Neural stages of spoken, written, and signed word processing in second language learners

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Running Title

Language modality and proficiency effects

Abstract

We combined magnetoencephalography (MEG) and magnetic resonance imaging (MRI) to examine how sensory modality and language proficiency affect two fundamental stages of word processing: (1) an early modality-specific word encoding stage, and (2) a later supramodal lexico-semantic stage. Adult native English speakers who were learning American Sign Language (ASL) performed a semantic task for spoken and written English words, and for ASL signs. During the early time window, written words evoked responses in left ventral occipitotemporal cortex, and spoken words in left superior temporal cortex, consistent with well-established modality-specific processing. Signed words evoked the strongest activity in right intraparietal sulcus, potentially analogous to the other modalities. During the later time window, all three types of words showed significant activity in the classical left fronto-temporal language network, the first demonstration of such activity in individuals with so little second language instruction in sign. However, a dissociation between semantic congruity effects and overall MEG response magnitude for ASL responses suggested shallower and more effortful processing, presumably due to the participants being significantly less proficient in that language. ASL also showed additional recruitment of right hemisphere and lateral occipital cortex consistent with previous research on non-dominant language processing in bilinguals with two spoken languages. These results demonstrate, in the context of previous work with various groups of signing and non-signing bilinguals, that proficiency affects processing in sign language, and is at least partially separable from the effects of language modality.

1. Introduction

Humans acquire language in an astonishingly diverse set of circumstances. Nearly everyone learns a spoken language from birth and a majority of individuals then follow this process by learning to read, an extension of their spoken language experience. Sign language is another language modality that exists independently from spoken language. When deaf children are raised by deaf parents and acquire sign as their native language from birth, they achieve fluency with the same timing and in the same manner as spoken language in hearing individuals [1,2]. This is not surprising given that sign languages have sublexical and syntactic complexity similar to spoken languages [3,4]. Neural investigations of sign language have also shown a close correspondence between the processing of signed words in deaf individuals and spoken words in hearing individuals [5-8], with the predominant finding being that left anteroventral temporal, inferior prefrontal, and superior temporal cortex are the main loci of lexico-semantic processing in both languages, and including both spoken and written forms [9].

In contrast to the processing of words' meanings, which occurs between ~200-400ms after the word is seen or heard [10], processing of the words' forms and sublexical structure appears to be modality-specific. Written words are encoded for their visual form primarily in left ventral occipitotemporal areas [11-14]. Spoken words are likewise encoded for their acoustic-phonetic and phonemic forms in left-lateralized superior temporal cortex, including the superior temporal gyrus and planum temporale [15-17]. Both of these processes occur within the first ~170ms after the word is presented. While an analogous form encoding stage presumably exists with similar timing for sign language, no such process has been identified. Thus, evidence from monolingual users of spoken/written and signed languages demonstrates that during a long latency time window between ~200-400ms, information converges on the classical left fronto-temporal language network where amodal meaning is extracted and integrated.

Much of the world's population is at least passingly familiar with more than one language, which provides a separate set of circumstances for learning and using words. Often, a second language is acquired later and with ultimately lower proficiency compared to the native language. Fluent, balanced speakers of two or more languages have little difficulty producing words in the contextually correct language, and they understand words as rapidly and efficiently as words in their native language [18]. However, prior to fluent understanding, the brain goes through a learning process that uses the native language as a scaffold, but diverges in subtle, yet important ways from native language processing. The extent of these differences (both behaviorally and neurally) fluctuates in relation to the age at which one begins acquiring the second language, the level of proficiency at any given moment during the learning process, the amount of time spent using each language throughout the course of the day, and possibly the modality of the newly-learned language [19,20]. Thus, bilingualism provides a unique opportunity to examine the role of experience in how the brain processes words.

In agreement with many bilinguals' intuitive experiences, several behavioral studies using cross-language translation priming have found that proficiency and language dominance impact the extent and direction of priming [18,21,22]. The most common finding is that priming is strongest in the dominant to non-dominant direction, although the opposite pattern has been observed [23]. These results are consistent with models of bilingual lexical representations, including the Revised Hierarchical Model

[24] and the Bilingual Interactive Activation + model [25], both of which posit interactive and asymmetric connections between word (and sublexical) representations in both languages.

An important question is how these behavioral proficiency effects manifest in neural activity patterns: How does the brain process less proficient words differently than more familiar words? There is extensive neuroimaging and neurophysiological evidence in support of these models, and particularly in support of a strong role for proficiency in cortical organization [20]. Two recent studies that measured neural activity with magnetoencephalography (MEG) constrained by individual subject anatomy obtained with magnetic resonance imaging (MRI) found that, while both languages for Spanish-English bilinguals evoked activity in the classical left hemisphere fronto-temporal network, the non-dominant language additionally recruited posterior and right hemisphere regions [26,27]. These areas showed significant non-dominant>dominant activity beginning during an early stage of word encoding (between ~100-200ms), and continuing through the time period typically associated with lexico-semantic processing (~200-400ms). Crucially, these and other studies (e.g., [20]) showed that language proficiency was the main factor in determining the recruitment of non-classical language areas, and that the order in which the languages were acquired did not greatly affect the activity.

These findings are consistent with the hemodynamic imaging and electrophysiological literatures. Using functional MRI (fMRI), proficiency-modulated differences in activity have been observed [28-30], and there is evidence for greater right hemisphere activity in the less proficient second language [31,32]. While fMRI provides spatial resolution on the order of millimeters, the hemodynamic response unfolds over the course of several seconds, far slower than the timecourse of linguistic processing in the brain. Electroencephalographic methods including event-related potentials (ERPs) are useful for elucidating the timing of activity, and numerous studies have found proficiency-related differences between bilinguals' two languages. One measure of lexico-semantic processing, the N400 (or N400m in MEG; [33]) is delayed by ~40-50ms in the second language [34-36], and this effect is constrained by language dominance [37]. In general, greater occipito-temporal activity in the non-dominant language (particularly on the right), viewed in light of delayed processing, suggests that lower proficiency involves less efficient processing, and the need for recruitment of greater neural resources. This is a well-established mechanism that applies to both non-linguistic [38] and high-level language tasks [39].

This overview of the literature demonstrates two main issues: (1) In nearly all subject populations that have been examined, lexico-semantic processing is largely unaffected by language modality, and (2) lower proficiency involves the recruitment of a network of non-classical language regions that likewise appear to be modality-independent. In the present study, we sought to examine the effects of language proficiency in the context of individuals who are learning a second language that differs in modality from their native language. This allows us to extend and refine previous reports of proficiency effects, and also to understand modality in two languages that have no inherent relationship (unlike spoken and written forms of a single language). We investigated a group of subjects with a unique set of circumstances as they relate to these two factors. The subjects were undergraduate students who were native English speakers who began learning American Sign Language (ASL) as an L2 in college. They had at least 40 weeks of experience, and were the top academic performers in their ASL courses and hence able to understand simple ASL signs and phrases. They were, however, unbalanced bilinguals with respect to English/ASL proficiency. Although there have been a few previous investigations of hearing L2 signers with extensive signing experience [40,41], no studies have examined word processing using methods that afford high spatiotemporal resolution to determine both the cortical sources and timing of activity during specific processing stages, nor have any studies looked at sign language processing in L2 learners with so little instruction. We combined MEG and structural MRI to examine neural activity in these subjects while they performed a semantic task in two languages/modalities: Spoken English, visual (written) English, and visual ASL.

While it is not possible to disentangle modality and proficiency effects within a single subject population, these factors have been systematically varied separately in numerous studies [8,9,26,27], and are well-characterized in isolation. It is in this context that we examined both factors in this group of L2 learners. We hypothesized that after a modality-specific word encoding stage between ~100-200ms (left superior planar regions for spoken words, left ventral occipitotemporal regions for written words, and an unknown set of regions for signed words), lower proficiency in ASL relative to English would result in a more extended network of brain regions used to process lexico-semantic content between ~200-400ms post-stimulus onset. These areas have previously been identified in unimodal bilinguals and include bilateral posterior visual and superior temporal areas [26,27]. Observing differences between ASL and English in the extended network this time period would provide novel evidence that proficiency effects extend across modalities, and would provide further support for the notion that the processing of meaning in these regions is supramodal, a particularly striking result given the vastly different sensory characteristics of spoken English and ASL.

2. Materials and Methods

2.1 Ethics Statement

Participants gave written informed consent to participate in the study, and were paid $20/hour for their time. This study was approved by the Institutional Review Board at the University of California, San Diego.

2.2 Participants

Eleven hearing native English speakers participated in this study (10 F; age range = 19.74-33.16 years, mean = 22.42). All were healthy adults with no history of neurological or psychological impairment, and had normal hearing and vision (or wore corrective lenses that were applied in the MEG). All participants had at least four academic quarters (40 weeks) of instruction in ASL, having reached the highest level of instruction at either UCSD or Mesa College. Participants were either currently enrolled in a course taught in ASL or had been enrolled in such a course in the previous month. One participant had not taken an ASL course in the previous four months. Participants completed a self-assessment questionnaire that asked them to rate their ASL proficiency on a scale from 1-10. For ASL comprehension, the average score was 7.1 ± 1.2; ASL production was 6.5 ± 1.9; Fingerspelling comprehension was 6.4 ± 1.6; and fingerspelling production was 6.8 ± 1.7. Six participants reported using ASL on a daily basis at the time of enrollment in the study, while the remaining participants indicated weekly use (one subject indicated monthly use).

2.3 Stimuli and Procedure

In the MEG, participants performed a semantic decision task that involved detecting a match in meaning between a picture and a word. For each trial, subjects saw a photograph of an object for 700ms, followed by a word that either matched (‘congruent’) or mismatched (‘incongruent’) the picture in meaning. Participants were instructed to press a button when there was a match; response hand was counterbalanced across blocks within subjects. Words were presented in blocks by language/modality for spoken English, written English, and ASL. Each word appeared once in the congruent and once in the incongruent condition, and did not repeat across modalities. All words were highly imageable concrete nouns that were familiar to the participants in both languages. Since no frequency norms exist for ASL, the stimuli were selected from ASL developmental inventories [1,42] and picture naming data [43,44]. The ASL stimuli were piloted with four other subjects who had the same type of ASL instruction to confirm that they were familiar with the words. Stimulus length was the following: Spoken English mean = 473.98 ± 53.17 ms; Written English mean = 4.21 ± 0.86 letters; ASL video clips mean = 467.92 ± 62.88 ms. Written words appeared on the screen for 1500 ms. Auditory stimuli were delivered through earphones at an average amplitude of 65 dB SPL. Written and signed word videos subtended < 5 degrees of visual angle on a screen in front of the subjects. For all stimulus types, the total trial duration varied randomly between 2600-2800 ms (700 ms picture + 1500 ms word container + 400-600 ms inter-trial interval).

Each participant completed three blocks of stimuli in each language/modality. Each block had 100 trials (50 stimuli in each of the congruent and incongruent conditions) for a total of 150 congruent and incongruent trials in each language/modality. The order of the languages/modalities was counterbalanced across participants. Prior to starting the first block in each language/modality, participants performed a practice run to ensure they understood the stimuli and task. The practice runs were repeated as necessary until subjects were confident in their performance (no subjects required more than one repetition of the practice blocks).

2.4 MEG Recording

Participants sat in a magnetically shielded room (IMEDCO-AG, Switzerland) with the head in a Neuromag Vectorview helmet-shaped dewar containing 102 magnetometers and 204 gradiometers (Elekta AB, Helsinki, Finland). Data were collected at a continuous sampling rate of 1000 Hz with minimal filtering (0.1 to 200 Hz). The positions of four non-magnetic coils affixed to the subjects' heads were digitized along with the main fiduciary points such as the nose, nasion, and preauricular points for subsequent coregistration with high-resolution MR images. The average 3-dimensional Euclidian distance for head movement from the beginning of the session to the end of the session was 7.38 mm (SD = 5.67 mm).

2.5 Anatomically-constrained MEG (aMEG) Analysis

The data were analyzed using a multimodal imaging approach that constrains the MEG activity to the cortical surface as determined by high-resolution structural MRI [45]. This noise-normalized linear inverse technique, known as dynamic statistical parametric mapping (dSPM) has been used extensively across a variety of paradigms, particularly language tasks that benefit from a distributed source analysis [26,27,46], and has been validated by direct intracranial recordings [47,48].

The cortical surface was obtained in each participant with a T1-weighted structural MRI, and was reconstructed using FreeSurfer. The images were collected at the UCSD Radiology Imaging Laboratory with a 1.5T GE Signa HDx scanner using an eight-channel head coil (TR=9.8ms, TE=4.1ms, TI=270ms, flip angle=8°, bandwidth = ± 15.63 kHz, FOV = 24 cm, matrix = 192 × 192, voxel size = 1.25 × 1.25 × 1.2 mm). All T1 scans were collected using online prospective motion correction [49]. A boundary element method forward solution was derived from the inner skull boundary [50], and the cortical surface was downsampled to ~2500 dipole locations per hemisphere [51,52]. The orientation-unconstrained MEG activity of each dipole was estimated every 4ms, and the noise sensitivity at each location was estimated from the average pre-stimulus baseline from -190 to -20ms for the localization of the subtraction for congruent-incongruent trials.

The data were inspected for bad channels (channels with excessive noise, no signal, or unexplained artifacts), which were excluded from all further analyses. Additionally, trials with large (>3000 fT for gradiometers) transients were rejected. Blink artifacts were removed using independent components analysis [53] by pairing each MEG channel with the electrooculogram (EOG) channel, and rejecting the independent component that contained the blink. On average, fewer than five trials were rejected for each condition.

Individual participant dSPMs were constructed from the averaged data in the trial epoch for each condition using only data from the gradiometers, and then these data were combined across subjects by taking the mean activity at each vertex on the cortical surface and plotting it on an average brain. Vertices were matched across subjects by morphing the reconstructed cortical surfaces into a common sphere, optimally matching gyral-sulcal patterns and minimizing shear [52,54].

All statistical comparisons were made on region of interest (ROI) timecourses from these group data. ROIs were based on a separate data set not included in this study that compared signed and spoken word processing in congenitally deaf and hearing subjects using the same task presented here (**Figure S1**; [8]). These ROIs were originally drawn on the grand average activity across both deaf and hearing participants, and thus are not biased toward either signed or spoken words. In the 80-120ms time window, we specifically tested bilateral planum temporale (PT) and superior temporal sulcus (STS) because these areas showed significant responses to spoken words, and are known to be involved in early word encoding in the auditory modality [55]. For the 150-200ms time window, we were specifically interested in ventral occipitotemporal (vOT) cortex because it is involved in written word form encoding [14]. While there are no previous studies of this stage for sign language, we selected bilateral intraparietal sulcus (IPS) because it has been implicated in some studies of non-temporally specific sign processing [56], and because it showed the strongest activity during this time window. For the lexico-semantic time window from 300-400ms, we tested all ten bilateral ROIs. With the exceptions of IPS and lateral occipitotemporal (LOT) cortex, these areas are known from extensive prior work to be involved in lexico-semantic processing, including anteroventral temporal areas that are hypothesized to be largely supramodal. We also included LOT because it has been implicated as a lexico-semantic area that is modulated by proficiency [26,27].

3. Results

3.1 Reaction Time and Accuracy

The following analyses use these abbreviations: **A = auditory, W = written, and S = sign**. Participants performed within normal ranges for both reaction time and accuracy compared to similar tasks in other studies. **Table 1** shows the average and standard deviations for each language/modality. Consistent with the fact that English was the subjects' native and dominant language and ASL was a recently learned L2, reaction times were significantly faster for A than for S [$t(10) = 6.85$, $p < 0.0001$], and for W than for S [$t(10) = 8.22$, $p < 0.0001$]. A and W were not significantly different. Similarly, participants were more accurate for A than for S [$t(10) = 5.13$, $p < 0.0001$], and for W than for S [$t(10) = 4.13$, $p = 0.002$], although accuracy for S was still quite good (nearly 90%). Accuracy for A and W were not significantly different.

3.2 aMEG – 80-120ms (Early Word Encoding)

Previous investigations have identified an evoked potential peak at ~100ms that shows selectivity for auditory speech stimuli compared to sensory controls in primarily left superior temporal and superior planar cortex [55]. We tested the MEG response during this window in two areas to determine whether an auditory-selective modality effect was present. We found a main effect of modality in left planum temporale (PT) [$F(1,10) = 3.58$, $p = 0.047$], and in left superior temporal sulcus (STS) [$F(1,10) = 6.22$, p

= 0.008] (**Figure 1, top**). The effect in PT was driven by trending A>W [t(10) = 1.95, *p* = 0.079] and A>S [t(10) = 1.93, *p* = 0.083] responses, and likewise for STS [t(10) = 2.77, *p* = 0.02; t(10) = 2.37, *p* = 0.039] (**Figure 2**). Similar effects were obtained in right PT [F(1,10) = 6.15, *p* = 0.008] and STS [F(1,10) = 10.74, *p* = 0.001]. While the right STS effect was driven by an A>W [t(10) = 4.00, *p* = 0.003] and A>S [t(10) = 2.81, *p* = 0.018] response, the right PT effect was driven by an overall smaller response to W compared with A [t(10) = 3.32, *p* = 0.008] and S [t(10) = 3.00, *p* = 0.013].

3.3 aMEG – 150-200ms (Early Word Encoding)

The early word encoding response to written words occurs later than for auditory words, and is centered in a left posterior ventral occipitotemporal (vOT) region. During a window from 150-200ms, we tested for a W>A and W>S effect in vOT (**Figure 3, middle**). In the left hemisphere, there was a main effect of modality [F(1,10) = 4.57, *p* = 0.023], driven by W>A [t(10) = 4.58, *p* = 0.001] and W>S [t(10) = 2.36, *p* = 0.04] responses (**Figure 2**). The homologous right hemisphere vOT region did not show significant effects (*p*s > 0.5).

Given that there are early word encoding processes for auditory and written words, it is reasonable to ask whether such a process exists for signed words. We examined the response to signs from 150-200ms, when we expect post-sensory, but pre-lexical processing to occur. The dSPM timecourses in **Figure 2** revealed a S>A and S>W pattern in right intraparietal sulcus (IPS), and indeed this region showed a marginal main effect of modality [F(1,10) = 3.20, *p* = 0.062], driven by a significant S>W response [t(10) = 2.51, *p* = 0.031] (the differences between W & A and S & A were not significant; **Figure 3, bottom**).

3.4 aMEG – 300-400ms (Lexico-semantic processing)

Based on results from a separate data set that compared sign processing in deaf native signers to spoken word processing in hearing native English speakers using the same task presented here [8], and on previous work examining both early and late processing in different language modalities [46], we selected ten ROIs to examine for sensitivity to semantic congruity: Inferior prefrontal cortex, anterior insula, planum temporale, superior temporal sulcus, posterior superior temporal sulcus, intraparietal sulcus, lateral occipitotemporal cortex, temporal pole, inferior temporal cortex, and ventral occipitotemporal cortex [8]. For each modality, we calculated dSPMs of the subtraction of incongruent-congruent words, extracted timecourses for each subtraction condition, and tested for within-subject effects of modality.

We calculated an omnibus ANOVA with three within-subject factors: Language/modality (3), ROI (10), and hemisphere (2). There were highly significant main effects of language/modality [F(2,20) = 6.96, $p = 0.005$], ROI [F(9,90) = 6.76, $p < 0.0001$], and hemisphere [F(1,10) = 10.07, $p = 0.01$]. There were significant interactions between language/modality and ROI [F(18,180) = 2.35, $p = 0.002$], and language/modality and hemisphere [F(2,20) = 9.75, $p = 0.001$], but no three-way interaction.

Based on *a priori* hypotheses about specific ROIs from previous studies (see Materials and Methods), we tested a series of planned comparisons across modalities. Overall, there was a highly similar response to A, W, and S words (**Figure 4**). While A and W appeared to show semantic effects of a similar magnitude, these were weaker for S across most regions (**Figure 5**). In the left hemisphere, there was a main effect in inferior frontal cortex [F(1,10) = 9.92, $p = 0.001$], driven by A>S [t(10) = 3.81, $p = 0.003$] and W>S [t(10) = 3.29, $p = 0.008$] responses. Similarly, in inferior temporal (IT) cortex, there was an effect of modality [F(1,10) = 5.94, $p = 0.009$] with A>S [t(10) = 2.40, $p = 0.038$] and W>S [t(10) = 3.50, $p = 0.006$]. In posterior STS (pSTS), there was a significant difference [F(1,10) = 4.97, $p = 0.018$], driven primarily by a W>S response [t(10) = 3.09, $p = 0.011$] and a trend for A>S [t(10) = 1.98, $p = 0.075$]. Superior temporal regions showed main effects of modality where all three conditions differed significantly from one another [PT: F(1,10) = 15.03, $p < 0.0001$; STS: F(1,10) = 24.71, $p < 0.0001$]. None of the other five left hemisphere ROIs showed significant language/modality effects.

In the right hemisphere, S elicited smaller responses in inferior frontal cortex [F(1,10) = 4.70, $p = 0.021$], with W>S [t(10) = 2.66, $p = 0.024$] and a marginal A>S difference [t(10) = 2.14, $p = 0.058$]. In STS, there was a main effect of modality [F(1,10) = 5.68, $p = 0.011$], driven primarily by a strong A>S response [t(10) = 3.51, $p = 0.006$] and a trend for A>W [t(10) = 1.88, $p = 0.09$]. None of the other eight right hemisphere ROIs showed significant language/modality effects.

3.5 aMEG – 300-400ms (Overall Responses)

The congruous/incongruous semantic manipulation in the task is only one way to examine the nature of the response during lexico-semantic processing. To understand which regions responded to words in each language/modality, but which were not necessarily influenced by semantic context, we also examined the grand average across both congruous and incongruous trials. While the previous analysis demonstrated small congruity effects for signed words, examination of the grand average revealed a different pattern (**Figure 6**). In the same ROIs, we tested these grand averages for modality effects (**Figure 2**).

In the left hemisphere, inferior frontal cortex showed a main effect of language/modality [F(1,10) = 3.65, $p = 0.044$] with S>W [t(10) = 2.36, $p = 0.04$] and S>A [t(10) = 2.76, $p = 0.02$]. IT showed a similar marginal effect [F(1,10) = 3.35, $p = 0.056$], driven by a marginal S>W effect [t(10) = 2.21, $p = 0.052$] and a trend for S>A [t(10) = 2.05, $p = 0.067$]. None of the other eight left hemisphere ROIs showed significant language/modality effects.

In the right hemisphere, we observed widespread effects where signs evoked greater activity than auditory or written words. Inferior frontal cortex showed this pattern [F(1,10) = 10.78, $p = 0.001$] with S>W [t(10) = 3.19, $p = 0.01$] and S>A [t(10) = 3.85, $p = 0.003$]. The same pattern was found for IPS [F(1,10) = 19.81, $p < 0.0001$] with S>W [t(10) = 7.03, $p < 0.0001$] and S>A [t(10) = 3.85, $p = 0.003$]. In lateral occipitotemporal (LOT) cortex, there was a main effect of language/modality [F(1,10) = 6.21, $p = 0.008$] with S>W [t(10) = 2.89, $p = 0.016$] and S>A [t(10) = 2.62, $p = 0.026$]. Similarly, both PT ([F(1,10) = 5.09, $p = 0.016$]; S>W [t(10) = 2.76, $p = 0.02$] and S>A [t(10) = 2.44, $p = 0.035$]) and pSTS ([F(1,10) = 4.97, $p = 0.018$]; S>W [t(10) = 3.38, $p = 0.007$] and S>A [t(10) = 2.01, $p = 0.072$] showed language/modality effects. The other five right hemisphere ROIs did not show significant language/modality effects.

3.6 Results Summary

We found that there were distinct patterns of neural activity related to the language/modality subjects saw or heard and their language proficiency. These effects began during the earliest stages of word encoding (~100ms for auditory, and ~150ms for written and signed words), and continued through lexico-semantic encoding (~300-400ms). **Table 2** summarizes the main findings by time window. **Figure S2** shows sensor-level data from a single representative subject.

4. Discussion

In the present study, we examined the spatiotemporal dynamics of word processing across two languages and modalities in a group of hearing, English native speakers who were new L2 learners of ASL. During an early word encoding stage (~100ms for spoken English, and ~150ms for written English and ASL), words evoked activity in modality-specific brain regions. Responses to English words in the auditory and visual modalities conformed to previous findings in superior temporal and ventral occipitotemporal areas. In contrast, ASL signs evoked a strong response in right IPS. During a later time window associated with lexico-semantic processing, a distributed network of bilateral regions responded to a semantic congruity manipulation. Several classical left fronto-temporal language areas showed stronger modulation for English (the native language) in two modalities relative to the second language, ASL. In contrast, when we examined the overall activity during this time window, signed words evoked greater activity than both English modalities in a network of mostly right hemisphere regions.

The early modality-specific word encoding responses are consistent with a large number of previous studies using a variety of methodologies. For written English words, we observed a peak in left vOT, a region that has been shown to be important for reading, and specifically for constructing written word-forms [11-14]. Although there is evidence that it is not a unimodal region [57], it does seem to play an important role in encoding written words. In addition to the location, the peak timing of the activity in this region at ~170ms is consistent with previous electrophysiological and neuroimaging studies [12,48]. Additionally, although written and signed words are understood through the visual modality, signs did not evoke activity in this region in this group of beginning ASL learners, underscoring the possibility that left vOT is specific to static written word forms.

Also consistent with previous studies, we observed an analogous process for encoding spoken words. Areas typically associated with this stage of processing in the auditory modality include a bilateral network of superior temporal and superior planar regions [15,16], and many of these areas are sensitive to subtle sublexical and phonetic manipulations [55] including the presence of the fundamental frequency [58] and alterations in voice-onset time [59]. In addition, specific neural populations within superior temporal cortex encode phoneme-specific information within the first ~150ms [17,60]. While the mechanisms and specific representations in superior temporal areas are unknown, the literature suggests that between ~60-150ms, the brain encodes spoken word information at a sublexical level. The timing and location of the peak for spoken English words in the present study is consistent with the majority of this previous work.

To date, there have not been any investigations into an analogous stage for sign encoding. In part, this may be due to the fact that most previous studies have used hemodynamic methods that do not afford sufficient temporal resolution to distinguish between early and late processing stages. While this finding must be viewed cautiously because we are documenting it in a group of hearing, non-native signers, there are several possible explanations for the ASL-specific response at ~150ms in right IPS. It has been suggested that the spatial components of sign languages (which are not found in spoken or written language) may preferentially recruit parietal regions involved in spatial and biological motion [6,56,61]. These studies generally focus on ASL classifiers, which are used to encode spatial relations and to show movement along a path [62]. Unlike other lexical signs, classifiers are poorly understood, multi-morphemic units that do not have fixed linguistic meanings. While right parietal responses have been observed in deaf native signers with purely lexical stimuli [63] and sentences containing both lexical and classifier signs [64], it is unclear whether such activity reflects linguistic encoding (analogous to sublexical amplitude envelope information in spoken language, for example) or quasi-gestural sensory characteristics related to space and motion [65,66].

It is important to note that since the participants were beginning L2 learners of ASL, the early response in right IPS may be influenced by proficiency or an interaction between proficiency and modality. However, our previous work with bilinguals' two spoken languages has identified a proficiency-modulated cortical network that does not include IPS [26,27], and we do not know of any other reports of proficiency effects in right parietal regions. Thus it may be unique to sign language, although possibly only at low proficiency levels. Additionally, the lack of a sensory control (e.g., amplitude-modulated and frequency-matched noise for spoken words, false fonts for written words, and spatial frequency- and movement- matched videos for signed words) means that we cannot completely rule out a sensory contribution to differences observed during the early stage. While left vOT for written words at ~170ms [11] and left STS/PT for spoken words at ~100ms [17,58-60,67] are well established word encoding processes that reflect abstracted representations of the sensory signal, there is no research precedent for signs, and further work with such controls is necessary to characterize this process.

After the early modality-specific responses, we found that words across both languages and modalities were processed in a highly similar left-lateralized network including inferior frontal, superior temporal, and anteroventral temporal areas. These regions are known to be involved in lexico-semantic encoding at a supramodal level [46,68], and are the main neural generators of the N400 response [46,47], even in infants who are only beginning to acquire language [69]. These areas all showed semantic modulation in the congruent/incongruent picture-word matching task (albeit to a lesser extent for ASL). Analyses of the overall magnitude of the response to words in each language and modality showed that both English and ASL evoke strong activity in these regions. Previous hemodynamic studies have found activity related to lexico-semantic processing in these areas for sign language [5-7], and N400 responses have been observed to sign [40]. To our knowledge, however, this is the first demonstration of such activation patterns after so little L2 instruction in ASL.

The different patterns we observed for the congruent-incongruent subtraction and the grand average of all activity provide a window into the nature of lexico-semantic processing. Up to this point, we have focused on modality-specific effects. We now turn to how the design of this study provides insights into the role of language experience on the neural processing of words. The participants had an average of almost 23 years of extensive experience with spoken English, approximately 19 years of experience with written English, but only a few months of primarily classroom instruction in ASL.

Proficiency has profound effects on neural activity, and even on brain structure [70]. Numerous studies have demonstrated experience-related differences in bilingual language processing [20,26-30]. Furthermore, there is a surprisingly small amount of exposure required to elicit automatic lexico-semantic processing [71], which we demonstrate extends to ASL as well.

As would be expected, an examination of the lexico-semantic effects in the present study indicates that proficiency-modulated activity also occurs in sign processing. In particular, we found that ASL words evoked greater grand average activity than both spoken and written English in a network of mostly right hemisphere regions (although two left hemisphere regions, IFG and IT, showed this effect, possibly due to the great disparity in proficiency between ASL and English in these novice second language learners). It is striking that some of these areas (right LOT, pSTS, and IFG) are nearly identical to those that showed a non-dominant > dominant pattern in hearing Spanish-English bilinguals [26,27]. The results for second language ASL learners provide additional evidence for the role these areas play in processing words in a less proficient language. The present results, together with our previous findings demonstrate that word processing can show an increase of activity in these regions. The recruitment of these areas in L2 word processing in both spoken and signed languages indicates that they function as an additional supramodal resource for processing meaning in a non-dominant language.

The dissociation between semantic congruity and overall activity across languages provides a finer-grained characterization of how proficiency affects neural processing. The English > ASL congruity effects in left fronto-temporal areas could suggest shallower or less complete processing of semantic content in the non-dominant language. The slower reaction times and lower accuracy for ASL support this hypothesis. However, given that subjects performed the task relatively well indicates that some neural processing strategy was used successfully. The ASL > English responses in the grand average MEG activity across both hemispheres suggest that additional neural resources were recruited to perform the task, although perhaps not at the same semantic depth. As these L2 learners improve their ASL proficiency, we might predict that the grand average activity will decrease to English-like levels, and the congruent/incongruent difference will likewise increase. This represents a testable hypothesis for tracking neural processing strategies during development [72,73] and later language acquisition in a bilingual context.

4.1 Conclusions

The present study examined the spatiotemporal neural dynamics of word processing with beginning second language learners in two languages and modalities. We have extended our previous work demonstrating that language modality affects early encoding, proficiency particularly affects late lexico-semantic stages of processing, and that the supramodal left fronto-temporal language network is engaged for words in the auditory, written, and signed modalities, even in L2 learners who are only at the beginning of the acquisition process. Our findings, including the discovery of a putative early signed word encoding stage centered in right parietal cortex, invite a range of new research aimed at understanding the fundamental neural mechanisms underlying word processing, how they develop, and how they are impacted by language and cognitive disorders.

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Figure Legends

Figure 1: Grand average group dSPMs during the early encoding time window from 80-120ms. Auditory words ('AUD'; top panel) show strong responses in bilateral PT and STS. Written ('WRT'; middle panel) and signed ('SIGN'; bottom panel) words show sensory processing at the occipital pole. F-values on the color bars represent signal-to-noise ratios.

Figure 2: ROI timecourses for the grand average across each language/modality. At 80-120ms in left PT, auditory words (blue lines) show a strong modality-specific peak. From 150-200ms, written words (red lines) show a word encoding peak in left vOT, and signed words (black lines) show a word encoding effect in right IPS. During a later time window from 300-400ms (thick gray bars), all conditions show similar responses in most left hemisphere regions, but signed words show much stronger responses in right hemisphere regions, including LOT, IPS, and PT. Asterisks represent statistically significant differences. Abbreviations: IPS, intraparietal sulcus; LOT, lateral occipitotemporal; PT, planum temporale; STS, superior temporal sulcus; TP, temporal pole; vOT, ventral occipitotemporal.

Figure 3: Grand average group dSPMs during the early encoding time window from 150-200ms. Written words ('WRT'; middle panel) show a modality-specific peak in left vOT, while signed words ('SIGN'; bottom panel) show a modality-specific peak in right IPS. F-values on the color bars represent signal-to-noise ratios.

Figure 4: Congruent-Incongruent subtraction dSPMs during the late lexico-semantic time window from 300-400ms. All three conditions show similar patterns of activity in predominantly left fronto-temporal regions, including PT, STS, inferior frontal, and anteroventral temporal. Signed words (‘SIGN’; bottom panel) show overall smaller subtraction effects. F-values on the color bar represent signal-to-noise ratios.

Figure 5: ROI timecourses for the Congruent-Incongruent subtraction across each language/modality. From 300-400ms (thick gray bars), auditory (blue lines) and written (red lines) words evoke stronger effects than signed words (black lines). This difference is most prominent in the classical left fronto-temporal language network. Asterisks represent statistically significant differences.

Figure 6: Grand average group dSPMs during the late lexico-semantic time window from 300-400ms. All three conditions show a similar pattern of activity in bilateral regions, but signed words (‘SIGN’; bottom panel) show much stronger activity, particularly in the right hemisphere. F-values on the color bars represent signal-to-noise ratios.

Figure S1: Diagram of bilateral ROI locations. These ROIs were selected based on an independent data set that compared sign in native deaf individuals to speech in hearing individuals.

Figure S2: Individual subject waveforms showing sensor-level language/modality effects. (**A**) Congruent-Incongruent waveforms for each modality for a left temporal channel (top) show greater responses for auditory (‘AUD’; blue) and written (‘WRT’; red) than for signed (‘SIGN’; black) words. In a right parietal channel (bottom), there are no strong responses in any condition. (**B**) Grand average waveforms for each modality for a left temporal channel (top) show an early word encoding peak at ~100ms for auditory words, followed by overlap between all three conditions at ~400ms. In the same right parietal channel (bottom), signed words evoke an early and persistent response that is stronger than the responses for both English modalities.

Table 1: Mean reaction time and accuracy data across languages/modalities

	Language/Modality		
	Spoken English	Written English	ASL
RT (SD) ms	582.64 (77.51)	542.80 (92.81)	719.49 (92.67)
Accuracy (SD) %	97.91 (1.14)	96.00 (3.46)	89.36 (5.01)

Table 2: Summary of MEG effects by time window.

	Time Window		
Effect	Early Encoding	Lexico-semantic (congruity)	Lexico-semantic (overall)
A > W & S	L PT L STS R STS	R STS	
W > A & S	L vOT		
S > A & W	R IPS		L IFG L IT R IFG R IPS R LOT R PT R pSTS
A & W > S		L IFG L IT L pSTS L PT L STS R IFG	

Figure 1

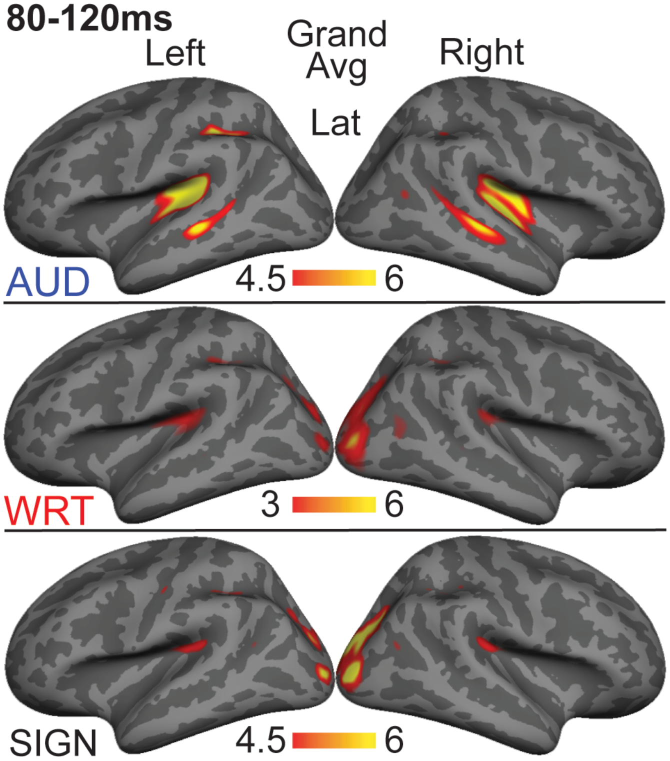


Figure 2

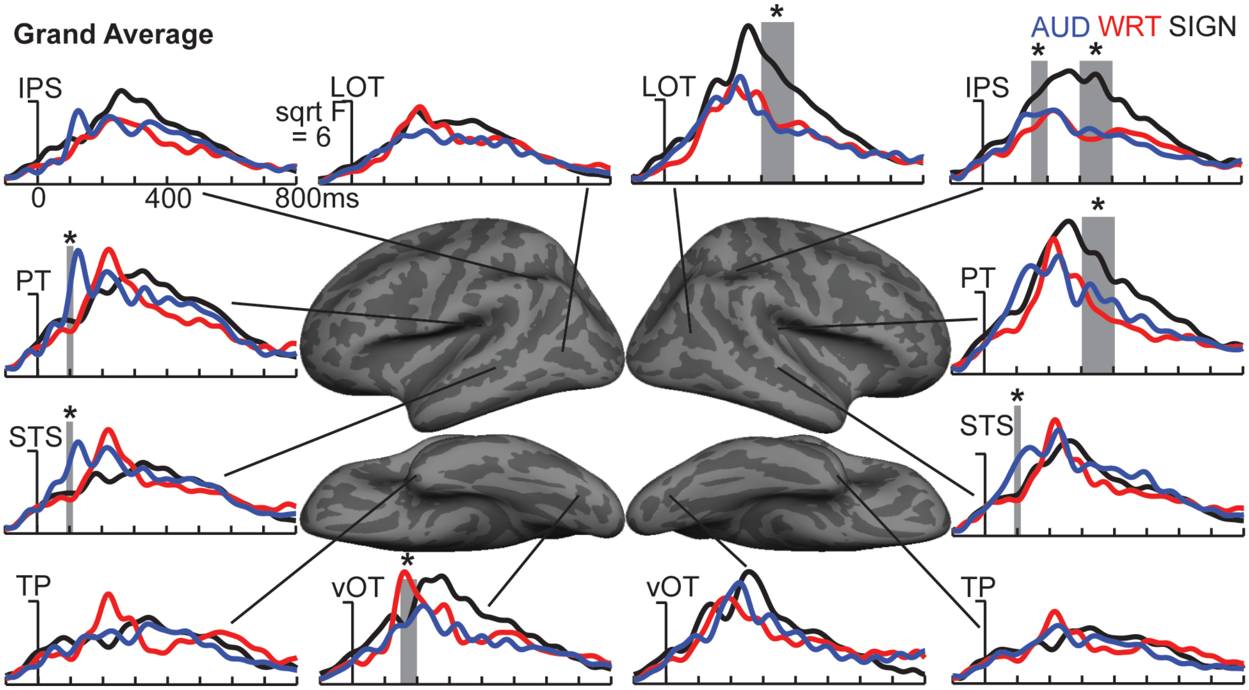

Grand Average
AUD WRT SIGN
IPS
LOT
sqrt F = 6
0
400
800ms
LOT
IPS
PT
PT
STS
STS
TP
vOT
vOT
TP
*

Figure 3

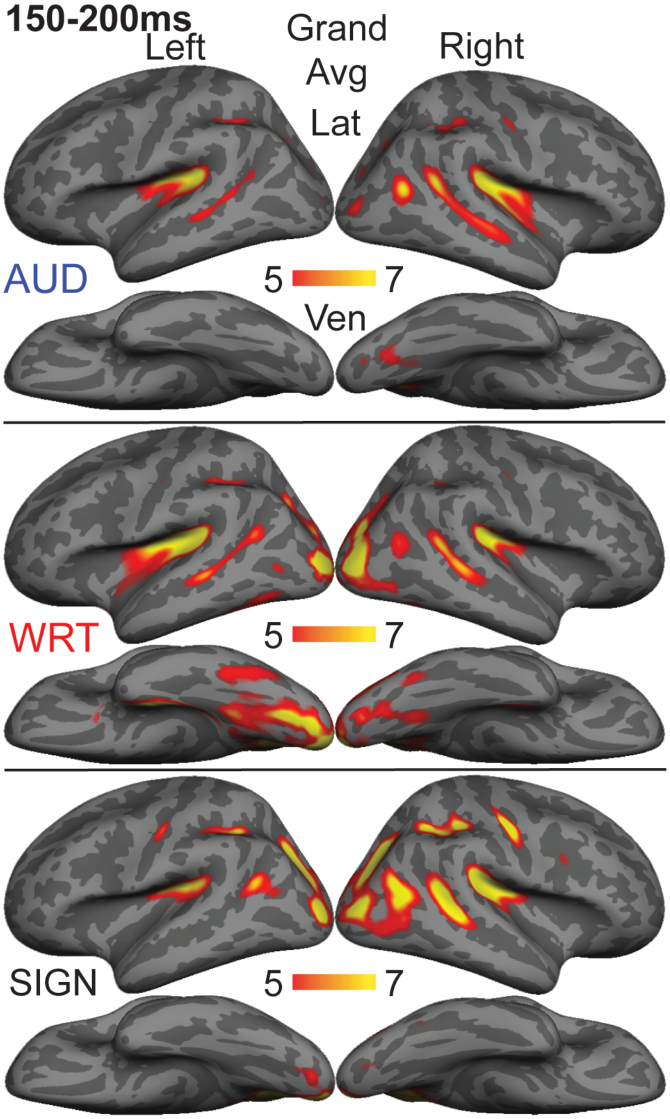


Figure 4

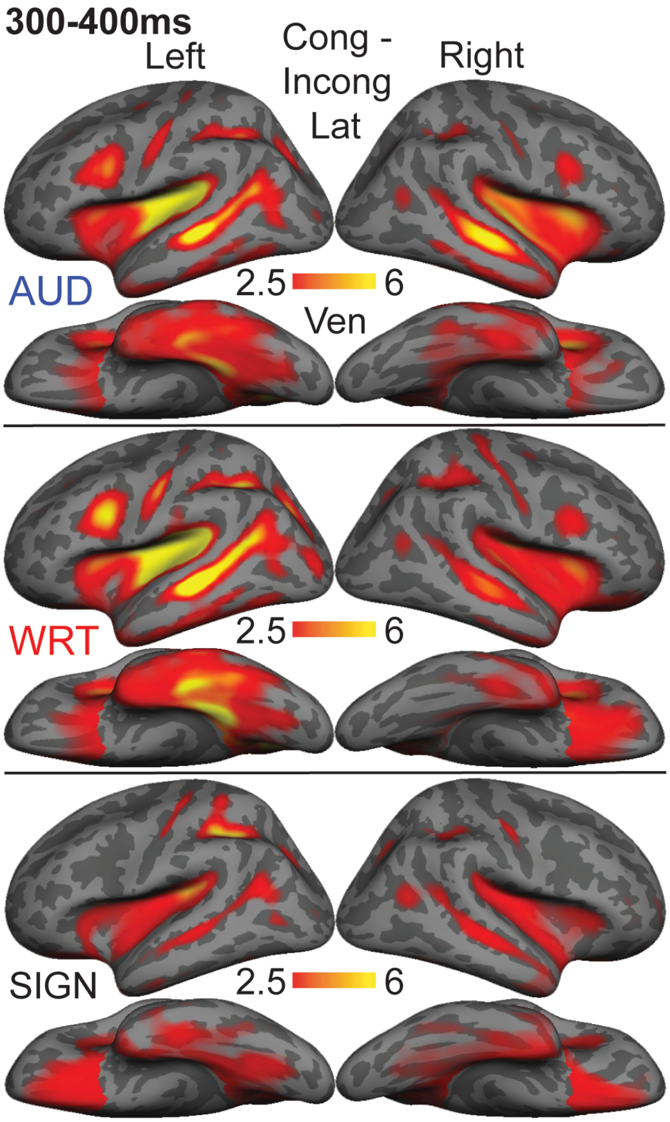
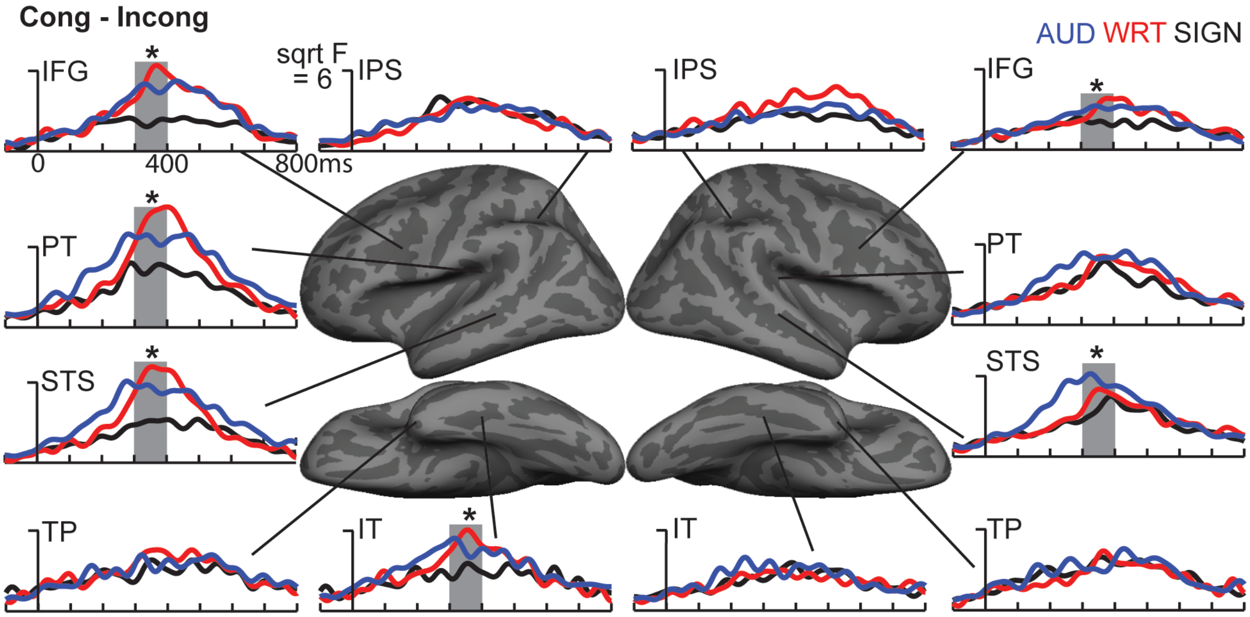

300-400ms
Left
Cong -
Incong
Lat
Right
AUD
2.5
6
Ven
WRT
2.5
6
SIGN
2.5
6

Figure 5


Cong - Incong
AUD WRT SIGN
IFG
*
0
400
800ms
sqrt F
= 6
IPS
IPS
IFG
*
PT
*
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STS
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IT
*
IT
TP

Figure 6

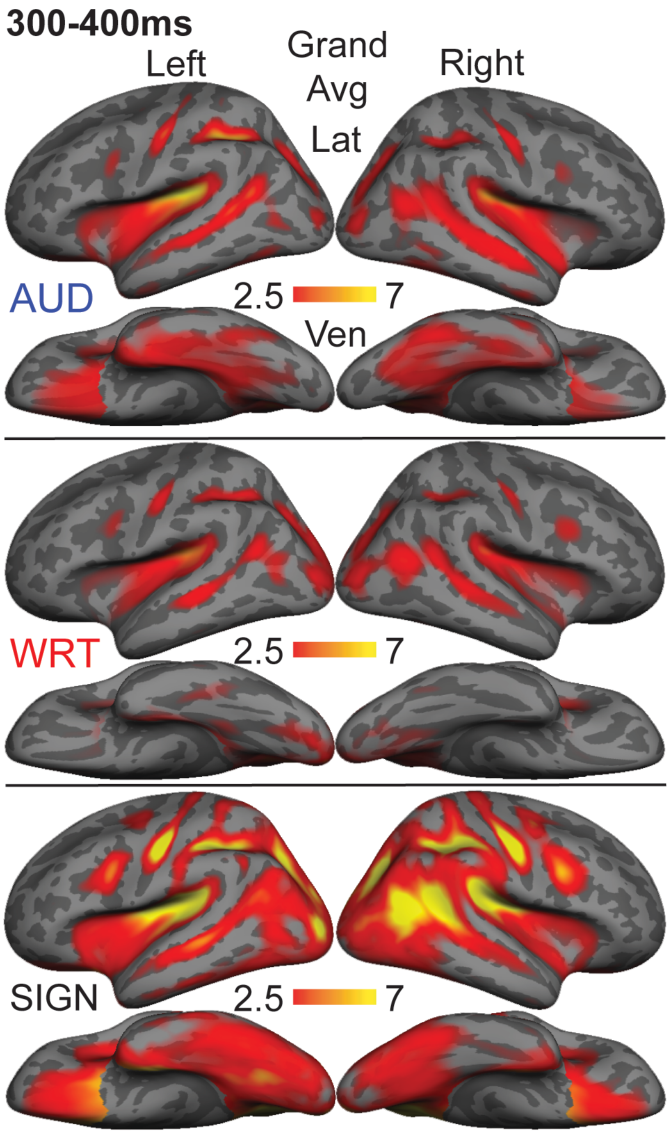
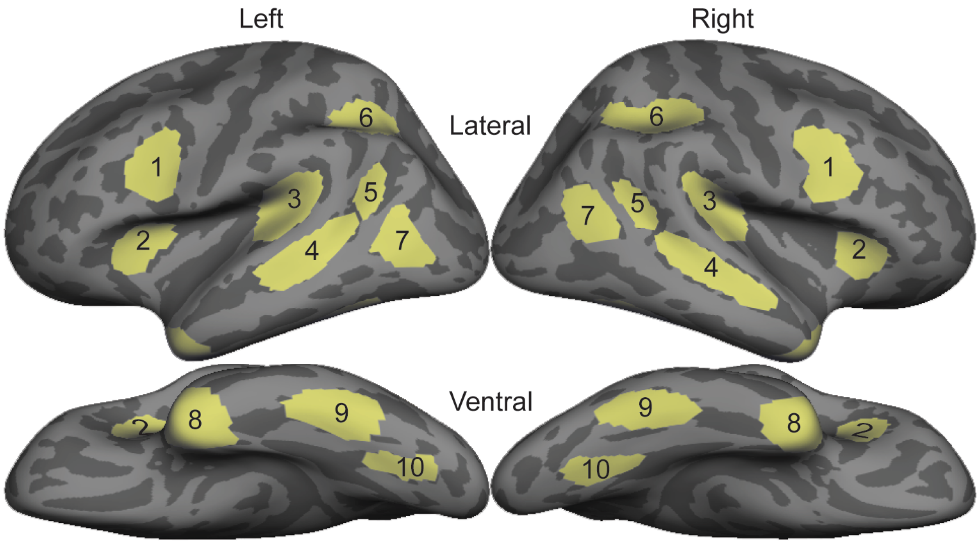

300-400ms
Left
Grand
Avg
Lat
Right
AUD
2.5
7
Ven
WRT
2.5
7
SIGN
2.5
7

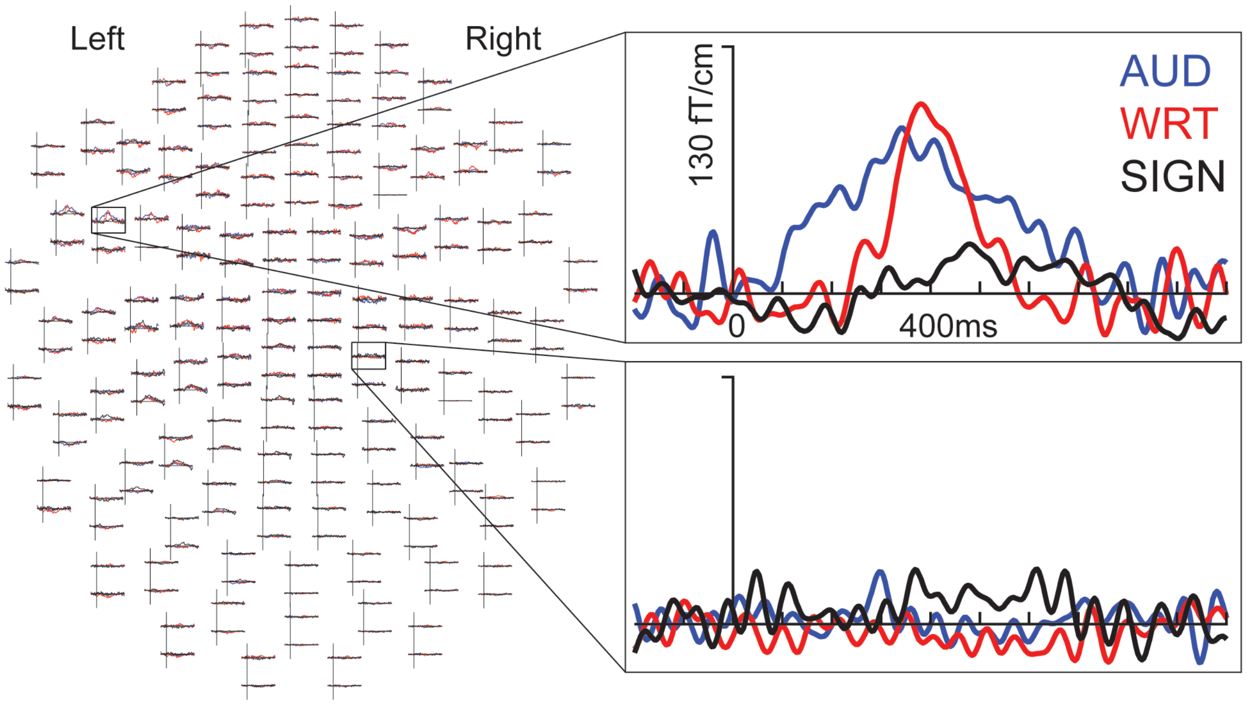
Figure S1



1. Inferior Prefrontal
2. Anterior Insula
3. Planum Temporale
4. Superior Temporal Sulcus
5. Posterior STS
6. Intraparietal Sulcus
7. Lateral Occipito-temporal
8. Temporal Pole
9. Inferior Temporal
10. Ventral Occipito-temporal

Figure S2

A Congruent - Incongruent Subtraction



B Grand Average