack of consensus about the details (Fiez and Petersen, 1998; Hickok and Poeppel, 2004; Price, 2000; Small and Burton, 2002). Studies of the distinction between speech comprehension and reading comprehension have certainly supported such a division (Booth et al., 2002a,b; Booth et al., 2003).

Each of the two pathways contains a region that has repeatedly been found to be responsive to semantics (see Fig. 3) and has been found to respond to lexicality (Fiebach et al., 2002). The first is the left posterior middle temporal gyrus (pMTG) and has been proposed to be involved in phonological code retrieval (Hickok and Poeppel, 2004; Indefrey and Levelt, 2004). The three sentence studies reporting pMTG activations (Baumgaertner et al., 2002; Kuperberg et al., 2000; Stringaris et al., 2007) found them at an averaged coordinate of $[-47 -54 6]$ or Talairach space $[-47 -52 8]$. The second will be termed the left fusiform semantic area or FSA, which according to one

review (Moore and Price, 1999) was centered at $[-32 -40 -20]$ or Talairach space $[-32 -40 -15]$ and was proposed to be a semantic region. Focusing on the sentence studies reviewed earlier, four of the seven displayed activations in one or both areas. The present analysis will therefore focus attention on these two regions.

Another likely location for cloze effects is the LIPC. Evidence suggests that there are two such areas of interest, an anterior LIPC (aLIPC) and a posterior (pLIPC) region (Gold et al., 2006; Wagner et al., 2001). Reports suggest that the pLIPC is concerned with controlled selection between competing semantic alternatives (Thompson-Schill et al., 2005, 1997, 1999; Thompson-Schill and Botvinick, 2006) via inhibition of alternatives (Cardillo et al., 2004; Gold et al., 2006) and thus accounting for a sensitivity to phonology manipulations (Gold et al., 2005; Snyder et al., 2007) whereas the aLIPC is more involved with controlled retrieval (Badre et al., 2005; Wagner et al., 2001) and facilitative priming (Gold et al., 2006). Although another study (Wheatley et al., 2005) reported priming effects under automatic conditions in both locations, it may be that they reflected subsequent post-lexical controlled processing. One would therefore expect the pLIPC to be more active to low cloze endings since there would be a need to suppress prepotent alternatives during the comprehension process. The need to conduct controlled searches for unexpected endings might also produce cloze effects in the aLIPC. One would also expect main effects of congruity in both locations since four of the six sentence studies reviewed earlier (Baumgaertner et al., 2002; Cardillo et al., 2004; Kiehl et al., 2002; Newman et al., 2001), reported effects of semantic incongruity. Although coordinates vary between studies, a recent meta-analysis (Vigneau et al., 2006) suggests a general central tendency for the aLIPC $[-44 26 2]$ and the pLIPC $[-49 16 24]$ in sentence studies.

1.2. Predictions

Given the complex nature of language processing and the number of fundamental issues still undergoing discussion, the primary aim of this study is simply to seek an incremental but meaningful advance over prior studies. Areas that respond to the cloze probability are more likely to reflect the direct effects of semantic context on language processing than areas that respond to main effects of congruity. Pure congruity effects could reflect decision regions, recognition of a potential comprehension error, efforts to repair the semantic comprehension process, or even generic alerting effects. Nonetheless, the existing literature would support an especial focus on the pMTG, FSA, aLIPC, and pLIPC in the fMRI data.

2. Results

2.1. Behavior

The average recognition performance for the 11 fMRI participants was 76% (not including missing data for one participant). For nine subjects d' was an average of 1.25 and beta was an average of 4.69. An additional subject had only 3 hits and no false alarms, resulting in incalculable signal detection

measures, but was retained in the sample due to the limited number of sessions available. The relatively limited accuracy therefore appears to be due to very conservative responses by the participants rather than low ability to discriminate the sentences.

2.2. fMRI

A conventional main effects analysis of congruity of the sentence ending words (estimated along with the residualized cloze parameter) yielded a significant cluster at the corrected level ($p < .001$, $k_E = 916$) for the incongruent versus congruent comparison. The most significant voxel of this cluster [SPM: $-52\ 22\ 24$; Talairach: $-51\ 22\ 21$] localized to the left inferior prefrontal cortex or LIPC (Brodmann Area or BA 45), as seen in Fig. 1. The congruent versus incongruent comparison yielded another significant cluster ($p = .001$, $k_E = 613$). The most significant voxel of this cluster [SPM: $-10\ -30\ 2$; Talairach: $-10\ -29\ 3$] localized to subcortical tissue, although the cluster includes the left parahippocampal gyrus (BA 35 and BA 27), as seen in Fig. 1.

The parametric modulation of the cloze probability (of the congruent endings) corrected for letter length yielded two significant clusters. The first significant cluster ($p = .001$, $k_E = 308$) had a most significant voxel [SPM: $-58\ -42\ -12$; Talairach: $-57\ -41\ -8$] localized to the left inferior temporal gyrus (at the boundary of BA 21 and BA 37), as seen in Fig. 1. The relationship between cloze and estimated hemodynamic response is illustrated in Fig. 2. The second significant cluster ($p < .001$, $k_E = 406$) had a most significant voxel [SPM: $14\ -10\ -14$; Talairach: $14\ -10\ -11$] in subcortical tissue, although the cluster includes the right parahippocampal gyrus (BA 34), as seen in Fig. 1.

In the ROI analyses, the only significant results were in the aLIPC and pLIPC regions for the incongruent versus congruent contrast. The aLIPC had a significant cluster ($p = .034$, $k_E = 17$) and a significant FWE-corrected voxel ($T = 3.99$, $p = 0.040$) at $[-48\ 30\ 0]$. The pLIPC also had a significant cluster ($p = .007$, $k_E = 68$) and a significant FWE-corrected voxel ($T = 5.56$, $p = 0.008$) at $[-52\ 18\ 26]$.

Fig. 2 suggests that the cloze effect essentially vanished during the fourth block. This change was not due to differences in the mean cloze ratings or the residualized cloze ratings as they were essentially identical across the four blocks (.39, .38, .40, and .38) and $(-.02, .00, .04, \text{ and } -.03)$ respectively. However, this effect was not statistically reliable: $T_{Wj/c}[3,6.67] = 2.24$, $p = .25$.

3. Discussion

The conventional congruity main effect analysis identified a left dorsolateral prefrontal region as being more active for incongruent word endings. Furthermore, a parametric analysis of cloze ratings yielded a left posterior inferior temporal gyrus (pITG) region that was more active for lower cloze (more unexpected) endings. Additional semantic effects were obtained in the vicinity of the left and right parahippocampal gyri (main effect and cloze effect respectively).

A limitation of this study is that although the intention was to better determine the loci of sentential context effects, this stimulus set was not designed to distinguish between intralexical versus message-level effects (see Gamblin et al., 2007; Faust et al., 2003; Simpson et al., 1989; Vandenberghe et al., 2002). The experimental design issues are quite complex

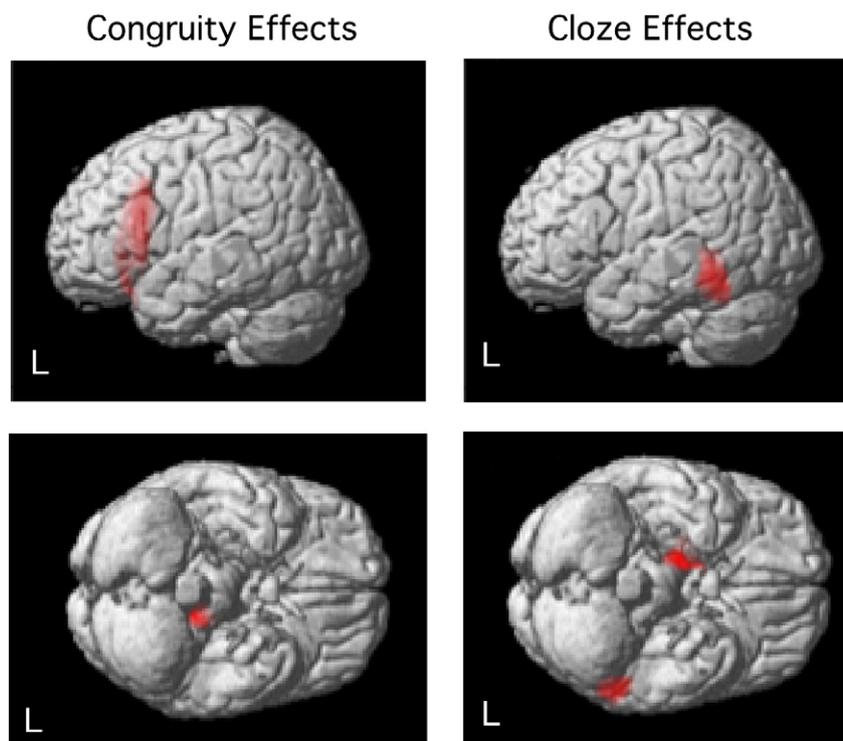


Fig. 1 – Rendering of fMRI activation areas.

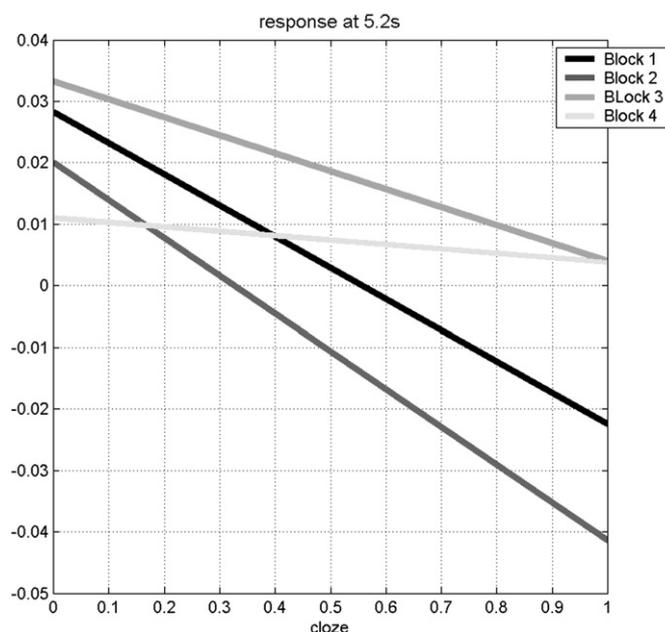


Fig. 2 – Parametric response to the residualized cloze parameter. The figures provide the relationship between the residualized cloze parameter and the estimated hemodynamic response, averaged over the entire significant cluster and over the participants. The parameters are provided for each of the four blocks of the experiment.

and so the decision was made to take an incremental approach, extending current studies that report main effects of semantic congruity.

Both the aLIPC and pLIPC regions fall within the extended prefrontal activation observed in the present study. A surprising observation is that this frontal region displays not even a trend towards responding to cloze probability, even with the ROI analyses. One possible interpretation is that the frontal functions were not required for congruent endings due to the guidance provided by sentence context. Conversely, there was a main effect of incongruity when the ending was wholly unexpected. It remains of interest, however, that there was no detectable difference between responses to high and low cloze congruent endings. This observation suggests that the frontal functions are not needed when sentence context provides guidance. Perhaps the semantic retrieval function is not differentially activated because the semantic set (see Becker, 1980) was activated in advance of the ending presentation and the semantic selection function is not needed when the ending word is a member of an active semantic set.

The activations near the parahippocampal region, enhanced for congruous endings on the left and enhanced for low cloze endings on the right. The location of these clusters makes it difficult to interpret them. The cluster test only indicates the presence of a statistically reliable effect within the boundaries of the cluster but not where. In cases such as this where the cluster encompasses qualitatively different types of regions (in this case, subcortical and cortical structures) it is difficult to make conclusions. If the parahippocampal gyri are involved, then it is possible that these effects reflect controlled episodic encoding since the experimental task was to memorize the sentences, consistent with the HIPER model (Strange et al., 2005). It may be that

congruent endings, especially low cloze endings, are especially memorable.

3.1. pITG effect

The pITG region is generally recognized as being part of the extended language-processing region but its role has thus far been unclear. Some clues are provided by lesion case studies. A case with a lesion somewhat more dorsal and extending posteriorly through extrastriate visual regions (BA 18 and 19) both laterally and medially, was reported with fluent speech, except for word finding pauses and anomia in object confrontation, alexia for all but highly recognizable words, and agraphia for all but some letters (Foundas et al., 1998). Similar symptoms have been reported for a lesion medial to the inferior temporal gyrus (Sakurai et al., 2000) and one that included the inferior temporal gyrus but just anterior to the pITG (Sakurai, 2004); of interest, these lesions primarily affected reading and writing of kanji, the ideographic Japanese script, compared to kana, the phonological Japanese script. Neither of these patients was reported to suffer from anomia. Thus, combinations of anomia, alexia, and agraphia appear in a number of posterior temporal lobe lesions, but the lesions did not overlap with the pITG region.

There are two chief theories of the role of the inferior posterior temporal region in general. What might be termed the Translation Model suggests that it contains the facility to link semantic representations with cross-modal naming codes, sometimes termed Wernicke's Wortschatz (Lüders et al., 1991), meaning vocabulary or perhaps thesaurus. An intracranial electrode study found that stimulation of the left fusiform gyrus disrupted reading in 8 of 22 patients (Lüders et al., 1991). Follow-up studies reported that the susceptible region extended to the inferior temporal gyrus (Burnstine et al., 1990; Krauss et al.,

1996; Schäffler et al., 1994); however, these findings are mostly located medially to the pITG implicated in the present study. A more recent paper (Schwartz et al., 1999) did report that intracranial stimulation of the pITG region resulted in both reading and naming disruptions. Similarly, a repetitive trans-magnetic stimulation (rTMS) study demonstrated that stimulation of the left posterior BA 37, but not the right, disrupted picture naming, although the exact anatomical site is unclear. This translational position has also been echoed in suggestions that the posterior inferior temporal gyrus region may be involved in mapping meaning onto sounds (Hickok and Poeppel, 2004; Vigneau et al., 2006).

The second model, that might be termed the Convergence Model, proposes that the inferior posterior temporal region has the role of binding together information located in other regions. The initial model (Nielsen, 1946) termed this region the Language Formulation Region (LFA) and suggested that it “constitutes a zone in which auditory, visual, and motor memories are synthesized to formulate concepts into finished language” (p. 33), based on the effects of temporal lobectomy’s that included this region versus those that did not. This view emphasized the symptom of anomia as an example of naming information becoming disconnected from semantic knowledge, both located in other portions of the cortex. Subsequent work expanded this view to the entirety of the lateral inferior surface of the temporal lobe, termed convergence zones, and provided both lesion and neuroimaging evidence that different types of stimuli involved different portions of this region (Damasio and Damasio, 1994; Damasio et al., 1996, 2004). Although the lesion symptoms did not seem specific to the activation region of the present study, positron emission tomography (PET) activation to naming tools did activate this region [–52 –46 –12] (Damasio et al., 1996). Anomia is considered to be a distinguishing symptom for damage to this system. This model therefore explicitly proposes that this region does not itself contain representations but rather coordinates representations maintained in other areas whereas the Translation Model leaves this issue open.

Thus, while there is general agreement that the activated region is part of a temporal lobe language network, there seems to be very little data specific to the pITG and none that account for the cloze effect found in the present study. Although the tool-naming region found in one PET study (Damasio et al., 1996) did correspond to the pITG, the stimuli in the present study are words rather than pictures and they are comprised of a wide variety of categories so the present results may reasonably be characterized as a generic word effect. Further confidence in the premise that this region mediates a language effect is provided by a prior fMRI study (Ashtari et al., 2005) that reported activation in this vicinity (a center of –51 –42 4, estimated from the published figure) for a cloze task (completing sentence stems).

3.2. Language formulation area hypothesis

A starting place for an account of the pITG is the hypothesis that the left pMTG and the FSA are involved in word form retrieval for each of the two pathways, perhaps corresponding to automatic spreading activation in a phonological input lexicon and in a visual input lexicon respectively. Automatic

priming conditions should highlight regions mediating such association effects. Focusing on single word priming studies using automatic conditions, there is a general pattern consistent with this division. In a lexical decision experiment (Gold et al., 2006) with visual word pairs, priming effects were found in the FSA [–40 –43 –15] under automatic conditions only. Likewise, a naming task with visual words also found FSA [–32 –42 –12] effects under automatic conditions (Wheatley et al., 2005). Furthermore, kanji letters (which require lexical analysis) yielded FSA [–29 –41 –13] effects (Nakamura et al., 2005). Conversely, two lexical decision experiments with auditory words under automatic conditions have produced left pMTG [–44 –58 29] [–61 –44 –7] semantic priming (Kotz et al., 2002; Rissman et al., 2003). Uncontrolled stimulus parameters affecting relative efficiency of lexical and non-lexical processing may account for why a visual priming study (Devlin et al., 2004) instead reported pMTG effects with masked primes [–70 –42 4]. Presumably, studies yielding effects in neither area (Copland et al., 2003; Mummery et al., 1999a, Mummery et al., 1999b; Rossell et al., 2001, 2003) represent Type II errors.

Evidence indicates that readers rely on the phonological route during sentence comprehension by subvocalizing (Huey, 1968). Indeed, it has been demonstrated that interference with the phonological route via a concurrent shadowing task disrupts the ability to make sentence acceptability judgments of incongruent sentence endings (Kleiman, 1975). The effects on this task and on making a phonemic task were much greater than effects on graphemic and categorical judgments, suggesting that these effects were primarily post-lexical. It was therefore suggested that subvocalization was being used to bolster the working memory storage of the sentence meaning (see also Carver, 1990). This reliance on subvocalization could only be strengthened in the current experiment where a full second separates the presentation of each word, compared to Kleiman’s experiment where the full sentence was presented simultaneously. Thus, one would expect robust activity in both pathways in the present dataset. Thus, in a sense, the phonological pathway could serve to provide some sentential context for the lexical pathway by maintaining a set of plausible sentence ending candidates.

The location of the pITG region suggests a possible role when considered with respect to the pMTG and the FSA. The pITG region is located directly between these two semantic regions, making it ideally situated to provide some kind of intermediary role between them (Fig. 3). It is widely thought that normal reading involves processing in both pathways. In such a system, there would be a need to eventually coordinate the processing occurring within these two separate pathways. Such a need is implicit in a number of current cognitive models of word recognition. In the dual-route cascaded model or DRC (Coltheart et al., 2001), serial grapheme-phoneme conversion in a separate non-lexical route then results in top-down activation of the visual lexicon; inconsistent activations increases total lexical activation, increasing decision time (pp. 230–1). In the multiple read-out model including phonology or MROM-P (Grainger and Jacobs, 1996), phonological representations are activated in parallel with the visual lexical entries; the conflicting read-outs from each domain would increase decision time. Interactions between the phonological and

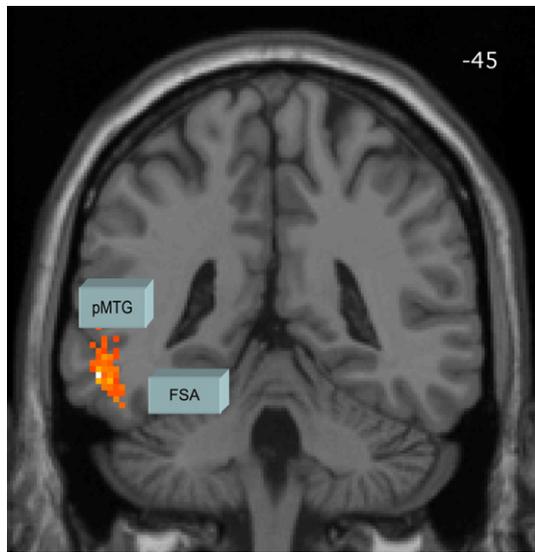


Fig. 3 – Language formulation area and adjoining semantic areas. The figure presents the activation area for the cloze effect, along with markers for the adjoining pMTG and FSA areas.

orthographic representations are described as being mediated by cross-code consistency (Grainger et al., 2005). In the resonance account of word perception (Van Orden et al., 1990; Van Orden and Goldinger, 1994), feedback mechanisms between visual, phonological, and semantic subsymbolic units take place until coherent pattern matching is achieved across all three parts of the system; lack of global coherence would require increased processing.

It is therefore proposed that the pITG provides this coordination role. In the current study, activity in this region reflected the need for coordination, with lower cloze probabilities increasing the unpredictability of the endings and thus the likelihood of the two pathways developing incompatible representations. In cognitive terms, such a coordination role could consist of mediating the reciprocal connections between the lexical and phonological representational systems (DRC and resonance models) or a decision-making system (MROM-P and resonance models). Anomia effects on this region (Nielsen, 1946) could result either from disconnection of the lexical and phonological regions or impairment of the local decision-making mechanism that adjudicates between competing alternatives. The reciprocal mediation role could be considered to be equivalent to the Convergence Model of the pITG and the decision-making mechanism could be considered to be equivalent to the Translational Model of the pITG.

This hypothesis will be termed the language formulation area (LFA) hypothesis in honor of Nielsen (1946), who first identified this region as apparently playing a role in language processing and gave it this label and an initial hypothesis of which the present formulation is just a refinement. Although one could certainly find some faults with this term, it seems inappropriate to the present authors to ignore the prior contribution of Nielsen by renaming this region or otherwise ignoring his terminology and not giving due credit to his work.

In addition, this term for this cortical area has the virtue that even if the present hypothesis was subsequently disproven, it is largely neutral with respect to the cognitive function involved, other than it having to do with some aspect of language processing.

Some support for this account is found in an fMRI study of speech comprehension (Rodd et al., 2005) in which the experimenters manipulated the presence of embedded words that required contextual information to disambiguate; high ambiguity sentences activated the pITG [$-52 -50 -10$] as well. Such an interpretation would require that auditory stimuli also be processed by both pathways, which would be consistent with the observation that auditory and even tactile input can at least sometimes activate the basal language regions (Price, 2000; Price et al., 2003). Some further support for this account is the observation that a similar pITG activation [$-50 -48 -12$] was reported in a study (Zemleni et al., 2007) with phrasewise presentation of visual words, where a phonological representation in short-term memory could presumably assist in bridging the gaps between phrase presentations. In contrast, another study (Mason and Just, 2007) of ambiguity resolution presented the entire sentence on the screen, adding the words one at a time, and did not report a pITG activation.

Some data that helps strengthen the argument that the pITG process relates to orthographic and phonological level representations rather than semantic level representations is the report (Hashimoto and Sakai, 2004) that learning to associate Hangul (Korean) letters with the corresponding sounds over the course of 2 days increases the activation in this region [$-54 -51 -21$] and increases its effective connectivity to the parietal-occipital regions implicated in phonological processing. This observation could be accounted for as being the result of increasing efforts to coordinate the nascent activations in the two pathways that have, as yet, imperfect correspondences.

Some further data that is consistent with this proposal is the report (Mechelli et al., 2003) that pseudowords compared to words in a silent reading task activate the pITG [$-44, -64, -16$] (for a similar finding, see also Xu et al., 2001), along with the left frontal operculum and the right cerebellum. These authors quite rightly noted that current cognitive models do not provide predictions regarding the neural architecture sufficient to interpret these findings or to evaluate their significance for these models. The present hypothesis therefore seeks to advance the status quo by doing so. The LFA hypothesis suggests that pseudowords are likely to require greater coordination activity in that the lexical and phonological pathways are more likely to diverge (with the phonological pathway decoding the pseudoword veridically whereas the lexical pathway would activate orthographic neighbors of the pseudoword (Siakaluk et al., 2002), which would not correspond to the phonological representation, resulting in cross-code inconsistency (Grainger et al., 2005).

Further evidence that the pITG relates to the coordination of the orthographic and phonological levels, rather than phonological analysis per se, is provided by the report (Paulesu et al., 2000) that when Italian students read aloud words and non-words derived from Italian (a language with a close

correspondence between orthography and phonology) activations were seen in superior temporal phonology regions whereas when English students performed the same task in their language (a language with a relatively opaque mapping between orthography and phonology) activations were seen in the pITG and the inferior frontal regions.

At this point, this account must be considered to be a preliminary hypothesis to guide future studies but it is suggested to be a stronger argument than current alternatives. One such alternative is that the pITG is specifically dedicated to mediating sentence context but there have been no lesion reports consistent with such an interpretation. Another alternative is that it is part of the phonological pathway (Hickok and Poeppel, 2004) but it has not been observed to activate in phonology tasks like rhyming (Booth et al., 2002a,b, 2003; Gitelman et al., 2005; Owen et al., 2004; Paulesu et al., 1993, 1996).

This account may provide some insight into dyslexia, a pathology of current interest. In two separate studies of dyslexics this region was less activated in the dyslexics (Brunswick et al., 1999): study 1 [–50 –48 –12] and study 2 [–42 –48 –6]. A similar report has been made in a cross-cultural study (Paulesu et al., 2001) of English, French, and Italians [–52, –60, –14]. Furthermore, it has been reported that reading skill is positively correlated with fMRI activity in the pITG [–53 –38 –5] in category and non-word reading tasks for both normal and dyslexia children (Shaywitz et al., 2002). It is possible that this deactivation reflects relative inactivity in one of the two pathways, resulting in a lesser need for coordination. Some support for this view is found in a study of semantic dementia involving anterolateral temporal cortex degeneration, which could similarly disable one or both pathways, resulting in deactivation of the pITG [–54 –52 –10] according to PET measures (Mummary et al., 1999a,b). Alternatively, one could speculate that this deactivation is a contributing cause towards, rather than a symptom of, dyslexia. If the two pathways were not being properly coordinated, this could result in poorer language performance. It is intriguing to note that this pITG region is situated close to the motion regions that have also been implicated in dyslexia (Eden et al., 1996a,b).

4. Conclusion

The present results help further implicate the posterior inferior temporal gyrus as being a language region, demonstrating that activity in this region is sensitive to sentential context. This paper has built on this finding to suggest, based on a literature review, that the function of this pITG is to coordinate representations in the lexical and non-lexical pathways. Consideration of existing studies suggests that the pITG may be of particular relevance for the understanding and diagnosis of dyslexia. We also suggest that it may be appropriate to term this part of the pITG the language formulation area (LFA) in honor of Nielsen, who first identified this region as possibly playing a role in language processing (Nielsen, 1946), especially since this term is relatively neutral in terms of specifying the nature of the language process.

5. Experimental procedures

5.1. Participants

11 volunteers (7 females) with an average age for the first three participants of 24 (age not available for the remaining eight as the demographic information was erroneously omitted when the session log form was changed midway through data collection) participated in the fMRI experiment on a volunteer basis. All had corrected-to-normal vision, were right-handed, and were native English speakers. None reported any history of brain injury, attention deficit disorder, or dyslexia.

5.2. Stimuli

The stimuli consisted of 150 sentences (Appendix A) derived from a published stimulus set (Bloom and Fischler, 1980). This set contained ten groupings of sentences, formed according to the cloze probability on the sentence's final word. The incongruent group (cloze probabilities equal zero) contains 75 sentences. The 75 congruent sentences are divided into nine congruent groups, three (mean cloze probabilities 0.2, 0.4 and 0.7) containing 9 sentences each, and six (mean cloze probabilities 0.15, 0.33, 0.52, 0.68, 0.82, and 0.99) containing 8 sentences each. The incongruous endings were chosen to be roughly matched (no statistically significant difference) to the congruous endings in terms of sentence length (7.8 vs. 7.7), word length (5.0 vs. 5.5), and word frequency (Francis and Kucera, 1982) (94.9 vs. 125.0). Subsequent analysis indicated that within the set of congruent stimuli, cloze was significantly correlated with word length: $r(73) = .26$, $p = .03$. For parametric analyses, a regression equation was used to partial out the portion of the cloze variable predictable from word length and the resulting residual was utilized for parametric analysis.

5.3. Procedure

The session started with a practice section with ten sentences. The experiment was then divided into four blocks, each lasting about 6 min. Participants were instructed to read the sentences for comprehension, as a recognition quiz was given at the end of each block for the full sentences. The sentences were presented via an IFIS stimulus presentation hood in the same randomized order in all sessions. Each word was displayed for 105 ms, and immediately replaced by a fixation mark, and then the next word was displayed following a 900 ms delay, until each word in the sentence was shown. The inter-trial interval was 1 s. The fixation mark was a 12-point “+” sign while the words were in 48-point font, both in Helvetica. The size of the fixation mark was chosen to be just large enough to provide a fixation point without being large enough to interfere with recognition of the words. The visual angle cannot be specified as the presentation hood did not allow for measurement of either the on-screen size or the viewer distance.

The stimulus presentation rate was chosen to maintain comparability with a prior ERP study (Dien et al., 2003) and to provide optimal separation of hemodynamic responses to the

sentence ending words (the sentences were an average of 7.76 words in length so the average separation between ending words was 8.76 s, sufficient to avoid overlap in the hemodynamic responses). The 1 word/s rate is also the same as that used in a previous fMRI sentence study (Kiehl et al., 2002). Furthermore, an ERP study (Kutas, 1987) has reported no apparent differences in the semantic effects for slow (700 ms SOA) and fast (100 ms SOA) presentation rates. The method of using sequential word presentations has been widely used for sentence reading paradigms in both neuroimaging experiments (Bavelier et al., 1997; Kiehl et al., 2002; Kuperberg et al., 2003) and ERP experiments (some examples being Camblin et al., 2007; Connolly et al., 1995; Coulson and Van Petten, 2002; Jost et al., 2004; Kuperberg et al., 2003; Kutas, 1987; Kutas and Hillyard, 1980a; Martin et al., 2006; Mitchell et al., 1993; Newman and Connolly, 2004; Osterhout and Nicol, 1999; Van Petten and Kutas, 1990). The repeated reports of distinctive and appropriate responses to syntactic anomalies (some recent examples being Hagoort, 2003; Koelsch et al., 2005; Kuperberg et al., 2003; Newman et al., 2007; Osterhout and Nicol, 1999; Palolahti et al., 2005) validates the subjective report that the sentences are being processed as sentences rather than word lists.

The sentences were presented in the same randomized sequence to all participants. There was no significant correlation between order and sentence types or sentence parameters. The procedure was approved by the Tulane University Medical Center Institutional Review Board and was in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

The fMRI data were collected on a 1.5T Siemens Symphony Quantum system at the Louisiana State University Health Sciences Center. Anatomical data were scanned using a 104-slice isotropic T1 image. Functional data were obtained using a 2D MOSAIC sequence with a TR of 3.6 and TE of 50 ms. Four six-minute blocks (defined as a contiguous recording period) were recorded from each subject, separated by rest periods. After each such block, the recognition questionnaire was administered over the intercom. The scans were begun two TRs (7.2 s) before the trials began so that they could be dropped to minimize T1 stabilization artifact. There were 22 axial slices and the voxels were 3.44×3.44×8 mm with zero interslice gap.

Analysis was conducted using SPM2 (Wellcome Department of Imaging Neuroscience, <http://www.fil.ion.ucl.ac.uk>). Realignment utilized a robust realignment algorithm (Freire and Mangin, 2001). After realignment the first three time points were dropped to reduce T1 stabilization artifact, leaving 97 time points in each of the sessions. Spatial normalization was performed by matching a mean echoplanar imaging (EPI) image from each participant to the EPI template provided with SPM2. Data were resliced into 2×2×2 mm resolution. Analysis was event-related (hrf function) of the sentence ending words and using random effects. Default high-pass filter was employed and no global proportional scaling was performed, to avoid scaling artifacts (see Desjardins et al., 2001). AR(1) correction was made for temporal autocorrelation (see Smith et al., 2007). Smoothing was applied to yield estimated smoothness of about 12 mm full-width half-maximum (smoothing of unknown parameters was applied at data acquisition time). Stimuli were presented with timing that

was not an even multiple of the image acquisition time (TR), resulting in staggered timing that enhances characterization of the hemodynamic response in event-related analyses (Josephs et al., 1997). Voxelwise height thresholds were set at .005. Conversion to the Talairach and Tournoux atlas coordinates were performed using Matthew Brett's MNI2tal function (<http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispac.html>).

ROI analyses were conducted using the small volume correction (SVC) option with a 6 mm sphere centered on the point of interest. The four ROIs were the aLIPC [-44 26 2], the pLIPC [-49 16 24], the pMTG [-47 -54 6], and the FSA [-32 -40 -20].

5.4. Statistical tests

Following standard lab procedure, robust test statistics using a combination of a Welch-James type approximate degrees of freedom (ADF) approach, trimmed means, and bootstrapping were used to test effects (Keselman et al., 2003): <http://www.people.ku.edu/~jdien/downloads.html>. A 10% 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 50,000. P-values are rounded to the second significant digit (where available).

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Appendix A

A.1. Incongruent

His view was blocked by the music.
 The gas station is about two miles down the hammer.
 On their visit to England, they took a formal sound.
 None of his books made any peace.
 The baby cried and upset her surface.
 He scraped the cold food from his chain.
 There's something grand about the onion.
 The paint turned out to be the wrong week.
 The governor vetoed the new grocery.
 Without food a man would die in several glaciers.
 The exit was marked by a large balloon.
 When the two met, one of them held out his lemons.
 The lawyer feared that his client was verbal.
 She called her husband at his matter.
 The final score of the game was helped.
 The kids fed the ducks some stale friends.
 In the first space enter your love.
 The whole town came to hear their mayor learn.
 The senator was startled by the sudden pain in his baby.
 His ability to work was yellow.

Jean hurriedly shoved her way through the pocket.
 The dough was put in the hot appetite.
 The boat passed easily under the spoon.
 Most cats see well at court.
 Seth couldn't imagine anyone less bumpy.
 They left the dirty dishes in the ocean.
 He liked lemon and sugar in his finger.
 The sun went down before we could pretend.
 John felt sorry, but it was not his game.
 The gambler had a streak of bad gas.
 The game was called when it started to kill.
 He shouted at the top of his skyscraper.
 I could not remember his flavor.
 John swept the floor with a container.
 He loosened the tie around his fruit.
 If the crowd quiets down the band will flow.
 Her new shoes were the wrong wife.
 The hungry bear found some stale film.
 They raised pigs on their firm.
 The old house will be torn awake.
 My sister bought tickets for the opening lie.
 The academic year began in the east.
 At night the old woman locked the city.
 I don't know why he didn't take his anger.
 It's hard to admit when one is young.
 The elderly sometimes lose their ghost.
 Some people have never had a square idea.
 Joan fed her baby some warm rabbit.
 All the guests had a very good pin.
 She went to the salon to color her disk.
 Tim threw a rock and broke the argument.
 The fertilizer enriched the evening.
 Vic asked her to repeat what she had grazed.
 He drove the nail into the liquid.
 The lecture should last about one cigarette.
 The wealthy child attended a private point.
 He lay down and went to church.
 The paper was too thick to do.
 Most shark attacks occur very close to size.
 Hank reached into his pocket to get the pottery.
 He crept into the room without a sip.
 He mailed the letter without a drill.
 His leaving home amazed all his spiders.
 Three people were killed in a major highway graduate.
 Captain Sheir wanted to stay with the sinking tone.
 He brought them in the candy hill.
 The dispute was settled by a third nature.
 Father carved the turkey with a telephone.
 Jean was glad the affair was under.
 The crime rate has gone up this group.
 His boss refused to give him a lick.
 She was named after her initiation.
 When you go to bed turn off the flesh.
 His job was to keep the sidewalk happy.
 The bill was due at the end of the nation.

A.2. Congruent

A.2.1. 0.15

Jill looked back through the open gate.

John poured himself a glass of gin.
 He was soothed by the gentle woman.
 Diane slowly sank into the hot shower.
 Even infants can be taught to listen.
 The hunter shot and killed a large animal.
 To tune your car you need a special machine.
 My uncle gave my mother a big rose.
 They went to the rear of the long hallway.

A.2.2. 0.2

Few nations are now ruled by a democracy.
 The police had never found a man so nervous.
 The choir sang hymns while the people hummed.
 They went to see the famous landmark.
 Joan showed her friend a new card today.
 Barry wisely chose to pay the debt.
 The kind old man asked us to come.
 Even their friends were left in the room.
 The car stalled because the engine failed to turn.

A.2.3. 0.33

There are times when life seems hopeless.
 She cleaned the dirt from her hands.
 Dillinger once robbed that train.
 Helen reached up to dust the lamp.
 The surface of the water was nice and warm.
 The long test left the class dazed.
 The young boy was granted a small prize.
 Larry chose not to join the team.
 His ring fell into a hole in the sewer.

A.2.4. 0.4

The judge warned about the dangers of lying.
 The death of his dog was a great loss.
 Coming in he took off his shoes.
 Ken built his new house on a quiet street.
 Every spring they held the annual festival.
 In the distance they heard the thunder.
 The storm made the air damp and humid.
 Rushing out he forgot to take his wallet.

A.2.5. 0.52

Sometimes success is simply a matter of luck.
 I thought the sermon was very good.
 It was a long class and every one was getting tired.
 The fire was small and there was no reason to worry.
 Rita slowly walked down the shaky ladder.
 Being stood up made Paul angry.
 You can't buy anything for a dime.
 The airplane went into a dive.

A.2.6. 0.68

Jim hit his horse with a whip.
 The rider walked his beautiful horse.
 Jim wanted to change the way he looked.
 The apple pie had a delicious taste.
 What you find depends on where you look.
 He was miles off the main road.
 He put his feet up on the table.
 The cup of tea felt very warm.

A.2.7. 0.7

While skiing, Randy broke his leg.
 They asked Dave to play tennis, but he was too tired.
 During the volley, Joe twisted his ankle.
 Autumn is a good time to buy some new clothes.
 The student went home during the break.
 Smoking can give you bad breath.
 David's shirt was made of cotton.
 It's easy to get lost without a map.

A.2.8. 0.82

Our guests should be arriving soon.
 Sam could not believe her story was true.
 The old milk tasted very sour.
 Don't touch the wet paint.
 The cows moved from the sun into the shade.
 I added my name to the list.
 Mrs. Martin told the bad student to stand in the corner.
 We sometimes forget that golf is just a game.

A.2.9. 0.99

They sat together without speaking a single word.
 At first the woman refused, but she changed her mind.
 Water and sunshine help plants grow.
 The children went outside to play.
 He wondered if the storm had done much damage.
 To pay for the car, Al simply wrote a check.
 Bill jumped in the lake and made a big splash.
 The movie was so jammed they couldn't find a single seat.

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