Full title: Modality-specific processing precedes amodal linguistic processing during L2 sign language acquisition: A longitudinal study

Authors: Joshua T. Williams^{1,2,3,*}, Dr. Isabelle Darcy^{2,5}, Dr. Sharlene D. Newman^{1,2,4}

Affiliations: ¹Department of Psychological and Brain Sciences, ²Program in Cognitive Science, ³Speech and Hearing Sciences, ⁴and Program in Neuroscience, ⁵Second Language Studies, Indiana University

***Corresponding Author**

Joshua Williams

Address: Cognitive Neuroimaging Laboratory, Indiana University, 1101 E. 10th Street, Bloomington, IN, 47405.

Phone: +1-812-856-1776

Email: willjota@indiana.edu

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Abstract

The present study tracked activation pattern differences in response to sign language processing by late hearing second language learners of American Sign Language. Learners were scanned before the start of their language courses. They were scanned again after their first semester of instruction and their second, for a total of 10 months of instruction. The study aimed to characterize modality-specific to modality-general processing throughout the acquisition of sign language. Results indicated that before the acquisition of sign language, neural substrates related to modality-specific processing were present. After approximately 45 hours of instruction, the learners transitioned into processing signs on a phonological basis (e.g., supramarginal gyrus, putamen). After one more semester of input, learners transitioned once more to a lexico-semantic processing stage (e.g., left inferior frontal gyrus) at which language control mechanisms (e.g., left caudate, cingulate gyrus) were activated. During these transitional steps right hemispheric recruitment was observed, with increasing left-lateralization, which is similar to other native signers and L2 learners of spoken language; however, specialization for sign language processing with activation in the inferior parietal lobule (i.e., angular gyrus), even for late learners, was observed. As such, the present study is the first to track L2 acquisition of sign language learners in order to characterize modality-independent and modality-specific mechanisms for bilingual language processing.

Introduction

The neurobiology of bilingual language processing has turned to understand the neurobiology of language that includes the study of sign languages (Emmorey, Giezen, & Gollan, 2015; Emmorey & McCullough, 2009). The study of the bimodal bilingual (i.e., bilinguals who use both a sign and spoken language) brain has been relatively sparse and has restricted itself largely to native bimodal bilinguals, or hearing individuals born into deaf signing families. However, many more adults are beginning to learn sign language in high school and college. As such, it is important to also study a group of late learning hearing adults during the acquisition of a signed second language (L2). More importantly, unlike a child who grew up with both languages simultaneously, hearing late learners have an established linguistic system that directly processes auditory-oral languages. Late learners must subsequently acquire a new language modality. The aim of the present study was to investigate how the brain is transformed by the acquisition of a language that uses a different sensorimotor modality. By using a longitudinal design, we can characterize the effect of modality on the acquisition of a second language. To our knowledge, this is the first longitudinal study of L2 sign language acquisition.

The study of bimodal bilinguals is important because there is growing behavioral evidence suggesting that both spoken and sign languages are co-activated during sign language comprehension (Geizen & Emmorey, 2015; Shook & Marian, 2012; Williams & Newman, 2015), despite neurobiological evidence of distinct patterns of activation for sign and spoken language processing across monolingual populations (Corina, Lawyer, & Cates, 2013; Emmorey, Giezen, & Gollan, 2014; Emmorey, McCullough, Mehta, & Grabowski, 2014). Of interest to the present study is how the bimodal bilingual brain processes sign language. Bimodal bilinguals show greater activation in the bilateral parietal cortex and bilateral occipitotemporal cortex

during sign comprehension (Emmorey et al., 2014; Söderfeldt et al., 1997). These areas are thought to be unique to the processing of sign languages, and have been activated by spatial classifiers and verbs in American Sign Language (ASL) in addition to other demanding visual processing tasks. Nevertheless, other studies have shown strikingly similar patterns of activation for signed and spoken words for native signers and speakers (Leonard et al., 2012; MacSweeney et al., 2002, 2006, 2008; Petitto et al., 2000). However, it is unclear whether such findings are a consequence of the native bimodal bilingual experience, and if not, what the time course is for developing such activation patterns in late learners. It is unknown whether such convergence of modality-independent neural mechanisms is present after short-term initial input of a sign language (see Schelegel, Rudelson, & Peter, 2012 for an example for unimodal bilinguals).

A functional change in brain processing has been seen for L2 learners after relatively little exposure to a second language. McLaughlin and colleagues (McLaughlin, Osterhout, & Kim, 2004) have shown that L2 learners rapidly acquire lexico-semantic processing in the L2 after only 14 hours of instruction. L2 learners of French were given a lexical decision task on semantically primed French pairs. ERPs were recorded during the lexical decision to characterize the presence (or absence) of an N400, an index of lexico-semantic processing. L2 learners indeed had N400 effects after only 14 hours of instruction despite not showing behavioral sensitivity to word-nonword distinctions in French. Furthermore, learners started to approximate native-like ERPs after only 60 hours of instruction (McLaughlin, Osterhout, & Kim, 2004; Osterhout, McLaughlin, Pitkanen, Frenck-Mestre, & Molinaro, 2006). These neuroelectrophysiological studies indicate that L2 learners can show rapid functional changes in neural processing of a second language. However, it is less known if such results generalize to bimodal bilinguals.

Another area that has garnered much attention in bilingual brain research is that of language control. Many studies have reported greater activation for language control regions, such as the left caudate and anterior cingulate gyrus, during bilingual language processing (Abutalebi & Green, 2008; Green & Abutalebi, 2013). This effect is often attributed to the need for unimodal bilinguals to control two languages within the same modality (Green, 1998). However, recent behavioral data has not been able to show a bilingual advantage for bimodal bilinguals. This lack of a bilingual advantage for bimodal bilinguals is thought to be due to the languages utilizing two different sensorimotor systems and therefore eliminating the necessity to compete during production – individuals can speak and sign simultaneously (Emmorey, Luk, Pyers, & Bialystok, 2008). As such, it has been hypothesized that bimodal bilinguals may not require greater cognitive control when processing language. However, a recent study has found contrasting neurobiological evidence, showing increased grey matter volume in the left caudate head for bimodal bilinguals (Zou et al., 2012). Nevertheless, it is still largely unknown whether bimodal bilinguals require cognitive control while processing sign language. Because beginning (or low proficiency) bilinguals often require much more language control (Abutalebi, 2008), the present study is situated well to investigate whether there is activation in regions known to be involved in language control during the processing of ASL.

As indicated above, the current study has two over-arching aims. One aim was to characterize the processing of ASL signs in hearing late L2 learners of ASL. Specifically, whether or not sign language processing moves from a general modality-specific stage of processing (e.g., visual, spatial, and motoric) to a more modality-independent linguistic processing stage (i.e., phonological and lexical) was investigated. That is, given that late L2 learners of ASL have an established spoken language linguistic system, it may be the case that

the acquisition of a sign language requires the acquisition of modality-specific neural mechanisms as a prerequisite, which may be different from native bimodal bilinguals whose language systems were acquired simultaneously. Additionally, the present study was interested in the time course of these neural changes due to learning a sign language. Given that previous studies have shown rapid neural changes related to L2 instruction (McLaughlin et al., 2004) and similar lexico-semantic processing early in L2 sign language acquisition (Leonard et al., 2013), we are also interested in whether and to what extent L2 acquisition is modality-independent. The second aim was to determine whether language control is evident in learning a second language in a different modality. Specifically, we examined the presence of activation in the left caudate and anterior cingulate regions during ASL processing, and when such activation first started to appear over time.

These questions motivated a longitudinal design in which naïve L2 ASL learners were followed starting before significant sign language exposure through 10 months of learning (two academic semesters). They were assessed three times: before exposure, after one semester of exposure and at the end of a second semester. The few longitudinal L2 neuroimaging studies that have been performed have only included two time points and have studied unimodal bilinguals (e.g., Stein et al., 2009). To our knowledge, this is the first longitudinal investigation of late bimodal language learners. Consequently, novel insight into the functional brain changes that occur during the acquisition of a language with a different sensorimotor modality from one's native language can be highlighted. Following the aims outlined above, the present study makes the following predictions across the three time points:

1. If hearing late learners of sign language require modality-specific neural mechanisms for sign language processing, then there will be mostly activation in visual (e.g., calcarine sulcus,

right inferior temporal sulcus) and motor (e.g., supplemental motor area) regions in response to ASL signs before any exposure to sign language (i.e., T0).

2. If hearing late learners of sign language acquire prerequisite modality-specific processing at early stages of acquisition and linguistic processing follows, then there will be greater phonological (e.g., left superior marginal gyrus) and lexico-semantic (e.g., left inferior frontal gyrus) activation seen at subsequent time points (i.e., T1 & T2) compared to the first timepoint.

3. Additionally, if hearing late learners of sign language show lexico-semantic processing, then it is expected to see greater activation of regions involved in language control and inhibition (e.g., caudate and anterior cingulate cortex) at the same time point at linguistic processing (i.e., T2), given that learners must resolve competition between lexical words and signs in their languages.

Materials and Methods

Participants

Twelve (male = 5) hearing English-speaking college students participated in this study. These 12 learners come from a larger study that examined phonetic processing by naive monolinguals, which was T0 in this study (Williams, Darcy, & Newman, 2015). The 12 subjects selected for this study were those students who volunteered to return for two subsequent experimental sessions, providing a full data set to examine longitudinal change in ASL processing. All learners were right-handed according to the Edinburgh Handedness scale ($M = 87.5$, $SD = 19.1$). All learners reported English as their first language. The learners in this study were recruited from introductory American Sign Language (ASL) courses at Indiana University.

The learners had little to no exposure to ASL (or any other spoken second language) before enrollment in the ASL course. All learners gave written consent to perform the experimental tasks, which was approved by the Indiana University Institutional Review Board.

At pre-exposure (T0), the learners had a mean age of 20 (1.7). Learners were recruited during their first week of Beginning ASL I enrollment. On average they had 1.06 (range = 0 – 5, SD = 1.49) hours of instruction. According to course instructors, the instruction in the first week of classes included introduction to the course, the target language and culture, but little linguistic instruction. Furthermore, most to all instruction was conducted in English during the first week. That is, these learners had minimal to no linguistic knowledge of the target language. Subsequently, learners had an average of 44.12 (1.00) hours of instruction at T1 and 89.5 (1.95) hours of instruction at T2.

Proficiency Tests

Learners rated their language proficiency and took an ASL vocabulary test at all three time points. The learners rated their proficiency in both English and ASL on a scale from 1 to 7 (1 = “Almost None,” 2 = “Very Poor,” 3 = “Fair,” 4 = “Functional,” 5 = “Good,” 6 = “Very Good,” 7 = “Like Native”) for their understanding and fluency abilities. Self-ratings were also collected because previous studies have shown that self-ratings often correlate with measured language proficiency (MacIntyre, Noels, and Clement, 1997; Bachman and Palmer, 1989).

Learners also took a vocabulary test to obtain a gross measure of their proficiency gains over time. A vocabulary test was selected because the following fMRI task only tested lexical processing. Additionally, grammatical knowledge in these early learners would not be well established relative to their lexical knowledge. The test was constructed by taking all of the signs

(minus duplicates) from the current ASL textbooks across all 4 semesters of ASL (Smith et al., 1988a, 1988b, 2008). During the vocabulary-translation task, learners viewed video clips of the signed words produced by a native signer. Learners were required to type in the English translation. The computer scored their translations for correct answers, including any synonyms (e.g., *bathroom* or *restroom* would be accepted for BATHROOM). A total score correct out of 142 was used as the learners proficiency score.

fMRI Task

The experimental design was the same as described in a previous study (Williams et al., 2015). The learners performed a phoneme categorization task at three different time points (T0, T1, and T2). There were 30 trials; the total duration was approximately 9 minutes. Learners viewed a native signer signing words with the speaker's full face and torso shown in front of a blue-gray backdrop. All stimuli were high frequency monomorphemic signs from various word classes. Signs were split into two groups: signs with place of articulation (i.e., location) on the head or face and signs with the location on the body, non-dominant hand, or neutral space (i.e., not on the face). In sign languages, signs contain phonemic subunits called formational parameters. Unlike spoken languages, these parameters include handshape, location, movement, and orientation (Liddell & Johnson, 1989; Sandler, 1989; Brentari, 1998). As such, the participants had to make a phoneme categorization discrimination based on the location parameter when deciding whether a sign was made on various locations of the body. This method was chosen because the task provided an opportunity to force learners to phonetically process the signs by splitting the signs into these two conditions if they knew the signs, but they could still perform the task with no ASL knowledge, which is most important for performance at

baseline (T0). Additionally, this task allowed us to examine the automatic language processing that was expected to occur as the participants became more familiar with ASL.

The functional task was presented in an event-related design. For each trial a 500-millisecond fixation point was presented before the video appeared. Each stimulus video varied in duration ($M = 1593.33$, $SD = 2.53$ ms) and was followed by a jittered interstimulus interval (ISI range = 4000 – 8000, $M = 6000$ ms). Learners were told to press the right index finger for signs that were produced on the face, and to press the left index finger for signs that were produced on the body. They were instructed to make their responses as quickly and accurately as possible. In addition to the ISI, a 30 second fixation was presented at the beginning of the task and was used as a baseline.

Imaging Parameters

Learners underwent 2 scans at each time point (for a total of 6 scans) using a 32-channel head coil and a Siemens 3 Tesla TIM Trio MRI scanner. The first scan was an anatomical T1-weighted scan used to co-register functional images. An MPRAGE sequence (160 sagittal slices; FOV = 256 mm, matrix = 256x256, TR = 2300 ms, TE = 2.91 ms, TI = 900 ms, flip angle = 9°, slice thickness = 1 mm, resulting in 1-mm × 1-mm × 1-mm voxels) was used. The other scan at each time point was the functional multiband EPI scans for experimental trials (58 axial slices using the following protocol: field of view = 220 mm, matrix = 128x128, iPAT factor = 2, TR = 2000 ms, TE = 30 ms, flip angle = 60°, slice thickness = 2 mm, 0 gap).

Data analysis

Functional images were analyzed using SPM8 (Wellcome Imaging Department, University College, London, UK, freely available at <http://fil.ion.ucl.ac.uk/spm>). During preprocessing images were corrected for slice acquisition timing, and resampled to $2 \times 2 \times 2$ mm³ isovoxels, spatially smoothed with a Gaussian filter with a 4 mm kernel. All data were high-pass filtered at 1/128 Hz to remove low-frequency signals (e.g., linear drifts). Motion correction was performed and motion parameters incorporated into the design matrix. Each participant's anatomical scan was aligned and normalized to the standardized SPM8 T1 template and then fMRI data were co-registered to anatomical images. At the individual level, statistical analysis was performed using the General Linear Model and Gaussian random fields using fixation as the common baseline. The video onsets and durations were entered as regressors in the model (Friston et al., 1995). For the second level (random effects) analysis on group data, paired t-tests were performed for all combinations in order to examine the within-subject change over time. To correct for multiple comparisons, the dimensions and smoothing parameter of processed data were entered into AFNI's AlphaSim program. With a voxel-wise $p < 0.01$, clusters greater than 62 voxels were considered significant at a corrected alpha = 0.05.

Results

Proficiency Results

At pre-exposure before any ASL exposure, the learners rated their proficiency average scores across both categories were 7 (0) for English and 1.21 (0.37) for ASL. ASL students' vocabulary knowledge ranged from 0 to 15 ($M = 8.08$, $SD = 3.3$) words. Overall, these findings suggest that at pre-exposure (T0), the learners were beginner or naïve ASL learners.

After one semester (approximately 13 weeks later), the learners were brought back for their first post-exposure scan (T1). They rated their ASL ability as a 3.12 (0.82) and their English ability as 7 (0). Course grades were also recorded. Learners had an average of 90.87% (4.26) in their ASL course. Their vocabulary score ranged from 30 – 60 ($M = 44.06$; $SD = 9.5$) words. These results show increased ASL knowledge [vocabulary: $t(11) = 14.61$, $p < 0.0001$] and proficiency [rating: $t(11) = 6.37$, $p < 0.001$] at T1 relative to T0.

After a second semester of ASL training, the learners were brought back for their second post-exposure scan (T2). Learners rated their ASL ability as a 3.92 (0.63). At T2, learners had an average of 91.7% (4.64) in their ASL course. Their vocabulary score ranged from 39 – 66 ($M = 55.83$; $SD = 9.2$) words. These results show increased ASL knowledge [vocabulary: $t(11) = 5.03$, $p < 0.001$] and proficiency [rating: $t(11) = 3.58$, $p < 0.001$] at T2 relative to T1.

Behavioral Results

Reaction times were filtered for outliers that were above or below 2 standard deviations from the mean for each subject (1.7%). Reaction times on correct trials were analyzed using a repeated measures analysis of variance (ANOVA) with time (T0, T1, T2) as the factor. Results showed that there was no significant difference across the time points in reaction times for making phoneme categorization [$F(2,22) = 1.433$, $p = 0.260$, eta-squared = 0.115; T0 = 1827 (114) ms; T1 = 1987 (134) ms; T2 = 1802 (134) ms]. Accuracy results showed a similar pattern insofar as there was no significant difference across the time points in accuracy [$F(2,22) = 1.007$, $p = 0.3820$, eta-squared = 0.084; T0 = 96.1% (1.6); T1 = 88.6% (8.0); T2 = 96.7% (1.7)].

Neuroimaging Results

<Figure 1 about here>

<Table 1 about here>

Activation to ASL signs relative to a fixation baseline for each time point can be found in both Figure 1 and Table 1. There was relatively little activation seen for ASL signs relative to fixation at pre-exposure (T0). There was activation in modality-specific areas, such as visual, motor, and spatial processing areas. Activation was seen in visual areas within the occipital lobe, including right cuneus and left calcarine sulcus. The right supplementary motor area was activated during ASL processing. Activation was seen in the left superior parietal lobule. Additionally, prefrontal cortex was activated during ASL processing, such as left inferior frontal gyrus (pars triangularis), and bilateral middle frontal gyrus.

There was much more activation present in response to ASL signs at the first post-exposure scan (T1). These areas still included modality-specific processing areas, such as left middle occipital gyrus and left inferior parietal lobule for visual processing. However, there was abundant activation of sub-cortical regions, including bilateral putamen, left caudate, and left medial dorsal nucleus of the thalamus. There was additional cingulate activation in both posterior and middle portions. Right recruitment of the inferior frontal gyrus was also seen.

Similar activation was found at the second post-exposure scan (T2) as in T1. These areas included left cuneus, left caudate, left middle temporal gyrus, left cingulate, and right postcentral gyrus. However, there was additional language-related temporal and prefrontal regions, including left insula, middle frontal gyrus, and inferior frontal gyrus. Additional sub-cortical

regions were recruited during ASL processing such as the left pulvinar and right ventral lateral nucleus of the thalamus.

To further explore the effect of ASL exposure a contrast analysis was performed to directly compare each time point. Using paired t-tests, the following time points were compared: $T2 > T1$, $T2 > T0$, $T1 > T0$, $T0 > T2$, $T0 > T1$, and $T1 > T2$ (see Figure 2 and Table 2 for results).

<Figure 2 about here>

<Table 2 about here>

The first post-exposure scan revealed more activation in the inferior temporal sulcus, inferior frontal gyrus, putamen, and parahippocampal gyrus relative to pre-exposure ($T1 > T0$). These regions were located to the right hemisphere, typical of low-proficiency bilingual language processing (Perani et al., 1998). There was also bilateral supramarginal gyrus activation found for $T1 > T0$. Similar results were found for the contrast between the second post-exposure scan ($T2$) and $T0$. However, there was additional activation in left-hemispheric areas, including the lingual gyrus and insula. The $T2$ minus $T1$ contrast revealed activation in left prefrontal regions (inferior frontal gyrus and middle orbital gyrus).

There were no regions found to show increased activation for $T1$ compared to $T2$. For both the $T0 > T1$ and $T0 > T2$ contrasts, the only significant difference was in the left supplementary motor area (BA 6).

To qualitatively characterize hemispheric recruitment and lateralization across the three time points, the number of voxels that were significantly activated in each hemisphere used to calculate a lateralization index (i.e., $(L-R)/[(L+R)/2]$; see Emmorey et al., 2003). A negative number indicates more voxels were activated in the right hemisphere relative to the left. A positive number is converse, where more activation in the left hemisphere than the right. The lateralization index at the group-level was -0.498, 1.21, and 1.89 for T0, T1, and T2, respectively. This result indicates a general qualitative left-lateralization with increased language exposure.

General Discussion

The goal of the present study was to characterize the neural processing of sign language during second language acquisition by hearing adults. By studying hearing adults acquiring sign language as a second language, the functional changes that occur during the acquisition of a language that is perceived and produced in another sensorimotor modality was directly tested. A second goal of the present study was to investigate these changes as a function of time by studying within-subject changes using a longitudinal design. A longitudinal design provides unique insights into neural changes over time relative to cross-sectional studies because changes can be observed while controlling for individual differences in cognition and experience. In the present study it was found that modality-specific processing precedes amodal linguistic processing during second language acquisition. Rapid changes to functional processing of sign language, lateralization, and language control mechanisms after only one semester of instruction were observed. As such, this is the first study to demonstrate neural changes in the processing of sign language while acquiring new language modality itself.

T0 activation

Activation at pre-exposure, before any significant sign language exposure, was sparse. Reduced activation while processing ASL signs can be attributed to the learners' lack of awareness of their linguistic properties. As such, learners likely processed the stimuli by focusing only on the visual-motor properties, which explains the increased activation in modality-specific processing areas. The posterior visual sensory activation was found in the calcarine sulcus, cuneus, as well as the posterior cingulate cortex. Previous studies have shown that deaf signers have greater grey matter volume in the calcarine sulcus, indicative of more intense, complex visual processing (Allen, Emmorey, Bruss, & Demasio, 2013). Additionally, previous functional imaging data has shown evidence for increased activation to British Sign Language signs in both the calcarine and cuneus relative to a static baseline (MacSweeney et al., 2006). The cuneus has also been implicated in nonlinguistic event perception, like watching movies of making the bed or other household chores, as well as biological motion of point-light displays (Servos, Osu, Santi, & Kawato, 2002; Speer, Swallow, & Zacks, 2003; Vaina et al., 2001; Zacks et al., 2001; Zacks, Swallow, & Vettel, 2006). The posterior cingulate activation observed here may be related to motion processing. For example, Cornette and colleagues (1998) found the posterior cingulate gyrus showed greater activation for onset of motion of dynamic dots relative to stationary dots. Together, these studies point to a more general motion and event processing of linguistic sign language stimuli at pre-exposure.

In addition to visual activation other modality-specific activation was found in the supplementary motor area (SMA) and superior parietal lobule. The SMA has been shown to not only be involved in the production of language, but also in the *perception* of human actions (Decety & Grezes, 1999; Grezes, Costes, & Decety, 1998). The superior parietal lobule (SPL)

has been associated with spatial-motor behavior (Grafton et al., 1996; Grefkes et al., 2004) and multisensory integration (Molholm et al., 2006). Additionally, the parietal lobe (including the superior parietal lobule) has been shown to be activated during sign language comprehension and production (Corina & Knapp, 2006; Emmorey et al., 2002, 2003; MacSweeney et al., 2002). Therefore, the SMA and SPL activation at T0 suggests that learners were focusing on the visuo-motor properties of the stimuli.

Other pre-exposure activation could be attributed to lack of prior sign language knowledge. Activation in the left inferior frontal gyrus may be due to hierarchical sequence processing (Clerget, Winderickx, Fadiga, & Oliver, 2009; Dominey et al., 2003; Fazio et al., 2010). The task of determining whether the sign was produced on the face requires the participant to segment a sequence of movements and categorize parts of that sequence. This is analogous to phonemic segmentation tasks that have been shown to activate the left IFG in both spoken (Burton, Small, & Blumstein, 2000; Newman et al., 2001; Zatorre, Evens, Meyer, & Gjedde, 1992; Zatorre, Meyer, Gjedde, & Evens, 1996) and sign languages (Williams, Darcy, & Newman, 2015). A previous study examining differences in sign language and non-linguistic action processing in hearing nonsigners showed left IFG and ventral premotor activation, which was also attributed to the mirror neuron system and human action processing (Corina et al., 2007). As such, similar activation in the present study at pre-exposure (T0) may indicate non-linguistic processing of signs for our hearing learners.

Activation in the posterior middle temporal gyrus could also be due to the learners' lack of vocabulary knowledge, given that pseudowords have been shown to activate the pMTG (Davis & Gaskell, 2009; Price, 2010). Additionally, degraded low-cloze speech activates bilateral posterior middle temporal gyrus (Obleser & Kotz, 2010). However, it is probable that

activation in left middle temporal gyrus may be attributed to biological motion processing (in addition to the cuneus and posterior cingulate as indicated above). Pelphrey and colleagues (2005) found activation to the processing of eyes and mouth in the right homologue of the middle temporal gyrus ($x = 62, y = -40, z = -4$), similar to what was found in this study on the left ($x = -56, y = -38, z = -2$).

It should be noted that the above activation found for T0 in these 12 learners was largely the same as that found for a larger group of naïve monolinguals presented in Williams et al. (2015). Activation in the left prefrontal cortex, bilateral parietal lobes, and visual cortex were the same across both studies. However, there was additional activation in the posterior temporal lobe in the present study. Additional posterior temporal activation may be simply due to individual differences within the subgroup of 12 learners in this study that may have been washed out in the larger group of learners in Williams et al. Nevertheless, largely consistent findings in larger clusters signify that the subset of learners in the present study is likely representative of a larger group of learners.

T1 activation

After one semester of ASL training there was increased activation in several brain regions in response to ASL. There was still persistent modality-specific activation seen in regions such as the left middle occipital gyrus and right posterior cingulate gyrus. There was also significant cerebellar activation in both the left anterior lobe and the right culmen, which are involved in motor planning, articulatory processes, and language processing (Desmond & Fiez, 1998; Nitschke, Kleinschmidt, Wessel, & Frahm, 1996). Additional hand processing activation was seen in the right inferior temporal sulcus (BA 19). This area has been found to be more activated for hand motion than face motion (Thompson, Hardee, Panayiotou, Crewther, & Puce,

2007). Motor-based activation in the cerebellum and inferior temporal sulcus suggest further changes of the neural requisites for processing a new sensorimotor modality, especially for that of hand processing. Acquisition of hand processing is often protracted for second language learners of ASL insofar as they often focus on the hands more than native signers, especially at lower proficiency levels (Morford & Carlson, 2011).

When examining the contrast between the first post-exposure scan and pre-exposure ($T1 > T0$), there was also greater bilateral supramarginal gyrus activation. The presence of bilateral supramarginal activation is consonant with greater phonological processing (Hartwigsen et al., 2010; Sliwinska et al., 2012; Stoeckel et al., 2009). Hartwigsen et al. (2010) demonstrated disruption to phonological judgments when transcranial magnetic stimulation was applied over the left supramarginal gyrus. This is consistent with a number of other findings that have implicated the left supramarginal gyrus in phonological processing (Romero, Walsh, & Papagno, 2005).

The putamen was also activated at $T1$. The putamen is functionally connected to the left IFG and subcortical regions provide cortical initiation of phonological representations (Booth, Wood, Lu, Houk, & Bitan, 2007). Greater phonological processing, as implicated by supramarginal gyrus activation in addition to greater hand processing, as implicated by cerebellar, putaminal, and inferior temporal sulcus activation, indicate that by the end of the first semester learners have transitioned into being able to process signs phonologically. As such, a primary speculation that can be inferred from the difference between activation at pre-exposure and after one semester of input is that the learner transitions from a more general motion processing strategy to a more phonologically-based strategy.

T2 activation

After the second semester (T2), there was greater language-related activation, especially in the left insula and left IFG. The subregion of the left inferior frontal gyrus active at T2 is involved in word retrieval and lexico-semantic processing (Heim, Eickhoff, & Amunts, 2009; Price, 2010; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). The left insula has also been implicated in language processing including word finding, language comprehension, and articulation (Ardila, Benson, & Flynn, 2007). Increased activation at T2 in the left IFG and insular regions suggests a transition from phonological processing to lexico-semantic processing. MEG studies of hearing late L2 learners also found lexico-semantic processing in fronto-temporal regions during early stages of acquisition (Ferjan et al., 2013; Leonard et al., 2013). Therefore, the present neuroimaging study was able to demonstrate sequential stages in which a hearing adults learning sign language moves through transitory stages from domain-general processing, to phonological processing, and subsequently to lexico-semantic processing — all of which takes about one year of instruction.

Although learners showed neural activation patterns suggestive of more thorough sign processing and phonological processing at T2, they did not show more accurate or faster performance on the behavioral task. One might expect that enhanced L2 proficiency would positively impact phoneme categorization. However, there may be several reasons for this null effect. First, it is likely that having only 12 learners did not provide enough power for behavioral differences to arise across time. Second, given that this task was also a spatial discrimination task, which could utilize domain-general spatial cognition skills, it is likely that additionally ASL exposure may not advantage these learners on this specific task. Lastly, it is possible that the task was too easy (i.e., T0 accuracy = 96.1%) and ceiling effects prevented from proficiency effects to arise. Nevertheless, the neural results presented herein are still representative of the changes at

the neural level, despite absence of behavioral effects. This distinction is meaningful because it demonstrates neural changes during second language learning that are independent of task.

Right hemisphere recruitment

During acquisition, typical right hemisphere recruitment with a trend towards left lateralization was found. Greater right hemisphere recruitment starting at T1 and persisting to T2 is consonant with previous work on unimodal bilingual language acquisition. Bilinguals may have greater right hemisphere activation relative to monolinguals (Perani et al., 1998). However, activation during language processing often converges to a left-lateralized language network with increased proficiency (Abutalebi & Green, 2007). Thus, it is somewhat unsurprising to find similar left-lateralization for these learners over time, where there was greater recruitment of the right hemisphere at T0 than T1 or T2. However, ASL learners still had right-hemisphere activation at later time points, which is similar to native signers (Neville et al., 1998; Bavelier et al., 1998). However, it was found in the present study that learners had right angular gyrus [45 - 65 47] activation at T2 (SVC $p_{\text{FWE}} < 0.05$). A previous study showed a critical period for right angular gyrus activation wherein only early signers, either monolingual or bilingual, showed right angular gyrus activation, but this was not present for those who learned sign language after puberty, like those learners in the present study (Newman, Bavelier, Corina, Jezzard, & Neville, 2001). Thus, this may be the first evidence for specialization of sign language processing for *late* (i.e., after puberty) learners of sign language, which is not constrained by age of acquisition.

Language control

Another area in which there is debate about learners of sign language is their ability to control both languages. A previous study showed that there is no bilingual advantage for native bimodal bilinguals in their ability to inhibit a prepotent response, which was argued to be due to

divergence between the language modalities (Emmorey, Luk, Pyers, & Bialystok, 2008). However, recent neural findings point to the need for language control in speech-sign bimodal bilinguals. Zou et al. (2012) found that bimodal bilinguals had greater grey matter volume in the left caudate nucleus, a region known for its involvement in language control (for review, see Abutalebi & Green, 2008). The authors argued that bimodal bilinguals indeed need inhibitory control to navigate between their two languages, regardless of modality differences. The present study extends these findings as there were many areas activated that are often implicated in language control. The first emergence of this type of activation was after the first semester of exposure where left caudate activation was observed. Left caudate activation was persistent through T2, which suggests that language control mechanisms were required up to at least 10 months of instruction. Typically, lower proficiency learners require more language control than those with higher proficiency, and as such, this suggests that within the first year of language acquisition, bimodal bilinguals still require a large amount of control, despite the divergence between the modalities. To drive home this point, there was also activation in the left anterior cingulate gyrus at T1, which has also been found to be involved in language control (Abutalebi et al., 2008; Abutalebi & Green, 2008). With activation of the left caudate and anterior cingulate cortex, this study was able to provide evidence that late L2 learners of ASL may exhibit language control when processing ASL despite the modality differences.

An alternative explanation for the involvement of the caudate and the anterior cingulate is that their activation may also be indicative of less automatic language processing (Friederici, 2006). Given that these learners were in very early stages of L2 acquisition sign language processing may be less automatic, more effortful and error prone. As such learners may be expected to require more controlled processing from the left caudate that is unrelated to

managing two languages. Nevertheless, it could be argued that greater controlled processing is the very role of the left caudate in language control, especially for bilinguals (Zou et al., 2012). Taken together, activation in the left caudate (and anterior cingulate cortex) may provide causal evidence that language control (or more controlled processing) is involved in bilingual processing, regardless of language modality. However, it should be noted that since there was no specific contrast within the present study to directly test language control, these findings are only speculative in nature.

Limitations

The method in our current study was able to tap into both spatial and linguistic processing regardless of the learners' knowledge of sign language. However, the present method did not have a non-linguistic spatial baseline to ensure that neural changes across time were due to sign language knowledge and not spatial attention. It has been shown previously that there is a dorsal frontoparietal network that is engaged during spatial attention (Corbetta & Shulman, 2002). Many of the regions that showed increased activation at T1 and T2 compared to baseline (T0) belong to this frontoparietal network. Thus, it may be the case that the activation seen in the parietal and temporal lobes at T1 and T2 are not solely due to linguistic knowledge, but rather enhanced spatial attention processing. Although we cannot fully rule out this possibility, the present findings are impactful nonetheless for a number of reasons. First, given that this task is a (uncued) simple spatial task that does not require working memory and learners can use relatively easy domain-general spatial processing to complete the task, we would expect little activation due to attention rather than language. Moreover, given that activation in frontoparietal lobes was correlated with the acquisition of vocabulary items, we would argue that this activation is more suggestive of phonological processing. Second, we would not argue that

spatial attention is not required during sign language processing; therefore, increased activation in the frontoparietal network due to attentional enhancements is indicative of enhanced signed language processing too. Taken together, we would argue that the present study was able to demonstrate time-specific changes to the neural processing of sign language that followed modality-specific (e.g., visuospatial) to a more modality-independent (e.g., attention, amodal linguistic, etc.) processing. Furthermore, any concomitant enhancements in spatial attention due to L2 sign language acquisition would be a further indication that learners are learning to process linguistic stimuli more robustly.

Conclusion

The present study tracked activation pattern differences in response to sign language processing by late learners of American Sign Language. Learners were scanned before the start of their language courses and twice more during their first two semesters (10 months) of instruction. The study aimed to characterize modality-specific to modality-general processing throughout the acquisition of sign language. Neural substrates related to modality-specific processing (e.g., visual and action processing) were present. Learners transitioned into processing signs on a phonological basis (e.g., supramarginal gyrus, putamen) before transitioning once more to a lexico-semantic processing stage (e.g., left inferior frontal gyrus) at which time language control mechanisms (e.g., left caudate, cingulate gyrus) came online. In conclusion, the present study is the first to track L2 acquisition of sign language learners for a better understanding of modality-independent and modality-specific mechanisms during bilingual language processing.

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Appendix

Head	Not Head
HOME	TIME
DRINK	NIGHT
FOOD	WORK
PARENTS	HAPPY
BORED	TOILET
MISS	WEEK
SEARCH	SORRY
CANDY	MILK
DEAF	PLAY
SICK	SAME
MAN	FEEL
WOMAN	LIFE
GIRL	GAME
BOY	SCHOOL
LAUGH	HARD

Figure Captions

Figure 1. Activation to ASL signs for all three time points: pre-exposure (T0), first post-exposure scan (T1) after 44 hours of instruction, and second post-exposure scan (T2) after 89 hours of instruction.

Figure 2. Three contrasts using paired t-tests across the time points at the same corrected $p < 0.05$ at $k = 62$.

Table 1 Brain regions activated at each time point (p -corrected < 0.05 ; $k_{min} = 62$)

Cerebral regions (Brodmann Area)	Voxels	MNI coordinates		
		<i>x</i>	<i>y</i>	<i>z</i>
T0				
R cuneus (BA 18)	726	32	-78	4
R supplementary motor area	229	12	-2	60
L superior parietal lobule	191	-32	-72	48
L inferior frontal gyrus/pars triangularis	143	-50	34	16
L middle frontal gyrus (BA 6)	97	-34	-4	58
L calcarine sulcus	77	-4	-102	-8
L posterior cingulate gyrus	73	-4	-28	38
L middle temporal gyrus	70	-56	-38	-2
R middle frontal gyrus	66	32	0	56
R posterior cerebellar lobe (vermis)	62	2	-70	-30
T1				
L middle occipital gyrus (BA 37)	8506	-54	-72	0
L anterior cerebellar lobe	8506	-32	-48	-34
R putamen	5133	30	-14	2
L inferior parietal lobule	3372	-48	-38	48
L cingulate gyrus (BA 24)	1790	-2	-4	48
R middle temporal gyrus	1309	58	-66	2
L caudate	453	-4	12	2
L putamen	453	-28	2	-4
R posterior cingulate gyrus	241	4	-34	26
L postcentral gyrus (BA 4)	203	-20	-28	68
L medial dorsal nucleus	125	-8	-16	10
R culmen	112	36	-56	-30
R inferior frontal gyrus (BA 46)	69	50	44	16
T2				
L cuneus	27669	-8	-82	18
L insula	2592	-40	-2	10
L middle frontal gyrus	637	-42	44	14
R ventral lateral nucleus	487	16	-14	16
L caudate	336	-8	8	14
L cingulate gyrus	227	-2	-32	34
R superior frontal gyrus	213	28	56	2
L middle temporal gyrus	199	-54	-30	-6
L pulvinar	139	-16	-24	6
R postcentral gyrus	118	22	-30	78
L paracentral lobule	71	-14	-42	66

Table 2 *Conjunction analyses (p -corrected < 0.05 ; $k_{min} = 62$)*

Cerebral regions (Brodmann Area)	Voxels	MNI coordinates		
		x	y	z
T2 > T1				
L inferior frontal gyrus (BA 45/47)	134	-48	38	-2
L middle orbital gyrus (BA 10)	115	-34	50	-2
T2 > T0				
L supramarginal gyrus (BA 40)	224	-58	-16	32
R supramarginal gyrus (BA 40)	119	54	-24	30
L insula/rolandic operculum (BA 13)	73	-42	-4	10
L lingual gyrus	129	-12	-70	-8
R inferior frontal gyrus/pars opercularis (BA 44)	74	56	10	14
R inferior frontal gyrus (BA 47)	82	38	16	-20
T1 > T0				
R supramarginal gyrus (BA 40)	268	56	-26	34
L supramarginal gyrus (BA 40)	318	-60	-26	28
R parahippocampal gyrus	112	36	-2	-12
R putamen	62	32	2	4
R inferior temporal sulcus (BA 19)	89	56	-66	-6
R inferior frontal gyrus/pars opercularis (BA 44)	86	54	8	14
T0 > T2				
L supplementary motor area (BA 6)	65	-8	2	62
T0 > T1				
L supplementary motor area (BA 6)	91	-6	2	62

Figure 1

Figure 2

T2 > T1

T1 > T0

T0 > T1